Attic Ventilation in Extremely Cold Climate - Field Measurements and Hygrothermal Simulation

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ABSTRACT

Attic Ventilation in Extremely Cold Climate - Field Measurements and Hygrothermal Simulation

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Concordia University, 2018.

Attic ventilation is typically recommended for the removal of moisture build-up caused by air leakage from indoors in cold climates, however, it may also increase the amount of snow and rain penetration into the attic, especially in the extremely cold climates. In northern regions, extremely cold temperatures can cause snow particles to become very fine, which will penetrate vents or unsealed openings. The snow accumulated in the attic would melt at temperatures above zero and penetrate to indoors through the ceiling and cause moisture problems. One of the solutions is to add filter membranes along a ventilation cavity behind the façade to prevent snow from entering the attic. The ventilated attics with filter membrane had some success but there were instances with reported water leakages and moisture damages. There have been also attempts to use un-ventilated cold roofs. Un-ventilated attics prevent snow accumulation but do not allow for effective removal of moisture, which could be risky and prone to moisture damages.

In this thesis, three houses in northern Canada are investigated, two of them have ventilated attics with different filter membrane designs located in Kuujjuaq and another has un-ventilated attic located in Iqaluit. Field measurements are setup in these three houses to monitor their hygrothermal performance under different venting systems. Measured results indicate ventilated attic has reasonable hygrothermal conditions which moisture content level on attic sheathing is under 20% and un-ventilated attic has higher risk of moisture problems. At the same time, hygrothermal modelling using WUFI Plus, a whole-building hygrothermal simulation software, are performed and simulation results are compared with measurements for model validation. Validated models are also performed in other location to further verify their universality. Attic ventilation rate, air leakage rate, un-intentional air infiltration rate and indoor conditions are set as variable parameters in WUFI Plus to discuss their effect on the hygrothermal performance of attics.

This thesis is intended to provide documented evidence of the hygrothermal performance of ventilated and un-ventilated attics in extremely cold climate. Simulation models validated by field measurements can be used under other climates. Recommendations on proper attic design are provided for Canadian northern housing.

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I also want to thank my whole family, it is no possible I can finish my graduate study without the supports from my parents and other family members, especially my mother. Their advanced ideas, visions and educations will benefit me for the whole life. It can be said that my family is always my strong backing and spiritual motivation.

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In the end, please allow me to summarize my graduate career in a personal style. The following two famous sayings quoted could best represent my graduate life and express my understanding of previous research experiences in the past three years:

- “吾生也有涯，而知也无涯” —— 庄子《庄子▪养生主》
  (Translation: Life is limited, while knowledge is unlimited.)
- “世事洞明皆学问，人情练达即文章” —— 曹雪芹《红楼梦》
  (Translation: A grasp of mundane affairs is genuine knowledge; Understanding of worldly wisdom is true learning.)

ACKNOWLEDGEMENT OF CONTRIBUTIONS OF MR. DANIEL BARIL

Mr. Baril designed the test protocol, calibrated and installed the sensors and equipment and set up the data collection for the field monitoring of the three test houses presented in this thesis. He made initial field observations and site visits. Chapter 3 is prepared mainly based on his work.

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Nomenclature

Symbols

Symbol	Parameter	Unit
Q_{wind}	volume of airflow	[m^3/h]
A_S	area of smaller opening	[m^2]
V	outdoor wind speed	[m/h]
K	coefficient of effectiveness	[-]
$Q_{buoyancy}$	volume of ventilation rate	[m^3/s]
C_d	discharge coefficient	[-]
A_i	free area of inlet opening	[m^2]
g	The acceleration due to gravity	[m/s^2]
h	vertical distance between inlet and outlet midpoints	[m]
T_i	average temperature of indoor air	[K]
T_o	average temperature of outdoor air	[K]
C_p	wind pressure coefficient	[-]
$\overline{\Delta C_p}$	wind pressure coefficient	[-]

Abbreviations and Acronyms

T	Temperature
RH	Relative Humidity
M	Mold Growth Index

MC	Moisture Content
ACH	Air Change per Hour
HR	Humidity Ratio
CFD	Computational Fluid Dynamics
NFVA	Net Free Vent Area
HDD	Heating Degree Days
KMHB	Kativik Municipal Housing Bureau
KSB	Kativik School Board
SIP	Structural Insulated Panel
OSB	Orientated Strand Board
SPF	Spray Polyurethane Foam
UCA	Unvented Cathedralized Attic
UCC	Unvented Cathedral Ceiling
BIPV/T	Building-Integrated Photovoltaic and Thermal
PMM	Point Moisture Measurement
UPS	Uninterrupted Power Supply
WiDAQ	Wireless Data Acquisition
BIG	Building Intelligence Gat-eway
CMHC	Canadian Mortgage and Housing Corporation
ASTM	American Society for Testing and Materials
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
NRC	National Research Council
AHFC	Alaska Housing Finance Corporation
HHFA	Housing and Home Finance Agency
BOCA	Building Officials Conference of America

HPA	High Performance Attics
U.S. DOE	United States Department of Energy
NRCA	National Roofing Contractors Association
ICC	International Code Council
IRC	International Residential Code
IBC	International Building Code
NECB	National Energy Code of Canada for Buildings
NBC	National Building Code
BC	British Columbia
FHA	Federal Housing Administration

Chapter 1 INTRODUCTION

1.1 Background

Northern Canadian communities face many challenges to sustain themselves and housing is one of the major ongoing problems. Well-designed housing with durable, affordable, fast-built and energy efficient constructions are urgently needed for the Canadian North to address rapidly growing population and extremely cold climate in this area. As low-cost structures, attic assemblies with properly ventilated and well-insulated design are widely used in houses in cold climates to control moisture. Developing and maintaining wood-frame housing in the arctic is much more demanding than that in the south. All the materials needed to construct wood-frame houses cannot be obtained locally and must be shipped from southern Canada. There lack skilled labors and an almost complete dependence on fossil fuels for energy since diesel generators are used to produce electricity. Residential construction costs in this area are 1.3 to 3.6 times higher than those in larger southern cities (NRCC, 1997). Consequently, housing shortages and crowding are common issues in many communities (Statistics Canada, 2008). Existing houses have exhibited numerous issues caused by poor design and construction. Accelerated deterioration of these houses is caused by a number of factors including the harsh climatic conditions, culturally inappropriate housing designs, and overcrowding. To help provide a sustainable future for the remote Arctic areas, affordable, energy efficient, and durable housing is needed.

A survey made by Canada Mortgage and Housing Corporation (CMHC) in the early 1980s showed that attic moisture problem always appeared in far northern climates, where there is a prolonged period of extremely cold weather (Buchan et al., 1991). The extremely cold temperatures can cause snow particles to become very fine like “icing sugar” penetrating vents and/or unsealed openings (AHFC, 2000). To avoid the penetration of fine snow particles into roofing systems, un-ventilated cathedral roof is typically built in higher latitudes of the north with smaller snow loads. This design ensures that high wind will not infiltrate into the attic space or displace the insulation and will not allow any fine snow particles to enter and accumulate. However, this type of roof reduces the amount of insulation thickness and generally has a higher construction cost. Un-ventilated cathedral roof needs to be built very air tight, in case any air leakage from the interior space entering in the roof, it will be difficult to remove the moisture.

The unconditioned ventilated attic roof construction is typically used in cold climate regions that are subjected to snow accumulation on the roofs to prevent unwanted ice damming. Having an unconditioned attic space also provides extra room for insulation above the ceiling and typically results in an overall lower cost for the roofing system. The purpose of introducing attic ventilation into roof construction is to minimize condensation and moisture accumulation in attics due to air leakage from the interior space (Rowley, Algren & Lund, 1941; CMHC, 1999; and Rose & TenWolde, 2002). This venting has three primary functions: (1) avoid ice-damming along the attic eaves; (2) remove extra moisture out of attic; and (3) cool down the attic during summer period (Blom, 2001; Roppel, Norris & Lawton, 2013). Adequate ventilation of the attic is important to ensure its performance (Lstiburek, 2006). Typically, a 1:300 ratio is recommended by most building codes when air barrier is present (TenWolde & Rose, 1999). Over-ventilation will introduce extra moisture from outside and increase attic relative humidity and moisture content in the sheathing (Rose & TenWolde, 2002). Too low ventilation also has negative effect on the moisture removal, in this case, moisture brought in attic will be more than what can be removed (Essah, Sanders, Baker & Kalagasidis, 2009). Through field measurements, Hagentoft and Kalagasidis found that if suitable ventilation was provided to cold roof, moisture risk can be reduced effectively (Hagentoft & Kalagasidis, 2010). Arfvidsson and Harderup concluded that inadequate amount of ventilation reduced the capacity of moisture removal in attic area and adding thermal insulation on the exterior sloped roofing surface contributed to moisture accumulation (Arfvidsson & Harderup, 2005).

Because of the advantages of being inexpensive and allowing for more insulation, the unconditioned ventilation attic construction has been adopted in extremely cold regions as well. However, the main issue with ventilated attic in extremely cold climates is the snow accumulation in attic spaces. The snow accumulated in the attic would then melts at temperatures above zero and penetrates to indoors through the ceiling and will cause moisture problems such as wood decay, mold growth and damages to interior finishes, etc. (United States Environmental Protection Agency, 2013). One of the solutions to deal with the snow accumulation in ventilated attics is to use a polyester filter membrane at the bottom of ventilated cladding and/or at the entrance of the attic to catch snow before it enters the attic. This strategy has been employed for several years in the Nunavik territory of northern Quebec. The design has been somewhat successful, however, from empirical evidence collected from occupants there have been reports about moisture problems and concerns of blown-in attic insulation displacement, which could be attributed to excessive attic venting. As well, there has been no extensive testing or research conducted to verify the success of this system.

Another approach to prevent snow from infiltrating attic spaces is to seal the attic such that it is not ventilated. This design has been attempted in a high-performance SIP Duplex constructed in Iqaluit, Nunavut (Baril et al., 2013). The main issue with the unvented attic is that they are very sensitive to air leakage from the house (Fugler, 1999; Ueno & Lstiburek, 2016). The moisture added to the attic spaces by air leakage from indoors escapes mainly via diffusion through the roof, which is a very slow process. Existing research shows that an unvented attic can perform well in cold climates given that air leakage is minimized (CMHC, 1993; Straube, Smegal & Smith, 2010). This sealed structure tends to maintain higher attic temperature and has limited capacity to remove built-in moisture, which may promote biological degradation of wood-based materials such as decay and mold growth (Gullbrekken, Kvande, Jelle & Time, 2016; Pallin, Boudreaux & Jackson, 2014). Through field investigation of six wooden un-ventilated cold attics in the South-Eastern region of Norway during winter season, Meloysund et al. concluded that un-ventilated attics posed some level of moisture risks (Meloysund, Blom, Bohlerengen & LianField, 2012).

To address the issue that there is limited information on the proper design of attics in extremely cold climates, a research project has been carried out to investigate the hygrothermal performance of ventilated and un-ventilated attics through field monitoring and hygrothermal simulation. This thesis reports field measured results of three test house (two houses are installed with ventilated attics and another is installed with un-ventilated attic) validated by WUFI Plus hygrothermal simulations. Parametric study based on validated models is also performed to provide recommendations to property attic design in extremely cold climate.

1.2 Objective, Methodology and Scope

The objective of this research is to 1) investigate the hygorthermal performance of ventilated and un-ventilated attics through on-site field measurements and hygrothermal simulations using WUFI Plus and, 2) provide recommendations and guide on proper attic design and help develop solutions for low-energy sustainable housing for Canadian North.

To investigate whether ventilated attics with filter membrane systems work effectively and whether un-ventilated attic is a suitable solution for the extremely cold climates, field monitoring was carried out in three houses with cold attics built in the Nunavik territory of Northern Quebec and Nunavut territory. Two of them have ventilated attics with different filter membrane designs and the third house is a Structural Insulated Panel (SIP) Prototype House with un-ventilated attic. To provide a systematic analysis of hygrothermal performance of attic ventilation under extremely cold climates, simulations using WUFI Plus are carried out. Firstly, simulation results are compared with measurements for WUFI Plus model validation and secondly, the validated models are used for parametric study to identify the influence of main variables on the hygrothermal conditions of attic. Relative humidity (RH) and temperature (T) of attic area and moisture content (MC) levels and temperature (T) of plywood sheathing are used as the main performance indicators. The validated WUFI Plus models can be used to assist proper attic design in northern arctic areas to improve attic's durability, extend attic's service life and to avoid the occurrence of moisture problems in attic space under future climates.

The analysis of more than one-year moisture content level (MC) and temperature (T) collected from plywood sheathing, roof truss and relative humidity (RH) and temperature (T) measured at attic air in different venting systems in remote northern arctic area are presented.

The scope of the research is as follows:

1) Field measurements and data analysis of hygorthermal performance of three houses with ventilated and un-ventilated attics;
    - Two houses with ventilated attic using different filter membrane designs in Kuujjuaq and one un-ventilated attic in Iqaluit are instrumented to collect field measured data (RH/T of attic air; MC/T of attic sheathing).

- Performance analysis including RH/T and seasonal moisture excess in attic air, MC/T of plywood sheathing, and mold growth index on plywood sheathing surfaces.

2) Validation of WUFI Plus models by comparing the simulation results with measurements including RH/T of attic air for House I (test house installed with ventilated attic located in Kuujjuaq) and House III (test house installed with un-ventilated attic located in Iqaluit), and MC/T of plywood sheathing for House I;
3) Parametric study is performed based on validated hygrothermal model;
   - For ventilated attic, outdoor air and indoor air are the main moisture sources which will affect attic hygrothermal performance. Therefore, attic ventilation rate (1ACH, 5ACH, 10ACH) and ceiling air leakage rate through ceiling plane (10%, 30%, 60%) are controlled as variable input parameters in WUFI Plus model.
   - For un-ventilated attic, indoor air is the main moisture source because of its fully-sealed construction. Therefore, air leakage rate through ceiling plane (10%, 30%, 60%) and background infiltration (0.05ACH, 0.09ACH and 0.18ACH) through attic construction are selected as variable input parameters in WUFI Plus model.
4) Design recommendations of attic constructions are provided for extremely cold climates.

1.3 Outline of the Thesis

This thesis is organized as follows:

- Chapter 2 presents literature review and identified knowledge gap. This chapter summaries research history, characteristic, mass balance within attic spaces, state-of-the-art research and knowledge gaps related to ventilated and un-ventilated attics. Meanwhile, as the key design factor of ventilated attic, the code requirements and industry guidelines of attic ventilation rate are introduced specifically.
- Chapter 3 presents the experiment setups in two test houses with ventilated attics under different filter membrane designs in Kuujjuaq and one test house with un-ventilated attic in Iqaluit. Detailed information of field observations and instrumentations are also introduced in this chapter.
- Chapter 4 presents data analysis results of field measured data (RH/T and humidity ratio of attic air, MC/T of plywood sheathing, calculated mold growth index on attic sheathing surface) in three test houses.
- Chapter 5 presents the hygrothermal simulation using WUFI Plus, including detailed settings of WUFI Plus models of House I and House III; model validation with field measurements and different locations.
- Chapter 6 presents parametric study results of House I (ventilated attic) and House III (un-ventilated attic) based on validated hygrothermal models. Meanwhile, the effects of ceiling air leakage rate and attic ventilation rate are investigated for ventilated attic. The effects of ceiling air leakage rate and un-intentional air infiltration are investigated for un-ventilated attic.
- Chapter 7 summarizes the research findings, conclusions, and contributions of this research. Research limitation and future works are also discussed.

Chapter 2 LITERATURE REVIEW

This chapter summarizes history, application and state-of-the-art researches of ventilated and un-ventilated attics. The conditions of extremely cold climate in Northern Canada is also described in this chapter. Meanwhile, attic ventilation rate is a significant parameter which will affect moisture accumulation in attic zone. Most of building codes stipulate 1:300th, which is the recommended NFVA (Net Free Vent Area) value for cold climate. Additionally, several previous studies for attic ventilation rate testing are summarized in this chapter.

2.1 Extremely Cold Climate in Northern Canada

Northern Canada Territory area of which accounts for 25% of the Arctic region and 40% of Canada's land mass (National Aboriginal Economic Development Board, 2016). Northern Canada, colloquially the North, has designated by Canadian government which is referring to three territories of Canada: Yukon, Northwest Territories and Nunavut politically. The tested houses monitored are located in Kuujjuaq in Nunavik and Iqaluit in Nunavut.

Figure 2-1. Heating Degree Days (HDD) map of Canada.

Extremely cold climate is also called as arctic climate or subarctic climate. As the term implies, this climate is more common in the Arctic Circle and surrounding areas. There is no clarified definition of Arctic climate, description of climate characteristic needs the support of long-term weather data (Cornick, 2005). The World Meteorological Organization defines “climate normal” based on the set of data during the period from 1971 to 2000 (World Meteorological Organization, 1989). Generally speaking, extremely cold climate specified refers to the climate has harsh cold condition in most of years comparing with normal climate. To be specific, average January temperatures under this climate usually range from about −40°C to 0 °C (−40°F to +32°F), and winter temperatures can drop below −50 °C (−58 °F) over large parts of the Arctic. Average July temperatures range from about −10°C to +10 °C (14 to 50 °F) with some land areas occasionally exceeding 30 °C (86 °F) in summer (Comiso & Hall, 2014). As shown in Figure 2-1, Iqaluit and Kuujjuaq are under extremely cold climate which have heating degree days (HDD) more than 7000 days. And based on ASHRAE 90.1/NECB/NBC climate divisions, Kuujjuaq and Iqaluit are in Climate Zone 8 which is named as “subarctic zone” (ASHRAE, 2010).

Global warming and rising sea levels will affect future climate change which are closely related to people’s daily life. Their influences are even worse for Northern Canada under extremely cold climate where always covers by everlasting snow in most of the year. This phenomenon is proved by both past climate and future climate in Northern Canada. According to statistics, there is a dramatic warming at the start of the current interglacial period during the past 150 years. The warming change of that 150 years is even greater than that of 10,000 years ago. On the other hand, overall model projections predict temperature in eastern and western parts of North Canadian regions will increase by about 2 ℃ with near 7% increase in rainfall (Prowse, Furgal, Bonsai & Edwards, 2009).

2.2 Northern Housing Challenges

In the last 30 years, Northern Canada has experienced considerable technological changes (Bolton et al., 2011). Even though vast improvements have been made to the infrastructures and housing over the past few decades, major issues including overcrowded housing and dependence on fossil fuels for heating and electrical generation remain as lingering challenges.

Overcrowding has led to many social and health problems among the mostly Inuit population (Khan, Dery & Menzies, 2010). Overcrowding tends to generate high levels of moisture in homes, which can cause moisture damage leading to premature failure of building components. A shortage of skilled labor and local building materials in the remote communities forces expensive transportation of supplies and workers from southern regions. Coupled with an annual population growth rate of 2% and a short construction season, it is challenging to catch up with the growing housing needs in the north (Kativik Regional Government and Makivik Corporation, 2010).

Northern Canada is also totally dependent on fossil fuels for heating and electrical generation, consuming 170 million liters of petroleum in 2005-2006 (Kativik Regional Government and Makivik Corporation, 2010). With the rising costs of fuels, and an increase in construction and natural resource exploitation, the need for new innovative building designs which can be constructed rapidly, energy efficient and sufficiently durable to withstand this harsh environment, are required to help provide a sustainable future for the Arctic.

2.3 Ventilated Attic in Cold Climate

Ventilated attic, also called as cold attic, is a typical structure normally used in North America. The aim of attic ventilation is to remove excessive moisture and then avoid the occurrence of durability issues. Attic ventilation can be affected by many factors, and it’s easy to find out design recommendations for specific design items of most of building codes in North America. Detailed design parameters, such as vent ratio, locations of attic vents and ceiling insulation thickness, should be considered in ventilated attic design. This section mainly introduces research history, functions and typical constructions, researches up to date under specific topics and knowledge gap of ventilated attic applied in cold climate.

2.3.1 Research History

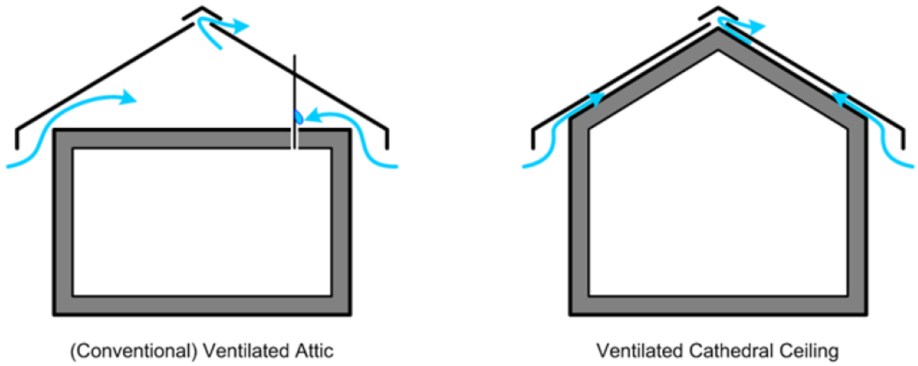


Figure 2-2. Typical ventilated roof construction (Smegal, Straube, Grin & Finch, 2017).

As a type of effective and economic design for pitched wood-frame roof structure, ventilated attic is a typical construction widely used in low-rise residential houses and light commercial buildings. Ventilated roof has two typical constructions: conventional ventilated attic and ventilated cathedral ceiling, which are shown in Figure 2-2 (Smegal, Straube, Grin & Finch, 2017). Meanwhile, ventilated attics are mostly used in residential houses in North America with unconditioned and unoccupied attic area (Blom, 2001).

As early as 1930s, attic ventilation is recommended for construction design from US Forest Products Laboratory (Browne, 1933). The first research about the relationship between attic ventilation and attic durability issues was conducted by Rowley et al., laboratory measurements of minimum attic ventilation rates were tested at the University of Minnesota (Rowley, Algren & Lund, 1941). Venting area requirement is set as 1:300 ratio according to the summarization by Housing and Home Finance Agency (HHFA) directed by Federal Housing Administration (FHA) in 1942 (Schumacher, 2008). Ralph Britton carried out a number of tests on evaluating the condensation risk of different types of wall and roof assemblies at Penn State University in 1948 and 1949. The detailed research results were published in 1995, which are considered as the first-hand formulation of 1:300 ratio (Rose, 1995). Attic ventilation becomes the requirements of Building Officials Conference of America (BOCA) which is the first Model Building Code established in 1948 (Building Officials Conference of America, 1948). The specific item on this code in section 115.3 is mentioned that *"All attic spaces and unoccupied spaces between roofs and top floor ceilings shall be ventilated by not less than (2) opposite louvres or vents with a total clear area of opening not less than one third (1/3) of one (1) per cent of the horizontally projected roof area."* Applications of attic ventilation have a long history, historical utilization of attic ventilation can be dated back to the National Building of Canada built in 1953. As shown in Figure 2-3, compared to past attic constructions, current ventilated attics have thicker ceiling insulations which will cut back heat flow and air leakage through indoor conditions (Dell, 2015). Cleary and Sondereger create a dynamic model to predict hourly attic air humidity ratio which is verified by comparing with long-term field measured data. This model established for studying humidity storage lays a good theoretical foundation for defining moisture flow in the attic zone (Cleary & Sondereger, 1987). This model is developed by Ford in 1982, his article derives the mathematical formula of attic ventilation velocity and reports the interrelation between attic air dry-bulb temperature and dew-point temperature based on on-site measurement in actual attics (Ford, 1982). Several researches indicate attic ventilation have a good performance for moisture removal within attic zone while there is no obvious effect on heat transfer mechanism with surroundings (Al-Obaidi, Ismail & Rahman, 2014). Ventilated attic is good to be applied in almost all climate zones, except for cold coastal climates which are always under high humidity levels and some regions of far north in Climate Zone 8 which always have the high snow load (Roppel, Norris & Lawton, 2013). This construction is especially beneficial for cold climates and previous studies have shown that attic ventilation has a significant effect on reducing condensation on roof sheathing (Rowley et al., 1941; Rose & TenWolde, 2002). In the early 2000s, "About Your House" series published by Canada Mortgage and Housing Corporation (CMHC) specially offer guidance to residential homeowners. The guidance of this series points out the performance of attic ventilation is overrated as a standalone strategy (Birkbeck, 2017). However, application of ventilated attic in extremely cold climate is still under development stage, this thesis provides documented evidences for this research area supported by field measurements and WUFI Plus simulation.

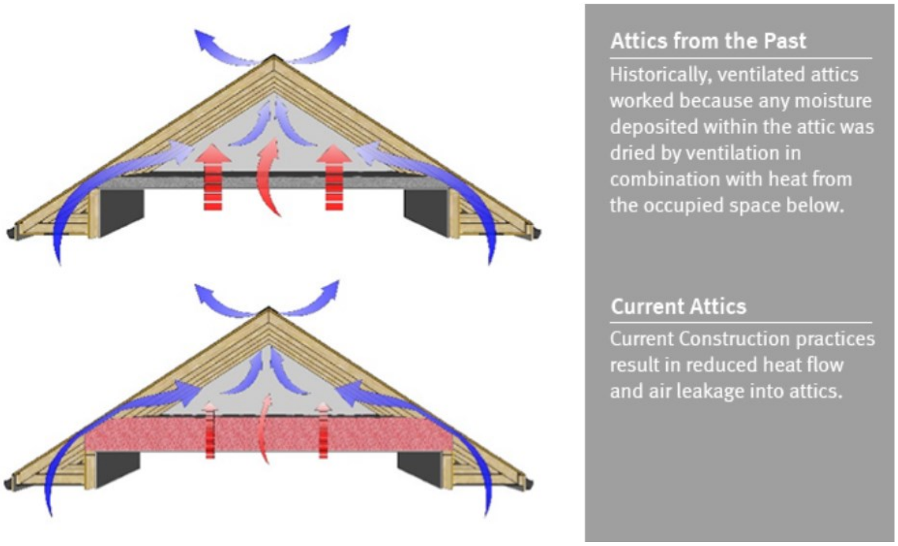


Figure 2-3. Comparison between traditional and current attics (Marcus, 2015).

2.3.2 Advantages and Disadvantages of Ventilated Attics

In cold climate, the primary purpose of attic ventilation is to maintain attic in relative cold condition to prevent snow from melting or ice damming in soffit vents and avoid any moisture-related issues (Samuelson, 1998). Besides, attic ventilation has other advantages listed as follows (Barth, 2015):

1) Good to avoid moisture damage issues. Excessive moisture build-up within attic will damage wood structure (hygroscopic materials), shorten attic's service life or cause mold or fungus growth;
2) Prevent damage of attic shingle caused by high temperature in summer and extend its service life;
3) Reduce energy consumption. Attic ventilation is a good method to cool down attic zone and exhaust additional heat, which cut the bill for air conditioning, especially for the living space below the attic.

It is pointed out that attic ventilation and air leakage through ceiling plane from living space are the two main moisture penetration paths of ventilated attic. However, attic ventilation has the risk to introduce excessive moisture through surrounding air, thus, adequate attic ventilation rate is an important factor to control moisture condition within attic zone. Indoor air penetrates through attic ceiling plane because of a lack of sufficient airtightness, which will affect moisture levels within attic place.

2.3.3 Mass Balance of Ventilated Attic

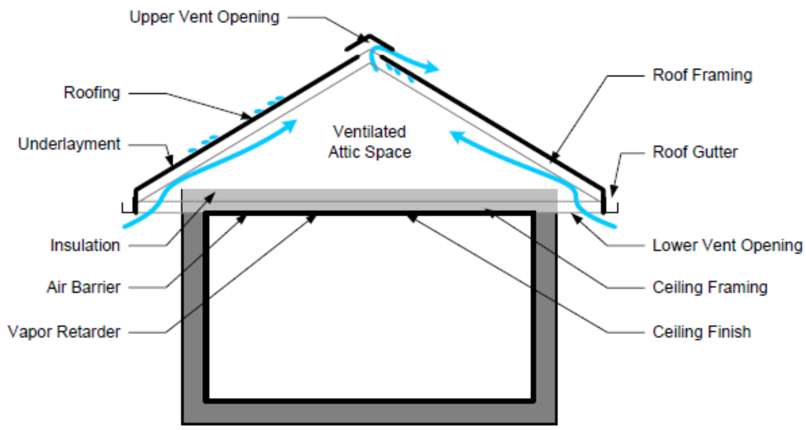


Figure 2-4. Airflow path for typical ventilated attic assembly (Schumacher, 2008).

Figure 2-4 shows detailed components and air movement process of a typical ventilated attic assembly. As defined in ASHRAE Fundamental 2013, ventilation is the process of intentional introduction of air from the outdoors into a building (ASHRAE, 2013). There are two types of attic ventilation divided by driving forces, natural attic ventilation and mechanical attic ventilation. In this thesis, only attic ventilation driving by natural air is involved. Wind forces and buoyancy forces (also called as stack effect) are the two main driving forces for natural attic ventilation.

Wind blows over attic construction will cause pressure difference between windward side and leeward side. Wind will be introduced in attic space through vents in windward side because this side generates positive pressure and exhausted in leeward-side openings. Wind speed, wind direction, surrounding topography and exposed level of building will impact the magnitude of attic ventilation rate and then affect natural ventilation process in attic space. The volume of wind-induced airflow is expressed in Equation 2.1 (Owens Corning Roofing and Asphalt LLC, 2015).

$$Q_{wind} = K \times A_S \times V \tag{2.1}$$

Where, Q_{wind} ——volume of airflow (m^3/h);

A_S —— area of smaller opening (m^2);

V —— outdoor wind speed (m/h);

K —— coefficient of effectiveness, which ranges from 0.4 (for wind hitting an opening at a 45-degree angle) to 0.8 (for wind hitting at a 90-degree angle).

Buoyancy-induced ventilation is caused by temperature difference between attic space and outdoor environment. Air density difference caused by temperature difference will make outdoor air enter attic space. At the same time, temperature difference also exists in upper and lower parts of attic which will cause air movement within attic space. The temperature difference between upper and lower parts of attics depends on angles of roof assemblies, i.e. the height between air inlet and outlet. Therefore, buoyancy induced ventilation is also called as stack effect. The volume of wind-induced airflow is expressed in Equation 2.2 (Walker, 2016).

$$Q_{buoyancy} = C_d \times A_i \times \sqrt{2gh\,(T_i - T_o/T_i)} \tag{2.2}$$

Where, $Q_{buoyancy}$ —— volume of ventilation rate (m^3/s);

C_d —— 0.65, discharge coefficient;

A_i —— free area of inlet opening (m^2), which equals area of outlet opening;

g —— 9.8 (m/s^2), the acceleration due to gravity;

h —— vertical distance between inlet and outlet midpoints (m);

T_i —— average temperature of indoor air (K), note that 27°C = 300 K;

T_o —— average temperature of outdoor air (K), note that 27°C = 300 K.

Moisture balance within attic space is a dynamic process because of attic ventilation. Outdoor air enters in attic induced by wind pressure and buoyancy effect through soffit vents and exhaust through rigid vents. Attic ventilation can remove excessive moisture inside of attic space while can also bring in outdoor moisture. There are three moisture sources considered in ventilated attic: outdoor air through attic ventilation, un-intentional air infiltration of attic construction and air penetrating from indoor space.

2.3.4 State-of-the-art Research

The purpose of introducing attic ventilation into roof construction is to minimize condensation and moisture accumulation in attics due to air leakage from the interior space (CMHC, 1999; Rowley et al., 1941; Rose & Anton, 2002). This venting has three primary functions: (1) avoid ice-damming along the attic eaves; (2) remove extra moisture out of attic; and (3) cool down the attic during summer period (Blom, 2001; Roppel et al., 2013). Attic ventilation can be applied in many different climates such as hot-humid or cold-dry climates. It has a positive effect on reducing space cooling energy and moisture control in hot-humid climate, such as Florida homes. However, there is also risky to introduce extra moisture to the attic space by attic ventilation in this climate, which may allow moisture transfer to indoor space when ceiling air sealing in not sufficient. Roof shingle color has a greater impact on attic temperature than attic ventilation summarized by review materials (Parker, 2005). Hutchinson makes recommendations to low-sloped attic assembly design under northern climates (ASHRAE Zone 4 and above) through reviewing failed designing cases and historical designs. He concluded that venting, vapor retarders in the ceiling planes and colors of roofing materials will affect attic performance and then determine the success or failure of attic design (Hutchinson, 2017).

Adequate ventilation of the attic is important to ensure its performance (Lstiburek, 2006). Typically, a 1:300 ratio is recommended by most building codes when air barrier is present (TenWolde & Rose, 1999). Over-ventilation will introduce extra moisture from outside and increase attic relative humidity and moisture content in the sheathing (Rose & TenWolde, 2002). Too low ventilation also has negative effect on the moisture removal, in this case, moisture brought in attic will be more than what can be removed (Essah, Sanders, Baker & Kalagasidis, 2009). Through field measurements, Hagentoft and Kalagasidis found that if suitable ventilation was provided to cold roof, moisture risk can be reduced effectively (Hagentoft & Kalagasidis, 2010). Arfvidsson and Harderup concluded that inadequate amount of ventilation reduced the capacity of moisture removal in attic area and adding thermal insulation on the exterior sloped roofing surface contributed to moisture accumulation (Arfvidsson & Harderup, 2005).

A number of studies have investigated the design parameters of attic construction. Most of building codes in North America prescribe a minimum net free ventilation ratio, minimum vent and insulation clearance and venting area under similar climatic conditions. However, there is no much detail to describe the design of attic baffle size and vent configuration. Iffa and Tariku investigated the effects of different baffle size and different locations of attic vents on attic air distribution under both summer and winter periods through field measured data and validated CFD model. Research results show that air flow distribution will enhance when upper vent is located at ¼ distance from the top ridge. And baffle size has a significant effect on attic ventilation rate (expressed on ACH value), ACH values increase dramatically with the increase of baffle sizes, when attic experiences wind-induced ventilation (Iffa & Tariku, 2015). Kimmo conducted field experiments to measure moisture content levels in three cold attics under controlled ventilation of wood-based pitched roofs in Sweden. Field measured data indicates moisture levels of 13% to 16% varied within an acceptable range over the testing period, while the initial MC levels were in high values. The change of measured results indicates drying potential of wooden constructions and provides data support to attic design (Kurkinen, 2017). The effect of wind pressure coefficient (C_p) on wind-induced attic ventilation is investigated through large-scale field measurements conducted by Gullbrekken et al.. The measured results show that wind pressure coefficient along eaves of attics is influenced by incident wind angles. And average value of wind pressure coefficient ($\overline{\Delta C_p}$) is 0.7 derived by measured data which can be applied to one- or two-storey houses with pitched roofs under different roof angles (Gullbrekken, Uvsløkk, Kvande, Pettersson & Time, 2018).

Baril setup field monitoring of hygrothermal performance of ventilated and un-ventilated attics in Canadian north. Preliminary measured results are presented in 2013 by Baril et al. and long-term measured results are further summarized and analyzed by Ge et al. (Baril, Fazio & Rao, 2013; Ge, Wang & Baril, 2018). Kayello et al. examined hygrothermal performance of a number of attics with different ventilation methods under arctic climate, including RH controlled ventilation, BIPV/T mechanical & natural ventilation, mechanical & natural ventilation and un-ventilated, using WUFI Plus (Kayello, Ge & Athienitis, 2017). Simulation results indicate that ventilated attics either mechanically or naturally have better hygrothermal performance within attic space. Thirunavukarasu investigates northern housing in Yellowknife and Northwest Territories, based on the interview of local builders and occupants, ventilated attic is the preferable construction because it's more durable to avoid moisture-related issues and comparatively economic (Thirunavukarasu, 2017).

2.4 Un-Ventilated Attic in Cold Climate

Un-ventilated attic, also called as hot attic or sealed attic, is getting popular in North America. Because of its fully-sealed structure, un-ventilated attics have the advantage of reducing heating load in cold climates. Under some climatic conditions, un-ventilated attic assemblies may be preferred than vented attic assemblies. This section summaries research history, advantages and disadvantages, moisture balance mechanism and current researches of un-ventilated attics.

2.4.1 Research History

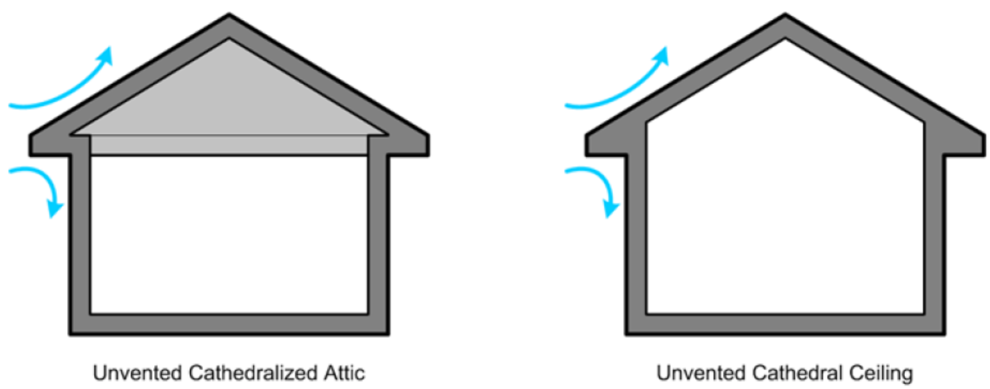


Figure 2-5. Typical un-vented roof construction (Smegal et al., 2017).

Un-ventilated (cathedralized) attics is also called as sealed attics, as its name implies, it's a sealed construction without any openings that allow air exchange between attic space and outdoor environment. Figure 2-5 shows two types of typically un-ventilated and unconditioned attic constructions: unvented cathedralized attic (UCA) and unvented cathedral ceiling (UCC) (Smegal et al., 2017). Compared to conventional attic assemblies, the thermal, moisture and air control layers of un-ventilated attic are moved to the plane of roof deck. And the structure of un-ventilated attics is also different from that of cathedral ceilings. Whether ventilated or un-ventilated, the key difference between these two constructions is the presence of interior finishing materials. Interior finishing materials are installed in the underside of attic framing and insulation in cathedral ceilings. While un-ventilated attics have no interior finishing materials, attic insulation and framing are directly exposed to attic air (Parker, 2005). Spray polyurethane foam (SPF) is the most common insulation material recommended by the majority of building envelope engineers and experts because of its good air-tightness characteristics. Meanwhile, both open-cell (low density) and closed-cell (medium density) SPF can be used as insulation materials of un-ventilated attics in all climates (Covestro LLC, 2016).

The first application of un-ventilated attic assemblies can date back to 1970s, which is a popular construction conforming to High Performance Attics (HPA) performance path compliance (California Energy Commission, 2015). According to the research conducted in 1996, un-ventilated attic assemblies are recommended to be widely applied in North America area by U.S. Department of Energy (U.S. DOE) because this type of structure have positive effect on energy saving under zone 6 climate (Icynene Inc., 2013). According to statistics, there are at least 100,000 un-ventilated attics have been built in new residential houses since 1995 in the U.S. (Schumacher, 2007). The earliest design recommendations of un-ventilated attic assemblies were adopted by International Code Council (ICC) in 2004 and published in the Section R806.4 of International Residential Code 2006. The performance monitoring of un-ventilated attics in the U.S. started with building demonstration houses in the early 2000's. These research results provide evidences on design guidance and codes development. Key factors which will affect durability performance of un-ventilated attic assemblies are well-sealed ceiling and controlled indoor humidity levels. While un-ventilated attic design has good in-service feedbacks and the detailed design guidance can be found in Canadian building codes (Birkbeck, 2017).

2.4.2 Advantages and Disadvantages of Un-Ventilated Attics

Un-ventilated attic is a construction that has air-impermeable insulation installed underneath roof deck instead of in the ceiling plane. The attic space is intentionally sealed from the outdoor environment. At the same time, attic insulations are connected with wall insulations which becomes a part of insulated building envelope. Air tightness is important to un-ventilated attics because it is a type of fully-sealed construction without any ventilated openings. And this construction also can effectively avoid the formation of ice dams which can extend the service life of building materials. The main advantages of un-ventilated attics are listed as follows:

1) Easy to build, there is no attic vents needed to install;
2) Prevent ice damming by adding enough insulation and avoiding air leakage;
3) Good to energy saving, un-ventilated attic is a construction which is warmer in winter and cooler in summer.

However, un-ventilated attics also have disadvantages:

1) Insulation installation at roof level is more difficult than at ceiling plane directly;
2) Higher roof sheathing temperature and shingle temperature because the sealed construction of un-ventilated attic without any openings.

2.4.3 Mass Balance of Un-Ventilated Attics

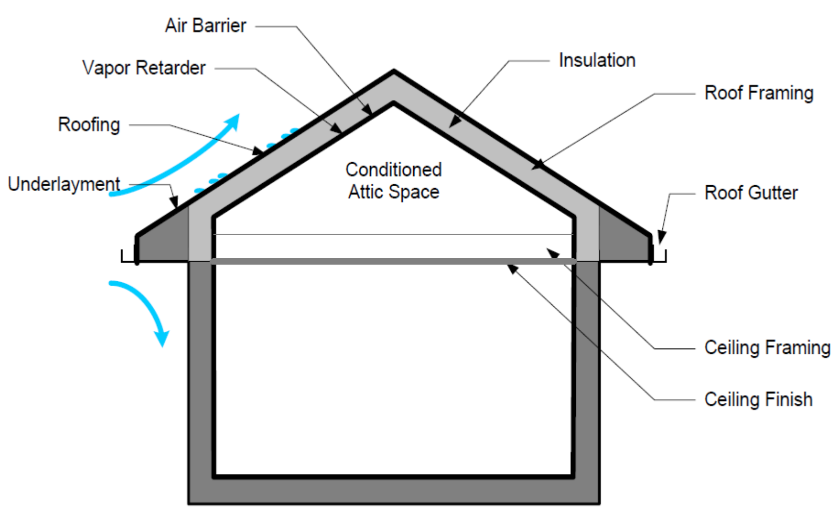


Figure 2-6. Airflow path for typical un-ventilated attic assembly (Schumacher, 2008).

Figure 2-6 shows the airflow path for typical un-ventilated attic (UCA) assembly (Schumacher, 2008). Un-ventilated attic area is a sealed independent space which can be used for mechanical equipment. Because there is no vent installed, moisture source from outdoor environment is only can through air leakage of un-intentional air infiltration which depends on airtightness characteristic of attic construction itself. However, the main moisture source of un-ventilated attic is from living space, humidity level and ceiling air leakage rate are the two key factors that will affect hygrothermal performance within un-ventilated attic space. Without venting systems, moist air in un-ventilated attic cannot be removed timely. When indoor moisture transfers to the attic space carried by air leakage through ceiling plane, especially under high indoor humidity level, moisture-related problems may occur and cause durability issues on attic plywood sheathing. Wood-based sheathing boards are sensitive to water vapour as a type of hygroscopic material. The MC level of attic sheathing can be selected as performance criteria because it always the first place where vapour diffusion and air leakage condensation will take place, especially during the heating season in cold climate (Smegal et al., 2017).

2.4.4 State-of-the-art Research and Knowledge Gap

Un-ventilated attic assemblies (UCA) can be applied in most climates all round world. However, there are limited research that have been reported on evaluating the performance of this type of attic structure under cold climate, especially under extremely cold climate. Research group from University of Waterloo and Building Science Corporation developed a research related to hygrothermal modeling covering all climate zones in the United States. Simulation results indicate that both SPF and fibrous insulation can be applied in UCA assembly when indoor humidity in wintertime is controlled and attic construction is under a good airtightness status. This paper summarizes the key factors should be considered in the design of UCA, which are the exposure duration of roofing, vaper permeance characteristic of insulation materials and indoor humidity levels (Straube, Smegal & Smith, 2010). Rudd from Building Science Corporation reported filed measured results of temperature of asphalt shingles tested in Jacksonville, Florida in the United States and the combination of attic pressure differentials and air leakage rates tested in Banning, California in the United States of UCA construction. For asphalt shingle temperature, field measured results of UCA are 0.2 ℉ greater than that of standard ventilated attic during the whole testing period. For attic pressure differential and air leakage rates, field measured results show roof plane carried 70% (15.7 Pa) pressure differential on average and ceiling plane carried the rest. These researches provide data support to future researches related to the performance of UCA construction, and the result is also good to promote the durability of roofing material. Moreover, it also can provide evidence to modify building design criteria because climates will affect the selection of insulated method and vapor diffusion resistance strategies of UCA assemblies (Rudd, 2005). One-year monitoring of hygrothermal conditions (attic air and plywood sheathing temperature) of UCA assemblies with medium colored tile roofs comparing with ventilated attics were setup in 1997 in Las Vegas. Testing results indicate houses constructed with UCA assemblies can be beneficial under the hot-humid climate (Rudd & Lstiburek, 1999).

As introduced in the previous section, open-cell and closed-cell SPF insulation are the most popular insulation materials used in UCA because of their good air-impermeable characteristic. There are no openings of UCA to remove built-in moisture, therefore, indoor humidity level should be controlled to avoid moisture transfer from living space to attic area. This specific construction makes UCA a better design in wooden areas which will have a positive effective on preventing wildfire (Schumacher & Reeves, 2007). ASTM D22.05 subcommittee on indoor air develop one-dimensional transient dynamic numerical simulation models to test SPF temperatures in UCA assemblies of residential houses (Duncan, 2017). Insulating methods and vapor resistance controlling are important to UAC design. ASTM International is developing a new standard named ASTM WK54379, Standard Guide for the Evaluation, Rehabilitation and Retrofit of Existing Steep Sloped Roof Assemblies (ASTM, 2017). This standard aims to improve the performance of sloped roof, include UCA construction, according to practical application cases and updated energy codes (Cyphers, Wagner & Knorowski, 2017).

2.5 Attic Ventilation Rate

For natural ventilation in attic, wind speed and wind direction have significant impact on attic ventilation rates. Several experiments were setup to measure ventilation rates under different climates, and the earliest study of attic ventilation rates testing can be traced back to 1977. Burch and Treado conducted an experimental study to investigate energy consumption conditions under different attic venting system. Three houses in Houston, Texas were tested. When the wind speed was 4 m/s and wind direction was from SSE, attic ventilation rates of 5.6 ACH and 4.4 ACH were measured under different air leakage rates from living space to attic area, respectively (Burch & Treado, 1979). Forest and Walker measured attic ventilation rate of two unoccupied houses through tracer gas injection method located near Edmonton, Alberta, Canada from Dec. 1990. Meanwhile, one attic (named as Attic 5) ventilates through the background leakage of the roof sheathing and gable ends without any other intentional openings, and other one (named as

Attic 6) has soffits and flush-mounted vents. The two-year measured results indicated that attic ventilation rates were particularly influenced by wind direction and increased with wind speed. Detailed data collection and analysis were published in 1995. Statistical results showed that ventilation rates in Attic 5 range from 0 to 7 ACH (average wind speed is 9 m/s) and while in Attic 6 varies between 0 and 50 ACH with mean ventilation rate is around 20 ACH when average wind speed is about 6 m/s (Forest & Walker 1992; Walker & Forest 1995). Attic ventilation rates of four typical sloped roofs with different vents and soffits design were tested in wooden structure buildings using tracer gas system in BC province. Test results show that weekly average ventilation rates range from 1 to 5 ACH under two measuring periods (December 8th to 15th and February 20th to 27th) (Roppel et al., 2013).

There are no field experiments conducted to test attic ventilation rate in extremely cold climate, especially in Northern Canadian region. The effect of fine-grained snow caused by extremely cold temperature blowing into attic space through attic ventilation is also needed to be investigated, especially the hygrothermal performance of attic.

2.6 Code Requirements & Industry Guidelines of Attic Ventilation Rate

Attic ventilation rate, in air-change per hour (ACH), is defined as the quantity of attic ventilation. It’s important to design attic under reasonable ventilation rate to guarantee its performance (Lstiburek, 2006). Too high ventilation rate has the risk of introducing excess moisture through outdoor air under high humidity environment which may cause durability issues of wooden constructions in attic space, such as mold growth and decay in sheathing and truss (Rose & TenWolde, 2002). However, too low ventilation rate also has side effects, especially moisture removal. Insufficient ventilation cannot remove most of build-up moisture inside the attic, and moisture accumulation in attic space will cause durability problems as well (Arfvidsson & Harderup, 2005).

Net Free Vent Area (NFVA) means the total unobstructed area (usually measured in square inches), through that air can enter or exhaust a non-powered ventilation component, which is used to describe vent area. A vent’s effectiveness is measured by its NFVA, which is normally presented by the ratio of the area of the ventilation openings in attic to the area of attic space. As the main indicator used for attic venting design, a 1:300 ratio is typically used in cold climates to avoid fine particles from outside penetration.

Minimum attic ventilation requirements of current codes are listed as follows:

International Residential Code * 2015 (IRC 2015)

International Residential Code * 2015 (IRC 2015) is applied to detached one- and two-family dwelling and townhouses, which is updated every three years. Section R806 in the latest version of IRC 2015: Roof Ventilation of IRC 2015 describes ventilation requirements. This code mentions that the minimum NFVA should be 1:150 ratio of the vented space (International Code Council, 2014). The detailed items are intercepted as follows:

- **R806.1 Ventilation required.** Enclosed attics and enclosed rafter spaces formed where ceilings are applied to the underside of roof rafters shall have cross ventilation for each separate space by ventilating openings protected against the entrance of rain or snow...
- **R806.2 Minimum vent area.** The minimum net free entilation area shall be 1:150 of the area of the vented space.

  Exception: The minimum net free ventilation area shall be 1:300 of the vented space provided one or more of the following conditions are met:

  1. In Climate Zones 6, 7 and 8, a Class I or II vapor retarder is installed on the warm-in-winter side of the ceiling.

  2. Not less than 40 percent and not more than 50 percent of the required ventilating area is provided by ventilators located in the upper portion of the attic or rafter space...with the balance of the required ventilation provided by eave or cornice vents.

- **R806.3 Vent and insulation clearance.** Where eave or cornice vents are installed, insulation shall not block the free flow of air. A minimum of a 1-inch (25 mm) space shall be provided between the insulation and the roof sheathing and at the location of the vent.
- **R806.4 Installation and weather protection.** Ventilators shall be installed in accordance with manufacturer's instructions. Installation of ventilators in roof systems shall be in accordance with the requirements of Section R903. Installation of ventilators in wall systems shall be accordance with the requirements if Section R703.1.
- **R806.5 Un-ventilated attic and vented enclosed rafter assemblies.** Un-ventilated attics and un-ventilated enclosed roof framing assemblies created by ceilings that are applied directly to the underside of the roof framing meembers and structural roof sheathing applied directly to the top of the roof framing members/rafters, shall be permitted where all the following conditions are met…

International Building Code * 2018 (IBC-2018)

International Building Code is promulgated every three years through the ICC Code Development Process, and the latest version is International Building Code * 2018 (IBC-2018). IBC-2018 can be applied to all buildings except detached one- and two-family dwellings and townhouses up to three stories (Kelechava, 2017). IBC-2018 requires that buildings shall be provided ventilation, normally through natural and mechanical means. The requirements of enclosed ventilated attics and un-ventilated attics are stated in Section 1202.2 (Roof Ventilation) of Chapter 12 (Interior Environment). This section describes the specific requirements of attic ventilation, for example: ventilation openings, ventilation in cold climate, ventilation area. Meanwhile, IBC-2018 specifies that NFVA shall be not lower than 1:150 of the area of the space ventilated. However, when this construction is located in Climate 6, 7 and 8, NFVA shall be reduced to 1:300.

The specific items of ventilated and un-ventilated attics are listed as follows:

- **1202.2.1 Ventilated attics and rafter spaces.**
  Enclosed attics and enclosed rafter spaces formed where ceilings are applied directly to the underside of roof framing members shall have cross ventilation for each esperate space by ventilation openings protected against the entrance of rain and snow. Blocking ad bridging shall be arranged so as not to interfere with the movement of air. An airspace of not less than 1 inch (25 mm) shall be provided between the insulation and roof sheathing. The net free ventilating area shall be installed in accordance with manufacturer's installation instructions.

  > **Exception:** The net free cross-ventilation area shall be permitted to be reduced to 1/300 provided both of the following conditions are met
  >
  > 1. In Climate Zones 6, 7 and 8, a Class I or II vapor retarder is installed on the warm-in-winter side of the ceiling.
  >
  > 2. At least 40 percent and not more than 50 percent of required venting area is provided by ventilators located in the upper portion of the attic or rafter space…….Where the location of wall or roof framing members conflicts with the installation of upper ventilators, installation more than 3 feet (914 mm) below the edge or highest point of the space shall be permitted.

- **1202.2.3 Un-ventilated attic and un-ventilated enclosed rafter asseblies.**

Un-ventilated attics and un-ventilated enclosed roof framing assemblies created by ceilings applied directly to the underside of the roof framing members/rafters and the structural roof sheathing at the top of the roof framing members shall be permitted where all of the following conditions are met.

NRCA's Guidelines on Attic Ventilation

National Roofing Contractors Association (NRCA) is a non-profit organization aiming to give practical guidelines for the roof industry. NRCA's technical reports provide applied guidance for roof assemblies, especially for installation and application. One of the technical reports named "Ventilation for Steep-Slope Roof Assemblies" pointed out proper attic ventilation is important for the steep-slope roof. The detailed requirements of attic ventilation in NRCA are listed as follows (Owens Corning Roofing and Asphalt LLC, 2015):

- NRCA recommends attic ventilation in the minimum amount of 1 square foot of net free ventilation area for every 150 square feet of attic space (1:150) measured at the attic floor level (e.g., ceiling).
- NRCA suggest the amount of attic ventilation be balanced between the eave and ridge. The intent of a balanced ventilation system is to provide nearly equivalent amounts of ventilation area at the eave/soffit and at or near the ridge.
- For a balanced ventilation system to function properly, approximately one-half of the ventilation area must be at the eave/soft and approximately one-half of the ventilation area must be at or near the ridge (e.g., ridge vents and static vents).

In summary, existing building codes and industry guidelines only provide recommended ventilated area (1:300 and 1:150) for general typical climates, and no detailed requirements for ceiling plane of ventilated attic to control air leakage rates penetrating through indoor conditions. There are no specific design recommendations for ventilated attic design under extremely cold climate. On the other hand, suggested design details of un-ventilated attic cannot be found in current code. Also, specific items don't provide information for un-ventilated attic design under extremely cold climate.

Chapter 3 EXPERIMENTAL SETUP

This chapter is prepared mainly based on the work that has been done by Daniel Baril, who designed the test protocol, calibrated and installed sensors and equipment, setup the data collection and made the field observation and periodical site visits.

3.1 Attic Construction under Investigation

Three houses with cold roofs in Nunavik territory of Northern Quebec were chosen for on-site field measurements. Two of them have ventilated attic with different filter membrane designs, which are House I (KMHB House) and House II (KSB House). The third one is House III (SIP Prototype House) which has an un-ventilated and unconditioned attic. Top view of three test houses shown by the screen shoot of Google Map are indicated in Figure 3-1. Their on-site photos are shown in Figure 3-2 and detailed envelope assemblies are shown in Figure 3-3 to Figure 3-5.

a) House I (KMHB House) and House II (KSB House).

b) House III (SIP House).

Figure 3-1. Top views of three test houses shown by screen shoot of Google Map.

a) House I (KMHB House).

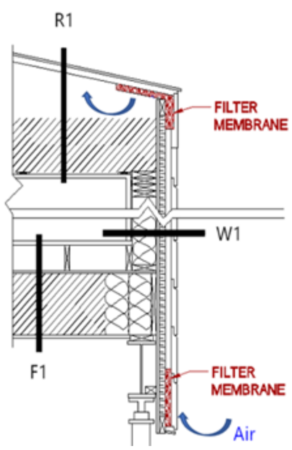
b) House II (KSB House).

c) House III (SIP House).

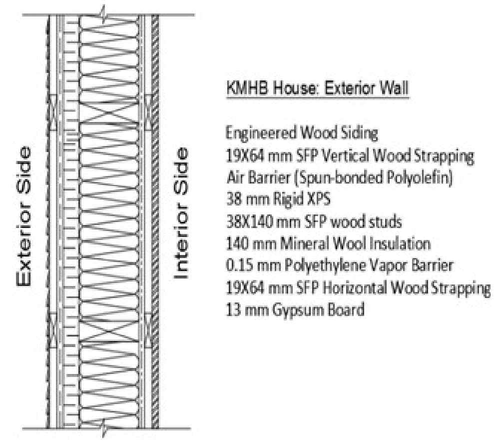
Figure 3-2. Photos of the three houses monitored.

3.1.1 House I – KMHB House

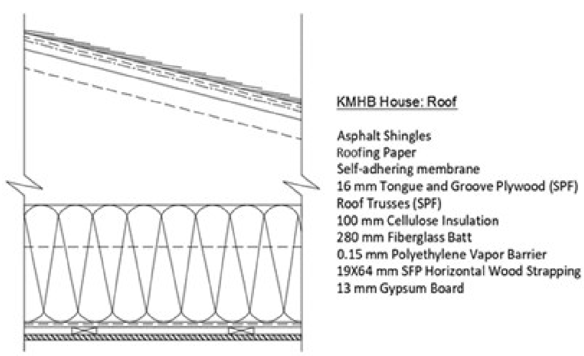
House I is a single-story duplex with two 92 m^2 (1000 ft^2) units and a shared mechanical room located in between. This house was built in Kuujjuaq in 2012. This single story, two bedrooms' social housing design is currently being constructed throughout the territory to catch up with the housing shortage. Figure 3-3 shows the venting system and typical building envelope components in House I. In the venting system of House I, the filter membrane is located at both the bottom of the ventilated cladding and the entrance of the attic space to catch snow (Figure 3-3-a)).



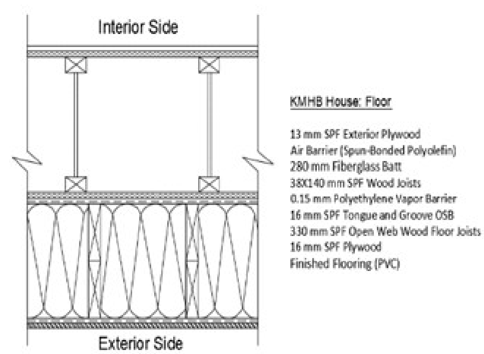
a) Venting system.



b) Wall cross section W1.



c) Roof section R1.

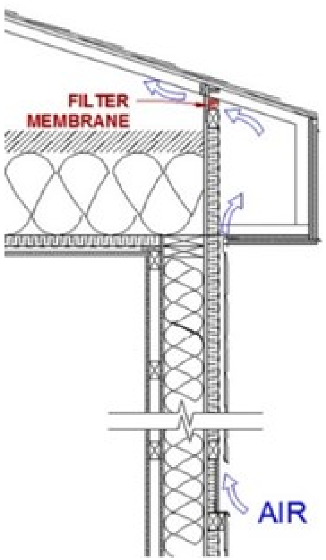


d) Floor section F1.

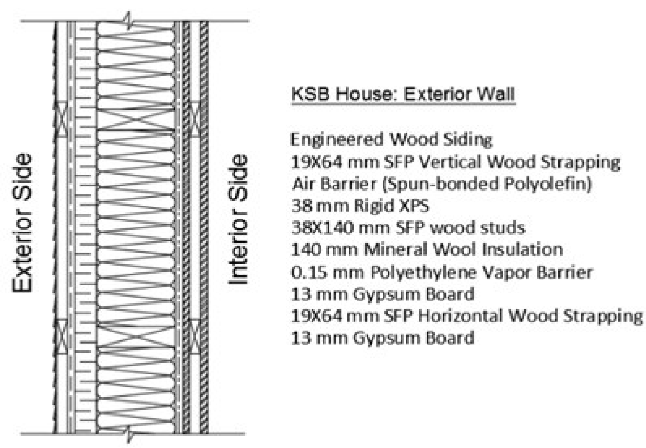
Figure 3-3. Venting system and typical building envelope components of House I (KMHB House).

3.1.2 House II – KSB House

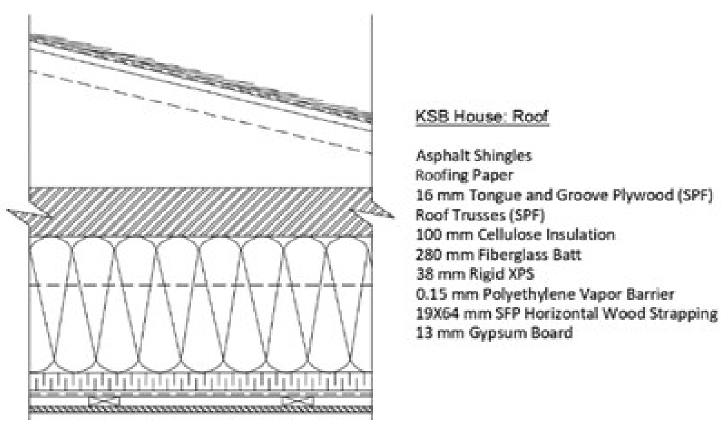
House II is a two-story duplex built in Kuujjuaq, consisting of two 148 m^2 (1600 ft^2) units with a shared mechanical room built in 2008. It has a ventilated attic with a cold roof and the design of the venting system is slightly different than that in House I. As shown in Figure 3-4-a), outdoor air directly enters the air cavity behind the cladding and goes to the eaves before finally enters in the attic space through the filter membrane. This house is owned by the Kativik School Board (KSB) and is used to accommodate teachers and their families. The envelope components are listed layer by layer of wall section and roof section which are indicated in Figure 3-4.



a) Venting system.



b) Wall section.

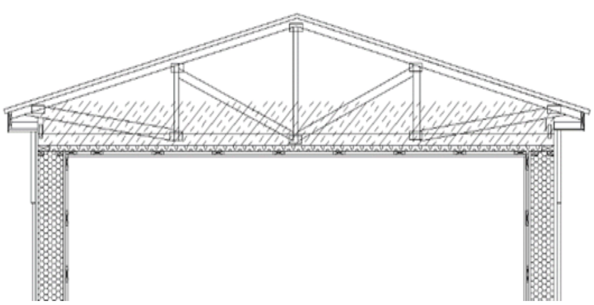


c) Roof section.

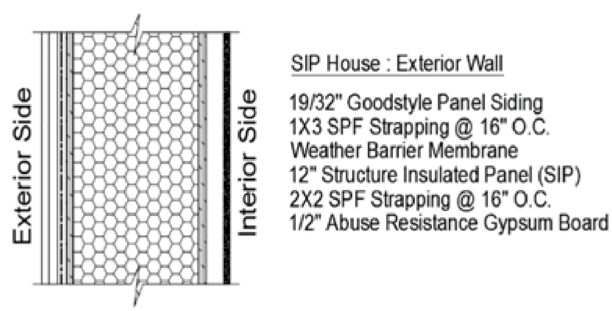
Figure 3-4. Venting system and typical building envelope components of House II (KSB House).

3.1.3 House III – SIP House

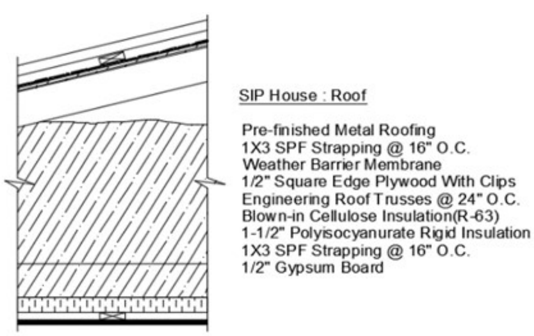
House III is a two-story SIP house built in Iqaluit in 2012, consisting of two 157 m^2 (1700 ft^2) units with a shared mechanical room. This house is owned by KOTT Group and is a prototype structural insulated panel (SIP) house that is a potential design to be used to rapid construct durable, energy efficient homes for the housing shortage. This SIP house has an un-ventilated cold roof, which relies on an airtight ceiling assembly that will keep the warm moist interior air from entering the un-conditioned attic space. The un-ventilated attic will prevent fine snow particles infiltrating the attic space from outside, if built properly. However, extensive researches have not been conducted on this type of attic system to determine if it will have sufficient drying potential and will be suitable for the extreme northern climate. Figure 3-5 shows the roofing system with the detailed construction of building envelope layer by layer.



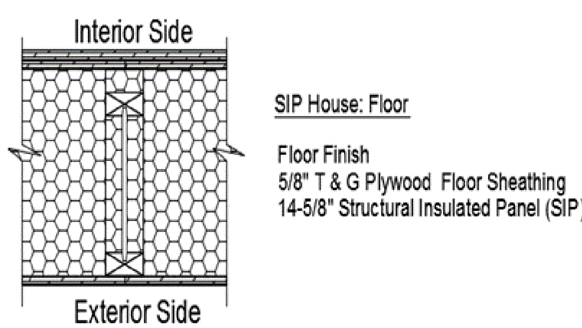
a) Un-ventilated SIP roofing system.



b) Wall section.



c) Roof section.



d) Floor section.

Figure 3-5. Un-ventilated attic system and typical building envelope components of House III (SIP House).

3.2 Instrumentation

To remotely monitor the hygrothermal conditions of the attic, indoor occupied space and outdoor conditions, wireless data acquisition systems were used. Moisture Content (MC) sensors were installed to monitor the moisture content levels of roof sheathing and top chord of roof trusses. The resistance type of MC sensors has built-in thermistor, which allows the MC correction for temperature and can operate under temperature within -40℃ to 125℃ with an accuracy of ±0.5℃. Un-insulated moisture pins were used with a MC range of 8-45% with a resolution of 0.1% and accuracy of ±2% below 30% MC level. The measurements of MC level on plywood sheathing using resistance type of moisture pins were verified by comparing to gravimetric measurement at a MC level of about 10% before their installation for the field measurements. Relative humidity and temperature (RH/T) sensors were installed to monitor the conditions in the attic air above the access hatch as well as in the ceiling insulation and can be used to determine the amount of moisture in the air at these locations. RH/T sensors were also installed outside the houses to monitor outdoor conditions as well as inside the living space to monitor the indoor conditions. The RH accuracy is ±3%~5% between 10%~95% and can be operated within -30℃ to 70℃.

The sensors were connected to battery operated multi-channel data logger, which has an extremely low power usage and can perform long-term monitoring from a three AA battery pack without the need for the installation of external power cables. It has three to five-year battery life depending on sampling rate and operating temperature of 0℃ to 40℃. To preserve the battery life, these data loggers were placed below the attic insulation on the warm side where built-in RH/T sensors monitor the insulation conditions. Collected data was wirelessly sent to an internet connected laptop located in the mechanical room of the houses. The data was then synchronized hourly to a website where readings can be monitored remotely as well as downloaded and analyzed at Concordia University in Montreal, Quebec. An Uninterrupted Power Supply (UPS) was installed to extend battery life of the laptop and provide power to the modem during electrical interruptions. The remote data logging system along with the sensors were provided by a manufacturer.

As shown in Figure 3-7, Building Intelligence Gateway (BIG) Computer System is a data collection system that continuously collects information from the distributed sensor and data logger network. It uses windows 7 platform for user-friendly configurations and local data as well as synchronization with the on-line monitoring and reporting system. Mobile Wireless Data Acquisition (WiDAQ) nodes interface with BIG system directly to transmit collected RH/T values, while multi-channel A3 wireless data loggers are installed between PMM and BIG system to gather MC data from each building component. The A3 multi-channel data logger has up to eight voltages or resistance sensor inputs.

Figure 3-6. A3 Wireless multi-channel data loggers.

Figure 3-7. Building Intelligence Gateway (BIG) computer system.

The A3 Wireless Multi-Channel Data Loggers (Figure 3-6) chosen are extremely low power usage and can perform long-term monitoring from a three AA battery pack without the need for the installation of external power cables. It has three to five-year battery life depending on sampling rate and operating temperature of 0℃ to 40℃. To help preserve the battery life in cold operating conditions, the A3 units were placed beneath the cellulose insulation where built in RH/T sensors monitor the insulation conditions. Figure 3-8 is the photo of moisture content sensor.

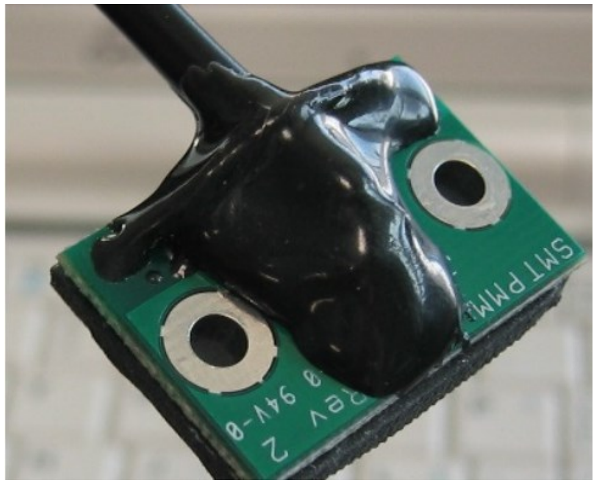


Figure 3-8. Moisture content sensor.

The details of experimental equipment are summarized in Table 3.1:

Table 3.1. Specifications of instruments.

Equipment Name	Performance
Point Moisture Measurement (PMM-03-030)	• Signal changes in the electrical resistance of the materials; • BIG software provides wood species' compensations, and built-in thermistor temperature sensor in the PMM permits for temperature adjustments; • Operating temperature is -40 ℃~125℃.
RH Sensor (HTM2500-02-030)	• Relative humidity transducer is based on a variable capacitor type (Humirel HTS2010 humidity sensor); • Temperature measurements made through an integrated MF52 precision Negative Temperature Coefficient (NTC) thermistor; • Hermetic housing provides resistance to chemicals and protection from water immersion, with a recovery time after 150 hours of condensation of 10s; • RH accuracy between 10% to 95% is ±3% to ±5%; • Environmental operating temperatures for humidity transducer is -30℃~70℃; • Temperature thermistor will operate safely from -55℃ ~125℃.
BIG-GW-001	• Continuous monitoring and data collection from distributed sensor network; • Windows 7 platform is used for user-friendly configurations and local data viewing, as well as synchronization with the on-line monitoring and reporting system.

A3-I22-H00-8R/8V	• Multi-channel data logging of external sensors; • Up to 8 voltage or resistance sensor inputs; • Three~five years' battery life depending on sampling rate. • Operating temperature is 0℃~40℃; • Internal memory capability of up to three years.
S-Pressure-04	• Uses sensirion's CMOSens technology which amplifies and performs analog to digital conversion on a single chip; • Differential pressure measured with a thermal sensor element; • Accurate pressure measurements below 10Pa and has a range of 62Pa; • Full-span Accuracy is 0.5%; • Operating temperature is -10℃~60℃.
A2-Typ.1	Built-in Honeywell HIH-4000-001 RH sensor has a resolution of 0.5% RH.

3.3 Field Observation and Sensor Location

3.3.1 House I – KMHB House

House I is a duplex house with two units (Unit A and Unit B) and a shared mechanical room between them, but now it is used as single-story house, so only hygrothermal conditions of Unit A was measured. Through field observation, there are no signs of moisture on building materials and no rust on roofing nails (Figure 3-11). Filter membranes were installed both at ridge vent and at wall air cavity entrance (Figure 3-13). And dead bolt locks installed to ensure hatch pulled tight onto weather stripping (Figure 3-12). Sensors' setting is as same as SIP house, Point Moisture Measurement (PMM) sensors were installed, two of them in truss and five of them in sheathing, one RH/T sensor for attic air was installed over attic hatch and three RH/T sensors for insulation were buried beneath the cellulose insulation beside the attic hatch. There are also four pressure differential sensors on the edge of roof slope. Sensors' locations (Table 3.2) and setting details (Figure 3-10) are as follow:

Table 3.2. Sensor locations of House I (KMHB House).

Unit Name	Sensor Amount	PMM Specific Locations
Unit A	Seven PMM Sensors	1) PMM-1 is on the western side of the northern slope sheathing; 2) PMM-2 is on the western side of the northern slope truss; 3) PMM-3 is on eastern side of the northern slope sheathing; 4) PMM-4 is on the western side of attic; 5) PMM-5 is on the western side of the south slope sheathing; 6) PMM-6 is on the western side of the south slope truss; 7) PMM-7 is on the eastern side of the south slope sheathing.
	Four RH/T Sensors	1) RH/T-1 is on the truss above hatch and below west sheathing; 2) RH/T-2 is beneath the cellulose insulation on western side of the north slope beside the attic hatch; 3) RH/T-3 is beneath the cellulose insulation on the western side of the south slope beside the attic hatch; 4) RH/T-4 is beneath the cellulose insulation on the eastern side of the south slope beside the attic hatch.

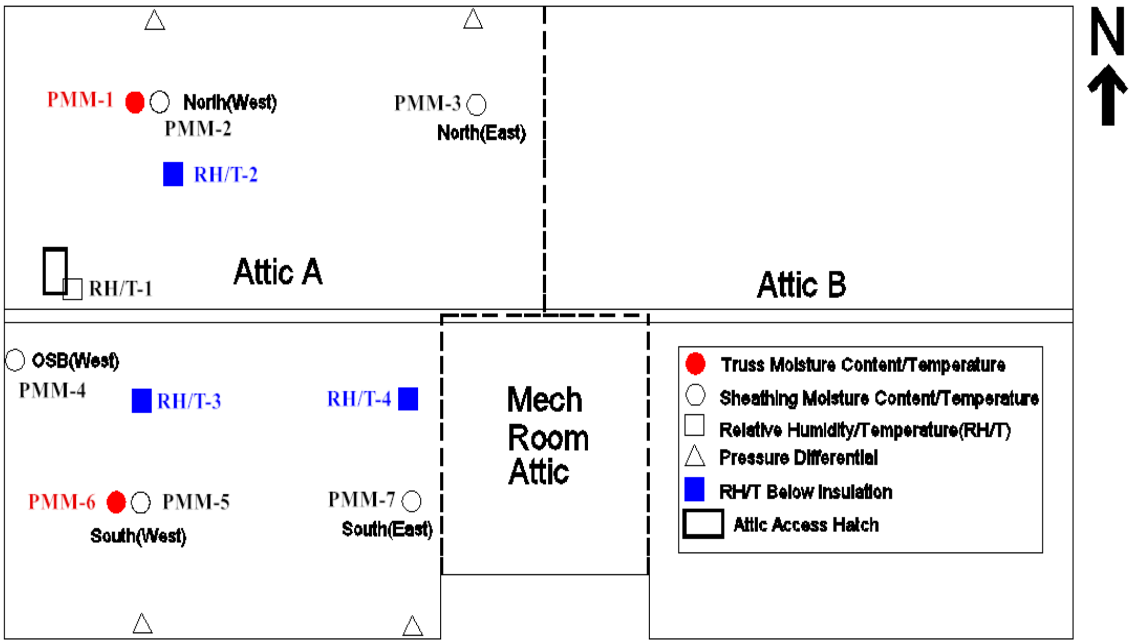


Figure 3-9. Attic sensor locations in House I (KMHB House).

Figure 3-10. Attic view. No signs of moisture on building materials. Roofing nails not rusted.

Figure 3-11. Dead bolt locks installed to ensure hatch pulled tight onto weather stripping.

Figure 3-12. Filter membrane installed at ridge vent.

3.3.2 House II – KSB House

Figure 3-13. No signs of moisture on building materials. Roofing nails not rusted.

House II is a two-story duplex house consisting of two 1600 ft^2 units with a shared mechanical room. Filter membrane only was installed on ridge vent. From site observation, building materials have no signs of moisture on building materials and roofing nails have no rust (Figure 3-14). Seven Point Moisture Measurement (PMM) sensors were installed, five of them in sheathing and two of them in truss, one RH/T sensor installed over attic hatch to monitor attic air and three RH/T sensors buried beneath the cellulose insulation beside the attic hatch to monitor insulation. There are also four pressure differential sensors on the edge of roof slope. The quantities and positions of sensors (Table 3.3) and details of their locations (Figure 3-15) are as follows:

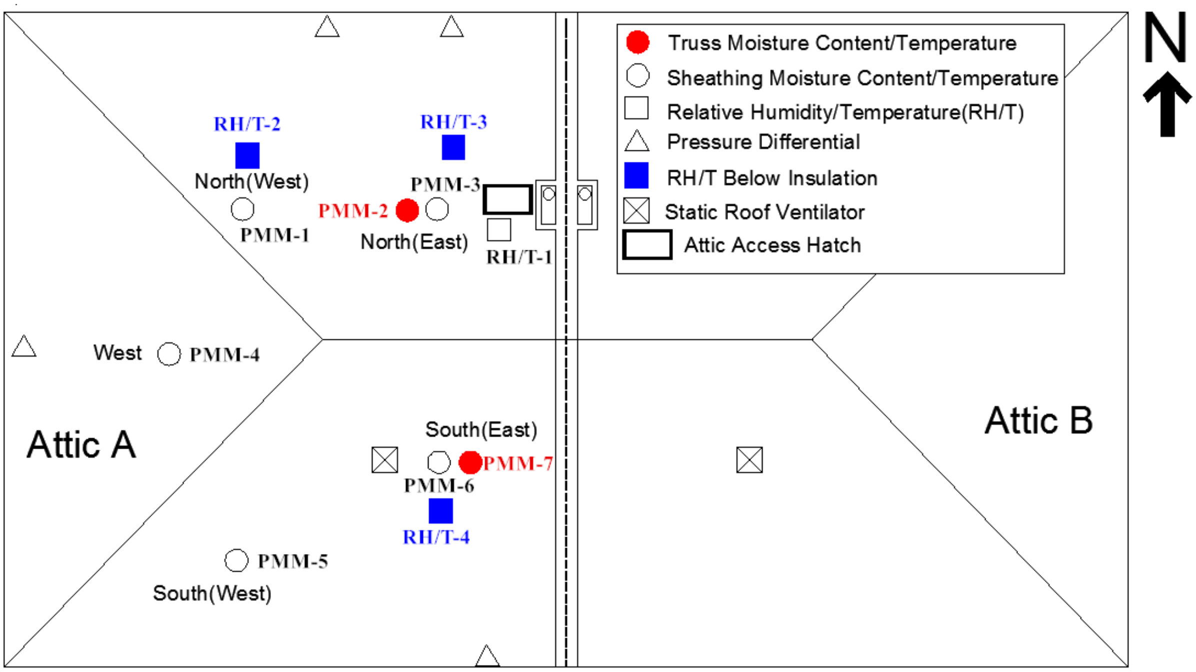


Figure 3-14. Attic sensor locations in House II (KSB House).

Table 3.3. Sensor locations of House II (KSB House).

Unit Name	Sensor Amount	PMM Specific Locations
Unit A	Seven PMM Sensors + Four RH/T Sensors	1) PMM-1 is on the western side of the north slope sheathing; 2) PMM-2 is on the eastern side of the north slope truss; 3) PMM-3 is on eastern side of the north slope sheathing; 4) PMM-4 is on the west side of attic; 5) PMM-5 is on the western side of the south slope sheathing; 6) PMM-6 is on the eastern side of the south slope truss; 7) PMM-7 is on the eastern side of the south slope sheathing.
		1) RH/T-1 is on the truss above hatch and below west sheathing; 2) RH/T-2 is beneath the cellulose insulation on western side of the north slope beside the attic hatch; 3) RH/T-3 is beneath the cellulose insulation on the eastern side of the north slope beside the attic hatch; 4) RH/T-4 is beneath the cellulose insulation on the eastern side of the south slope beside the attic hatch.

3.3.3 House III – SIP House

Figure 3-15. Weather stripping installed on opening trim in all units.

Based on four access hatches in SIP house, the attic of that house is divided into four units, they are Unit A upstairs (UA-US), Unit A downstairs (UA-DS), Unit B upstairs (UB-US) and Unit B downstairs (UB-DS). From field observation, it's easy to find that all of the four units installed weather stripping (Figure 3-16) which is as an air sealing to make the attics being sealed off from indoor area and closed cell sponge rubber tapes were also installed around openings for the hatches to be seated on in all units. Gasket systems around all attic hatches opening were not installed during construction. Upon opening of all attic hatches, area of moisture could be discovered on plywood sheathing and trusses. Figure 3-17 indicates intuitive durability issues within un-ventilated attic observed in House III. The specific observation problems are showed on the Table 3.4 which is as follow:

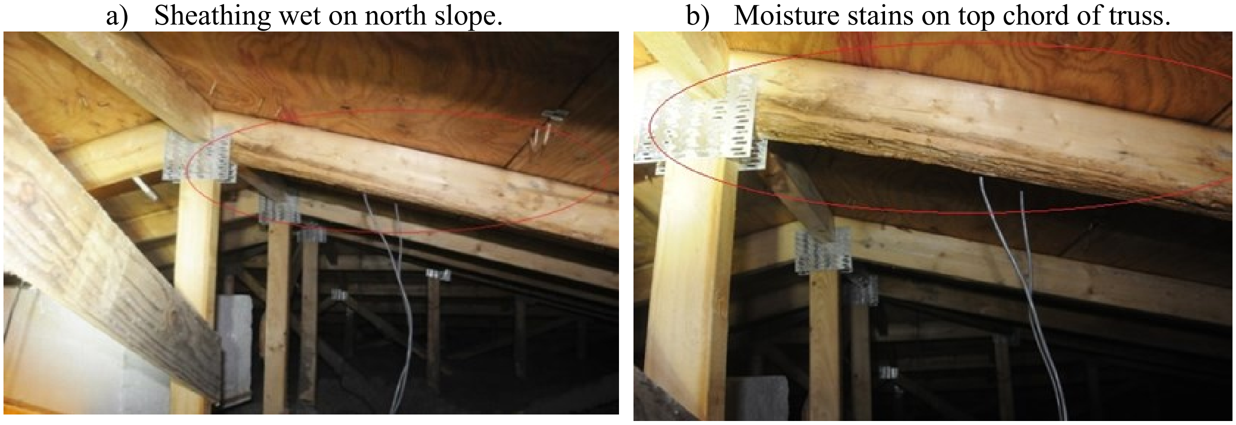
Table 3.4. Observation problems of House III (SIP House).

Unit Name	Observation Problems
Unit A Upstairs (UA-US)	1. Decay of truss occurs above hatch location; 2. Wet sheathing on north slope; 3. Black spots on truss.
Unit A Downstairs(UA-DS)	1. Moisture on truss in several locations; 2. Moist sheathing surface in several locations.
Unit B Upstairs (UB-US)	1. Decay starting on truss; 2. Moisture stains on top chord of truss; 3. Wet sheathing on north slope; 4. Rusty roofing nails.

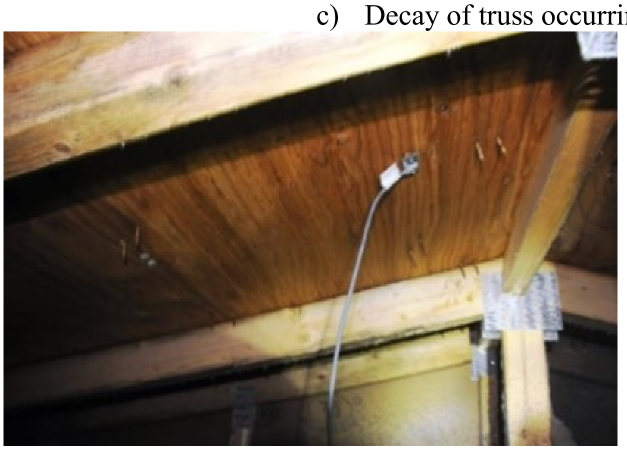
Unit B Downstairs (UB-DS)	1. Wet sheathing on south slope; 2. Moisture on sheathing absorbed into truss; 3. Rusty roofing nails; 4. Black spots on truss.

a) Sheathing wet on north slope.

b) Moisture stains on top chord of truss.



c) Decay of truss occurring above hatch location.

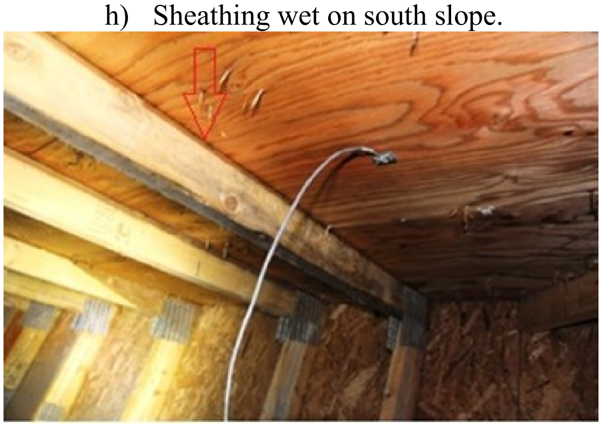


d) Sheathing wet on north slope.

e) Black spots on truss.


f) Rusty roofing nails. g) Decay starting on truss.


h) Sheathing wet on south slope. i) Nails rusty. Black spots on truss.




j) Moisture on sheathing absorbed into truss.

Figure 3-16. Field observation of un-ventilated attic of House III (SIP House).

RH/T of insulation and attic air are measured through RH/T sensors. The A3 wireless data logger with built-in RH/T sensors was buried beneath the cellulose insulation beside the attic hatch to monitor RH/T condition of insulation part. RH/T sensors also were installed on the truss above hatch and below wet sheathing to measure hydrothermal conditions of attic air. Point Moisture Measurement (PMM) sensors are installed on wet sheathing and truss, their specific positions (Figure 3-18) and amounts (Table 3.5) are indicated as follows:

Table 3.5. Sensor locations of House III (SIP House).

Unit Name	Sensor Amount	PMM Specific Locations
Unit A Upstairs (UA-US)	Four PMM Sensors + Two RH/T Sensors	1) PMM-1 is on the north slope truss above the attic hatch; 2) PMM-2 is on the north slope sheathing above the attic hatch; 3) PMM-3 is on western side of the north slope sheathing; 4) PMM-4 is on the eastern side of the north slope.
		1) RH/T-1 is on the truss above hatch and below west sheathing; 2) RH/T-2 is beneath the cellulose insulation beside the attic hatch.
Unit A Downstairs (UA-DS)	Four PMM Sensors + Two RH/T Sensors	1) PMM-5 is on the west slope truss above the attic hatch; 2) PMM-6 is on west-sloped sheathing; 3) PMM-7 is on the western side of the south slope sheathing; 4) PMM-8 is on the eastern side of the south slope above the hatch.
		1) RH/T-3 is on the truss above hatch and below west sheathing; 2) RH/T-4 is beneath the cellulose insulation beside the attic hatch.
Unit B Upstairs (UB-US)	Four PMM Sensors + Two RH/T Sensors	1) PMM-9 is on the north slope truss above the attic hatch; 2) PMM-10 is on the north slope sheathing above the attic hatch; 3) PMM-11 is on western side of the north slope sheathing; 4) PMM-12 is on the east slope sheathing.
		1) RH/T-5 is on the truss above hatch and below west sheathing; 2) RH/T-6 is beneath the cellulose insulation beside the attic hatch.
Unit B Downstairs (UB-DS)	Four PMM Sensors + Two RH/T Sensors	1) PMM-13 is on the western side of south slope truss above the attic hatch; 2) PMM-14 is on the western side of south slope sheathing above the attic hatch; 3) PMM-15 is on eastern side of the south slope sheathing; 4) PMM-16 is on the east slope sheathing.
		1) RH/T-7 is on the truss above hatch and below west sheathing; 2) RH/T-8 is beneath the cellulose insulation beside the attic hatch.

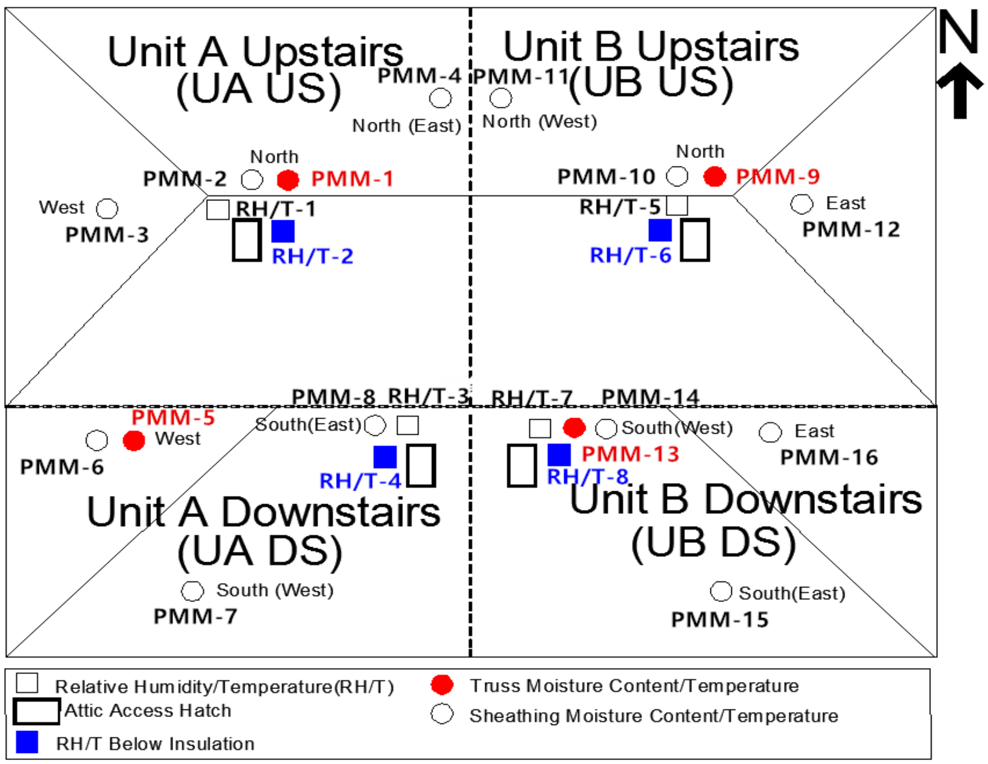


Figure 3-17. Attic sensor locations in House III (SIP House).

Chapter 4 ANALYSIS RESULTS OF FIELD MEASUREMENTS

The hygrothermal performance of attics is analyzed based on its temperature, relative humidity, MC levels in sheathing and trusses, humidity ratio difference between attic and outdoor air, i.e. moisture excess, and mold growth index. The performance for each house is presented in the following section separately. The performance comparison of these three houses is included in the discussion section.

4.1 Moisture Content, RH and Moisture Excess

4.1.1 House I

Figure 4-1 shows the comparison between the hourly temperature measured on the plywood sheathing SW and outdoor air, and Figure 4-2 shows the daily averaged moisture content measured on four plywood sheathing and one wood truss in House I during the monitoring period from July 2013 to Jan. 2015. Seasonal variation in MC and temperature can be observed during this one and half year period. In general, the sheathing temperature was higher than the outdoor air in a range of 10-15℃ with occasions as high as 30℃, especially during summer with high solar radiation due to the thermal mass effect. The difference in sheathing temperature of the five locations is not significant although the maximum temperature on the south-orientation was typically about 5℃ higher than that on the north orientation (49℃ versus 44℃), therefore, only temperatures measured on SW sheathing are plotted in Figure 4-1 as an example. Similar temperature profiles on wood trusses were observed.

The daily averaged MC levels varied between 11% and 23% for the five locations monitored on plywood sheathing. In general, the MC levels in plywood sheathing were low in the summer time between 11% and 13%, while gradually increased during the fall and winter and peaked at around 17% for the three sheathing locations (NE, NW and West), about 20% for SE sheathing, and 23% for SW sheathing in Jan. 2014. For the SW sheathing, MC levels increased starting from the beginning of Nov. 2013, reached above 20% in early Jan. 2014 and peaked at 23% and stayed above 20% till the end of Feb. 2014 and then started to decrease with greater daily fluctuations. The MCs were able to drop to around 11% during the summer. As for the SE sheathing location, MCs had greater fluctuations than other locations, while the average MC was lower than that of SW sheathing and was similar to other locations.

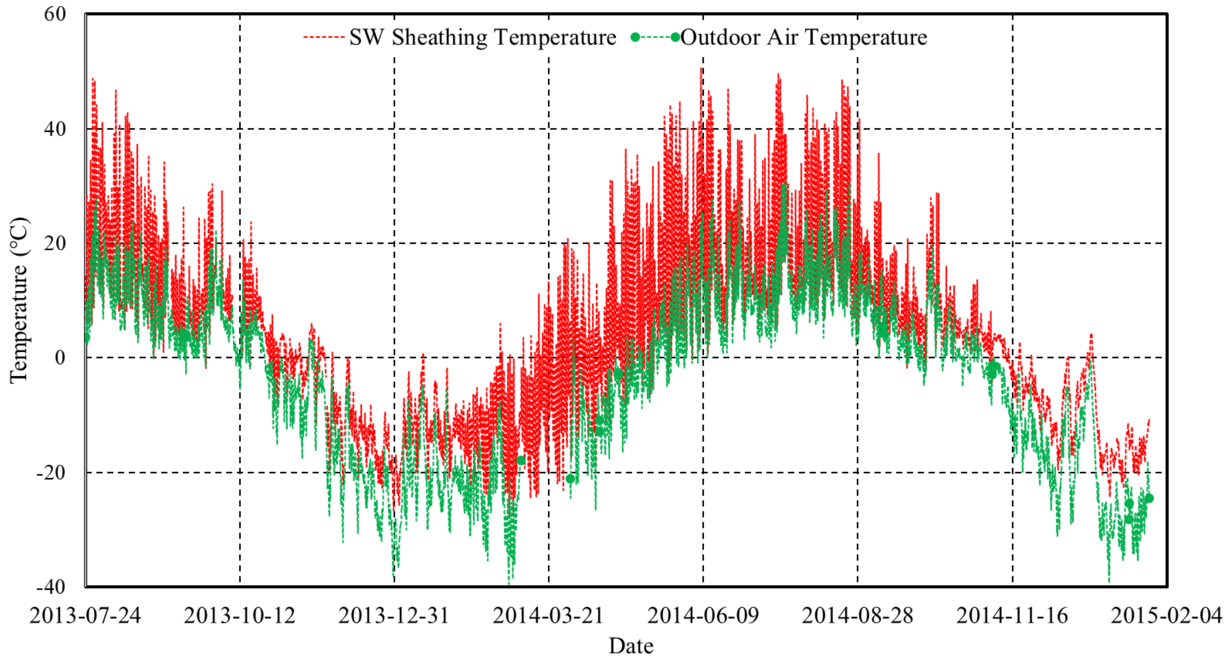


Figure 4-1. Comparison of hourly temperature of plywood sheathing SW and outdoor air in House I during the monitoring period from July 2013 to January 2015.

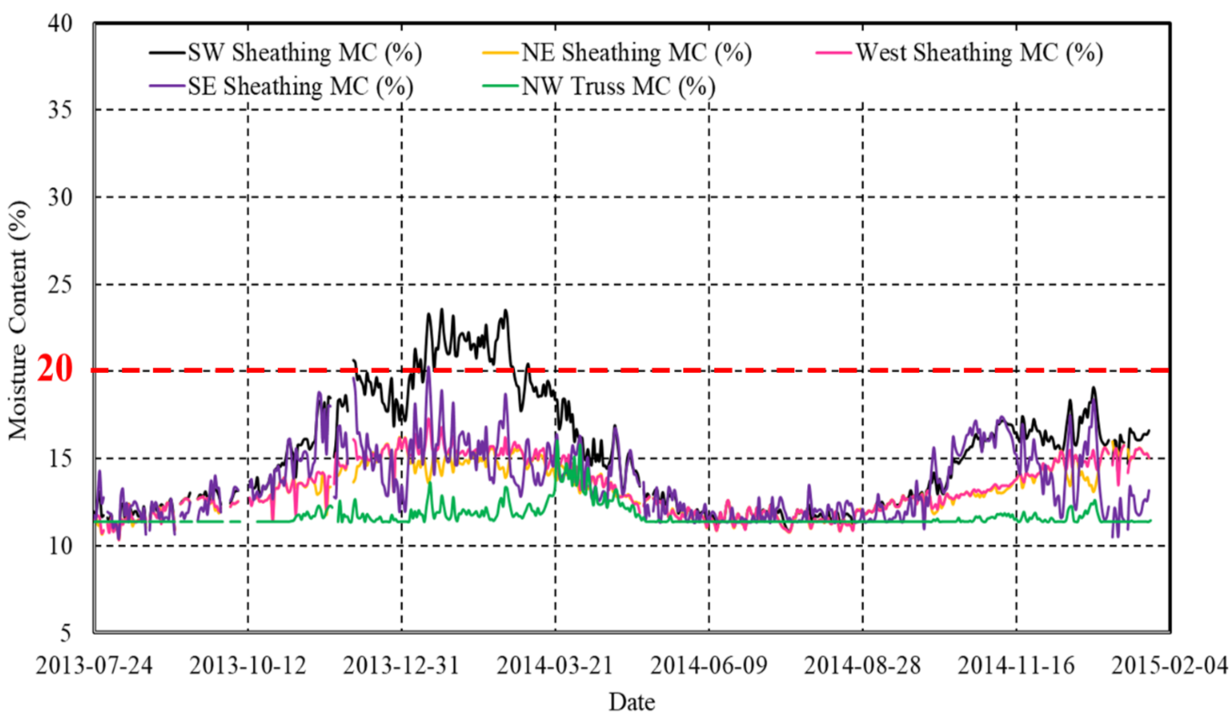
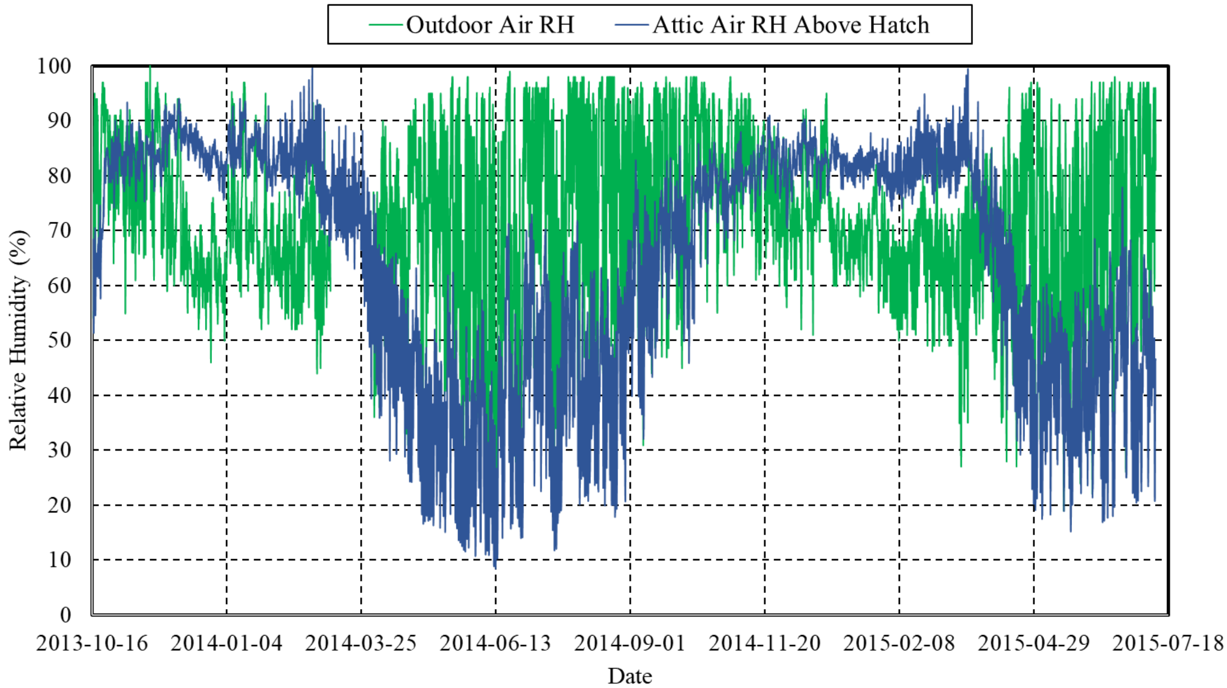


Figure 4-2. Daily averaged moisture content of plywood sheathing and wood truss measured in House I during the monitoring period from July 2013 to January 2015.

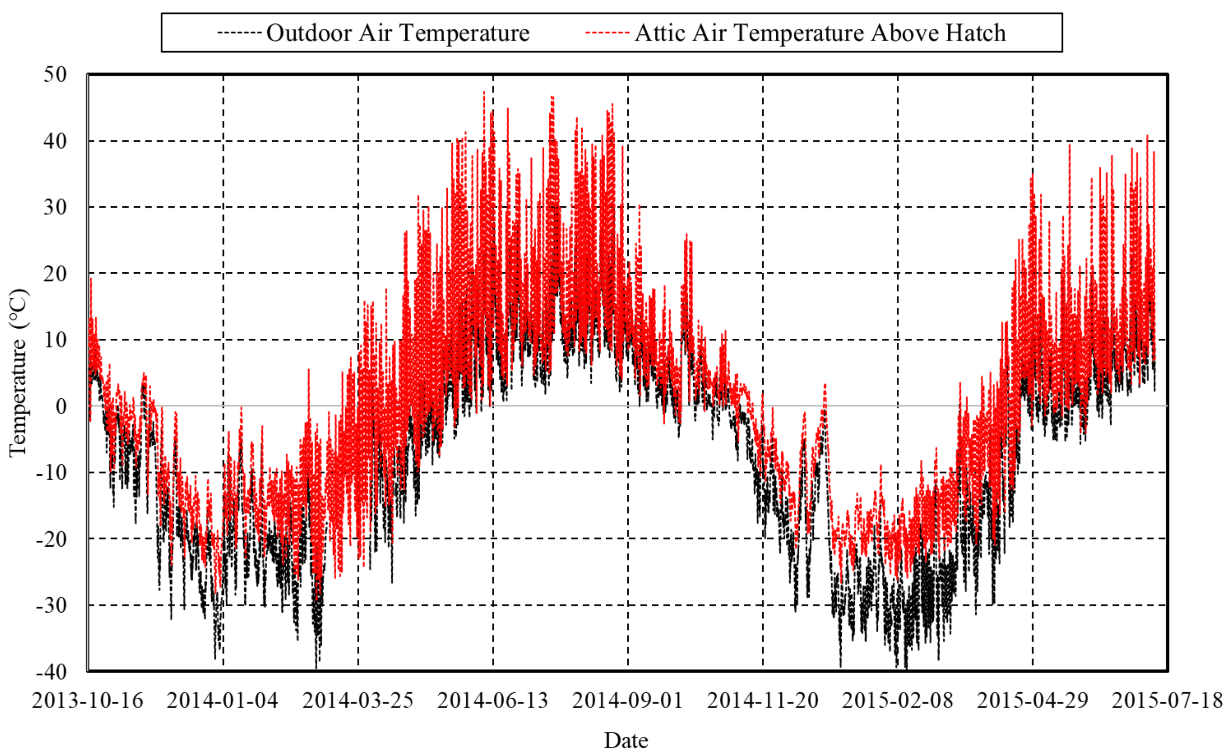
In general, the MC levels on wood trusses were lower than those on the plywood sheathing, varying between 11% and 16%. For the NW truss, the MCs remained around 11% from the beginning of the monitoring and started increasing from mid-March 2014 and peaked at 16% and then decreases from early April to around 11% throughout the summer. For the SW truss, the MC levels followed a similar pattern as SW sheathing, varying between 11% and 16%. The MC profiles for NW sheathing and SW truss are similar to NE sheathing, therefore, their MC profiles are not included in Figure 4-2.

Figure 4-3 shows the comparison of relative humidity and temperature in the attic air and outdoor air. It can be seen that outdoor air temperature varied between -40℃ to 25℃ with a long winter period. The attic air temperature followed a similar trend as the outdoor air and typically higher than outdoor air temperature in a range of 5-15℃ with occasions as high as close to 30℃ especially during summer with high solar radiation due to the thermal mass effect. During the summer time, there were also occasions with attic air temperature being lower than outdoor air temperature due to clear sky radiation. In the winter time, the difference was within 10℃.

There were slightly seasonal variations in RH level of outdoor air but generally the outdoor RH was high with an annual average of 72% and the maximum RH can get as high as close to 100% in spring and summer time. In winter time, RH level of the attic air remained around 80%, which was higher than the outdoor air. In the summer time, attic RH was significantly lower than outdoor RH due to the much higher attic air temperatures.



a) Attic air RH compared to outdoor air RH.



b) Attic air temperature compared to outdoor air temperature.

Figure 4-3. Attic air RH/T compared to outdoor air RH/T conditions in House I (KMHB House).

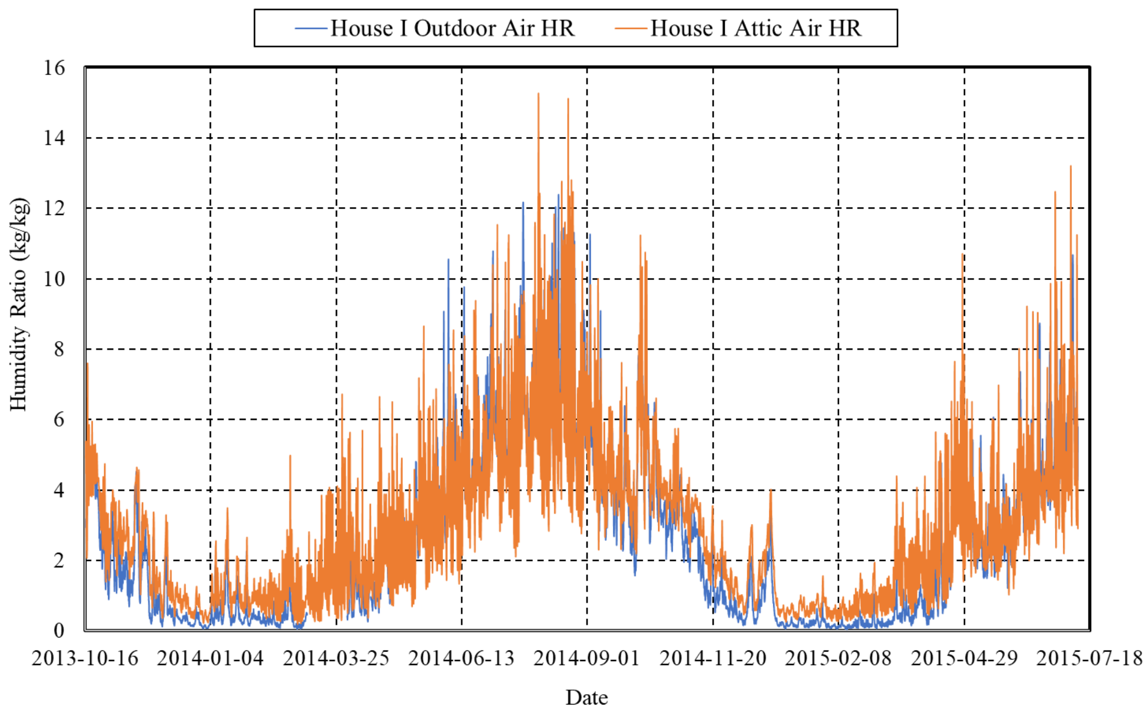
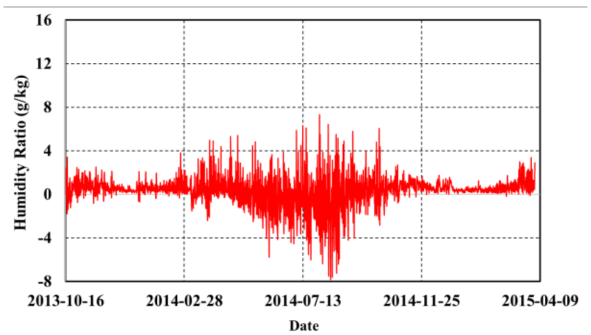
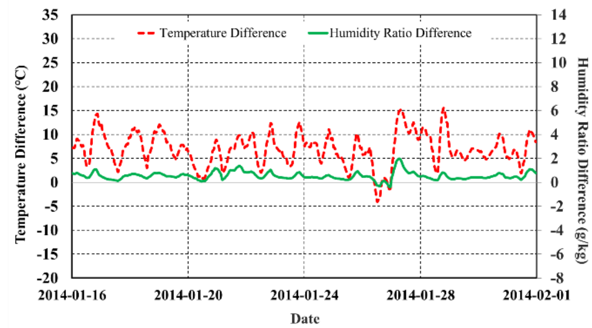


Figure 4-4. Attic air HR compared to outdoor air RH/T conditions in House I (KMHB House).

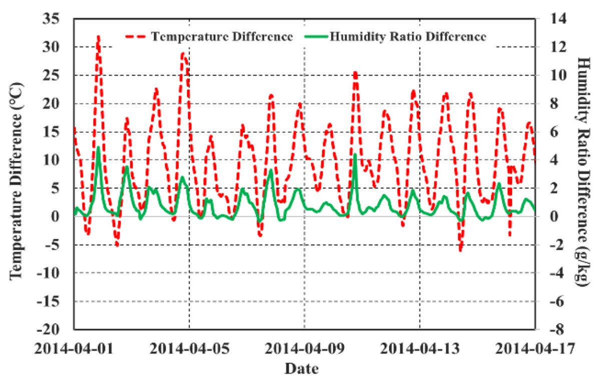
Figure 4-4 shows the comparison of the humidity ratio between attic air and outdoor air. In the winter and spring time (Figure 4-5-b) and Figure 4-5-c)), the humidity ratio (absolute amount of moisture) in attic air remains higher than that of outdoor air and the difference increases when weather warmed up, while the difference is smaller compared to that in the summer time (Figure 4-5-d)). During the winter time, moisture entered in the attic space from indoor was absorbed by hygroscopic materials in the attic and low attic air temperature won't allow the air to hold much moisture, therefore, the humidity ratio difference between attic air and outdoor air is quite small, less than 2 g/kg with an average of 0.5 g/kg. When solar radiation becomes available during the spring time, attic wood structure starts to dry out and releases moisture absorbed during the winter time into the attic space, which increases the humidity ratio of the attic air (less than 4 g/kg with an average of 0.8 g/kg). During the spring time, attic moisture excess has a greater fluctuation due to the adsorption and desorption of moisture from hygroscopic materials in attic space as a result of solar radiation and higher outdoor air temperature. During the summer time, the humidity ratio difference fluctuates more with similar magnitudes of negative and positive values (from -7.8 g/kg to 6.4 g/kg with an average of absolute difference of 2.1 g/kg, shown in Figure 4-5-d)). Higher air temperature and solar radiation allow the release of moisture from roofing structure to the attic space and attic ventilation helps the removal of this moisture out of the attic space during daytime. During night time, especially with clear-sky, the clear-sky radiation cools down the attic air lower than the outdoor air, resulting in humidity ratio in attic air lower than outdoor air. Under this situation, the attic ventilation will bring in outdoor moisture into the attic and increase the moisture content level of roofing wood structures. This effect can also be seen by the daily fluctuation of MCs in plywood sheathing and wood truss, as shown in Figure 4-2.



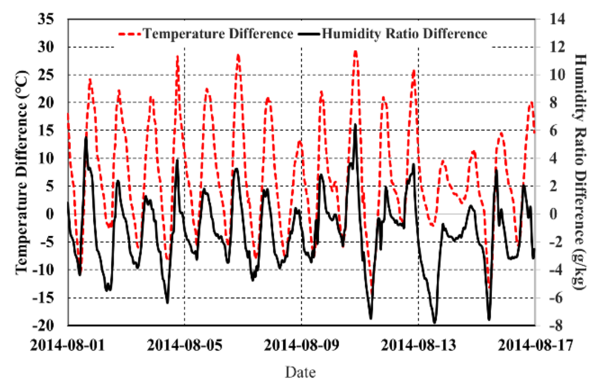
a) Entire monitoring period.



b) Two weeks in winter.



c) Two weeks in spring.



d) Two weeks in summer.

Figure 4-5. Difference in humidity ratio and temperature between attic air and outdoor air in House I (KMHB House).

In general, the attic ventilation system in House I seems working well, except for one location on SW plywood sheathing as shown in Figure 4-2, which had moisture content level reaching risky level during the spring time, however it was able to dry to a safe level during the summer time. The temperature and humidity ratio differences between attic and outdoor air indicate that some levels of attic ventilation induced by wind and stack effect exists, and attic ventilation is helpful to the removal of moisture.

4.1.2 House II

Figure 4-6 shows the comparison between hourly temperature measured on the plywood sheathing SW and outdoor air, and Figure 4-7 shows the daily averaged moisture content measured on five plywood sheathing and one wood truss in House II during the monitoring period from Aug. 2013 to Jan. 2015. Seasonal variation in MC and temperature can be observed during this period. The sensor installed on NE wood truss malfunctioned, therefore, only the data collected at the five locations on plywood sheathing and one on wood truss are shown in this part.

Similar to what has been observed in House I, in general, the sheathing temperatures were higher than the outdoor air in a range of 10-15℃ with occasions as high as 30℃ especially during summer with high solar radiation due to the thermal mass effect. The differences in sheathing temperatures of the five locations were not significant although the maximum temperature on the south-orientation was typically about 6℃ higher than that on the north orientation (49℃ versus 43℃), therefore, only temperatures measured on SW sheathing are plotted in Figure 4-6 as an example. Similar temperature profile on wood truss is observed.

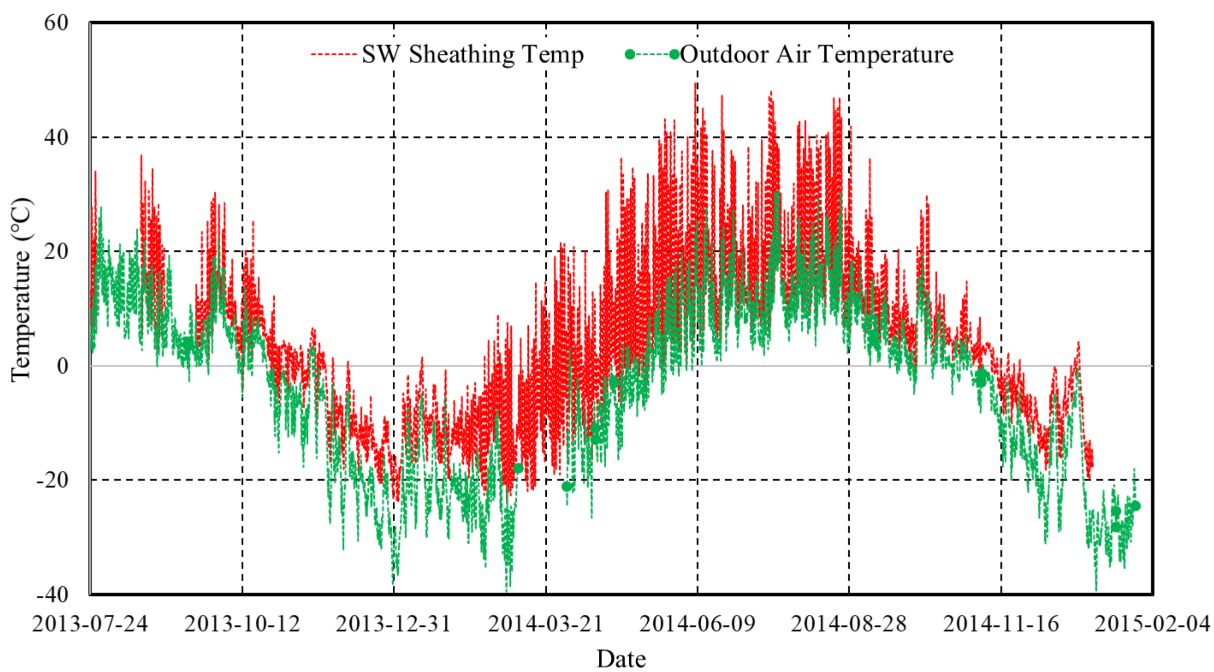


Figure 4-6. Comparison of hourly temperature on plywood sheathing SW with outdoor air during the monitoring period from August 2013 to Janurary 2015 in House II (KSB House).

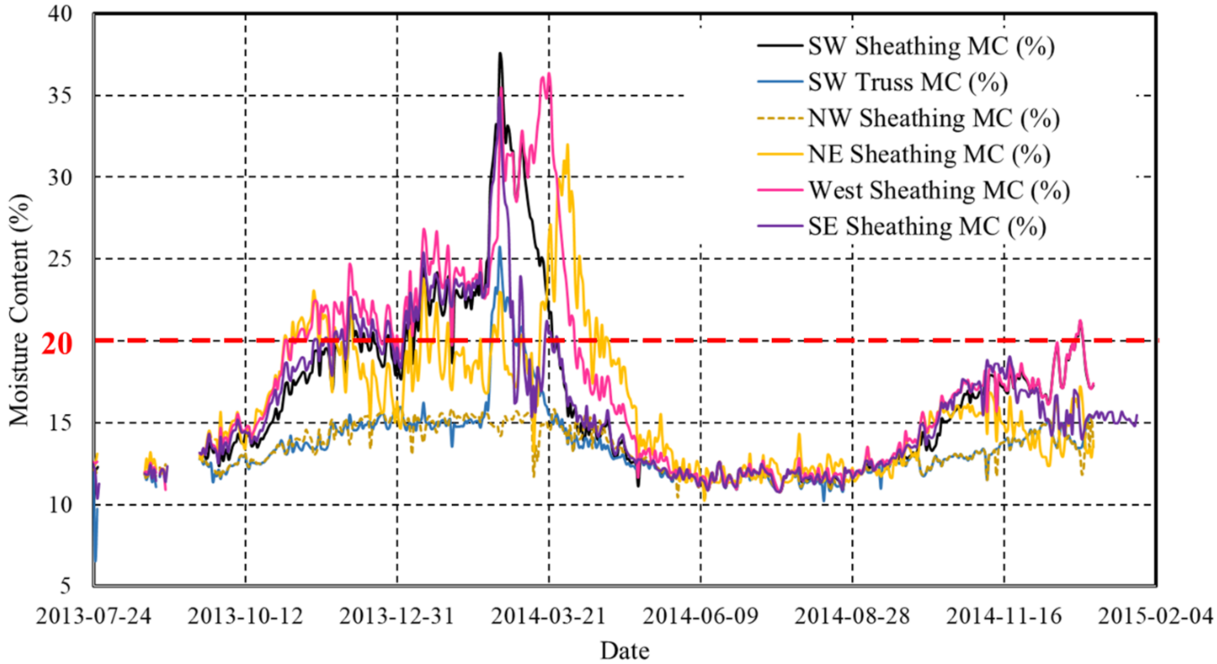


Figure 4-7. Daily averaged moisture content of plywood sheathing and wood truss measured during the monitoring period from August 2013 to January 2015 in House II (KSB House).

The daily averaged MC levels vary between 9% and 28% for the five locations on plywood sheathing. In general, the MC levels in plywood sheathing were low in the summer time about 10%, while gradually increased during the fall and winter. Starting from mid-Feb. 2014, the MC levels at SE, SW and West locations abruptly increased and peaked at 28% at SW sheathing and 26% at SE and West sheathing, respectively. The MC of SE sheathing started to drop first and dried to below 20% by the end of Feb. 2014, followed by SW sheathing, which dried to below 20% early March 2014. The MC of West sheathing stayed at levels above 20% longer until the end of March 2014. The MCs of NE sheathing had greater fluctuations and the abrupt increase in MC started from mid-March, peaked at about 24% at the end of March, and dried to below 20% by early Apr. 2014. The MCs were able to drop to around 10% during the summer for all these locations. The quick increase in MC in plywood sheathing during the period of mid-Feb. to mid-March was most likely due to the availability of solar radiation and warming up of the air temperature that allowed the moisture frozen in the wood structure to melt, therefore, elevated MC readings. It is interesting to see that the peak of MC level in plywood sheathing started from SE followed by SW, W and NE, which is an indication of the influence of solar availability on different orientations of the roofing structure. The MC on SW wood truss remained below 15%

until mid-Feb. 2014, and then increased abruptly above 20% and peaked at 26%, finally started to drop to below 20% in early March 2014. The period of MC levels above 20% is about two weeks.

The relative humidity and temperature profiles in attic air and outdoor measured in House II were similar to those in House I, therefore, the plots are not included in this paper. Similar to what have been observed in House I (Figure 4-3), the attic air temperature followed a similar trend as the outdoor air and typically higher than outdoor air temperature in a range of 5-15℃ with occasions as high as 30℃, especially during summer with high solar radiation due to the thermal mass effect. During the summer time, there were also occasions with attic air temperatures lower than outdoor air temperatures due to clear sky radiation. In the winter time, the differences were smaller within 10℃. There were slightly seasonal variations in RH level of outdoor air but generally the outdoor RH was high with an annual average of 75% and the maximum RH can get as high as close to 100% in spring and summer time. In winter period, RH level of attic air remained above 85% and sometime reached 100%, which was higher than the outdoor air. In summer period, attic RH was significantly lower than outside RH due to the much higher attic air temperatures.

Figure 4-8 shows the comparison of the humidity ratio between attic air and outdoor air over the entire monitoring period (HR difference plots for individual seasons are not included given the profiles are similar to what presented in Figure 4-8 for House I). Similar to what have been observed in House I, the humidity ratio in attic air remained higher than that of the outdoor air during winter and spring time and the difference increased when the weather warmed up, while the difference was smaller compared to that in the summer time. During the winter time, the humidity ratio difference was less than 2 g/kg with an average of 0.5 g/kg, while during the spring time, the humidity ratio difference was less than 4 g/kg with an average of 0.9 g/kg. During the summer time, the humidity ratio difference fluctuated more with similar magnitudes of negative and positive values (from -6.9 g/kg to 8.9 g/kg with an average of absolute difference of 2.3g/kg). The humidity ratio difference within ventilated attic of House II is slightly higher than that in the attic of Houses I, which is consistent with the measured RH level in attic space and MCs in the plywood sheathing and wood truss of House II.

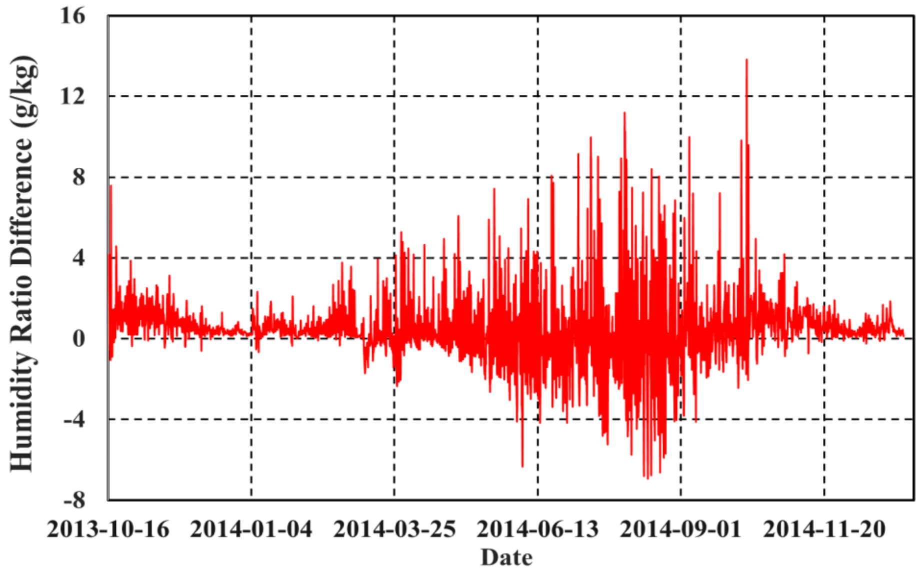


Figure 4-8. Difference in humidity ratio between attic air and outdoor air over the monitoring period from October 2013 to December 2014 in House II (KSB House).

4.1.3 House III (un-ventilated)

The hygrothermal conditions of all four attic spaces in the SIP house were monitored. The sensors installed in Unit A downstairs lost power, therefore, only data collected at the other three attic spaces are analyzed. In general, there is no significant difference in RH and temperature among these attic spaces with slightly higher RH levels in the upstairs attic spaces. The hygrothermal conditions at selected locations and attics are included in this section for the purposes of analysis and discussion.

Figure 4-9 shows the comparison between hourly temperature on plywood sheathing measured on North sheathing in Unit B upstairs attic and outdoor air, while Figure 4-10 shows the daily average MCs on three plywood sheathing locations and one wood truss, selected as examples for the monitoring period from July 2013 to August 2014. Seasonal variation in MC and temperature can be observed during this one-year period. As discussed earlier, the difference in sheathing temperature among different locations is not significant, therefore, only the temperatures on North sheathing of Unit B upstairs are shown as an example. Similarly, in general, the sheathing temperatures were higher than the outdoor air in a range of 5-15℃ with occasions as high as 25℃ especially during summer time with high solar radiation.

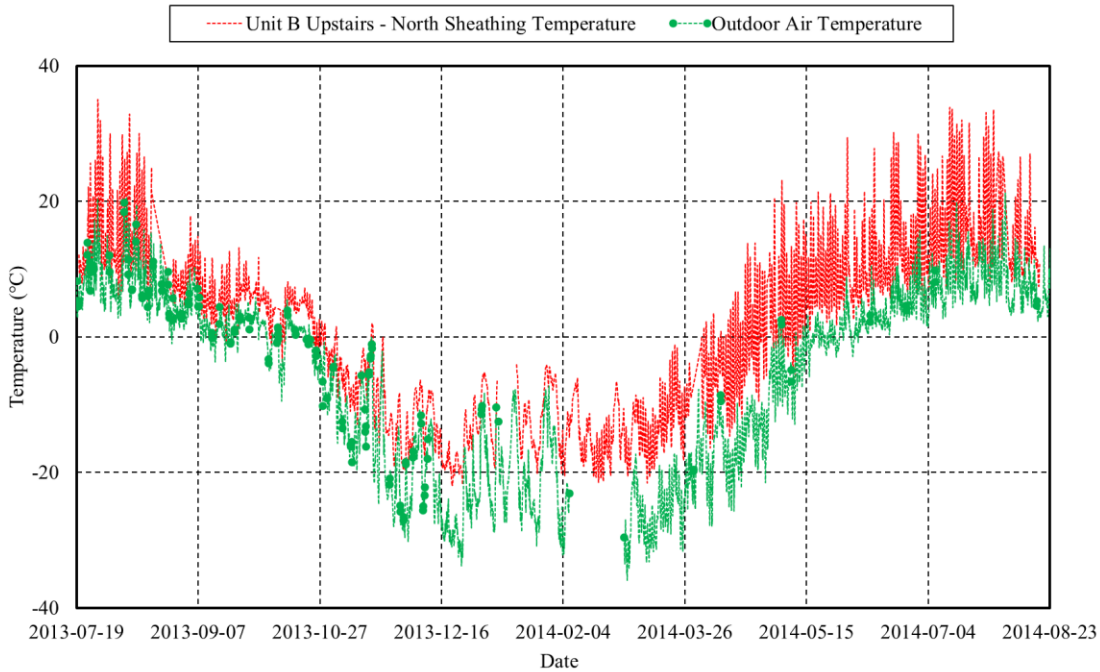


Figure 4-9. Comparison between hourly temperature of plywood sheathing and outdoor air in Unit B of House III (SIP House) measured during the monitoring period from July 2013 to August 2014.

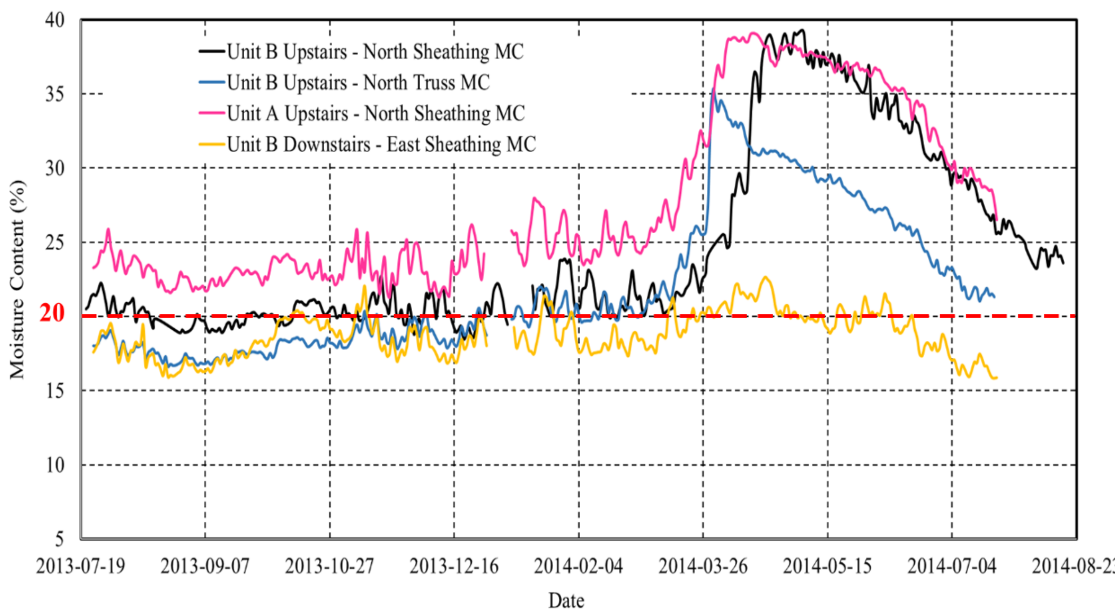
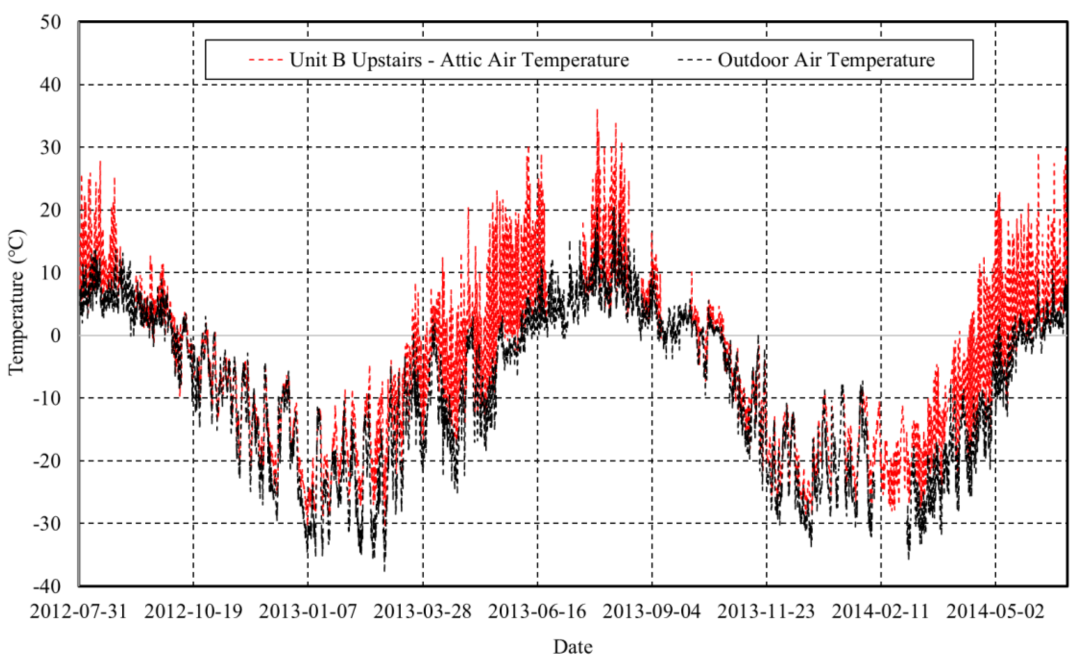
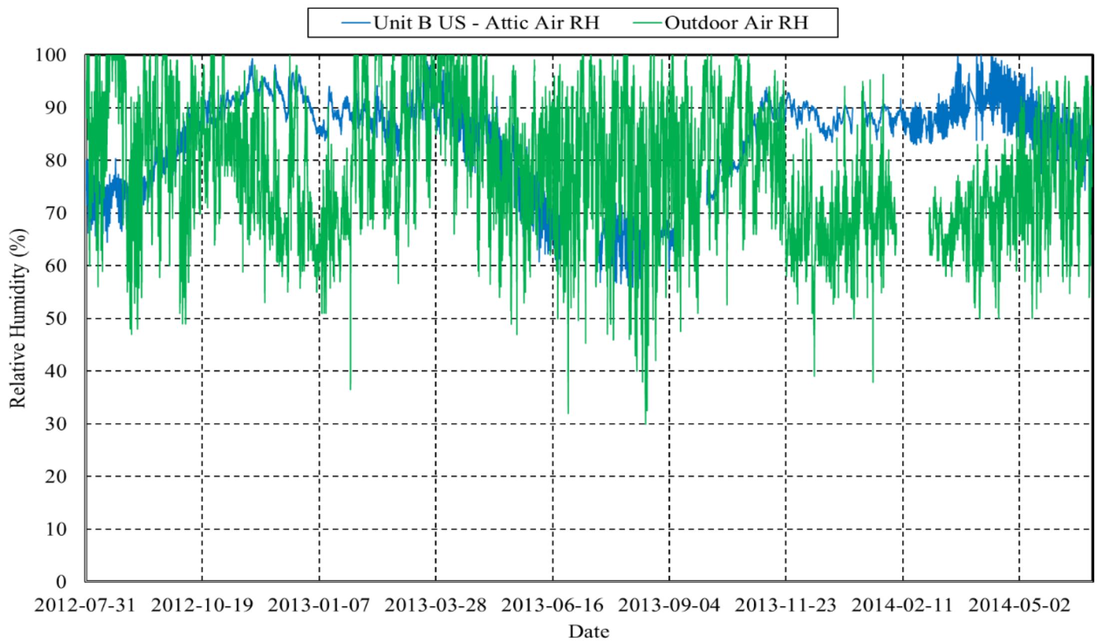


Figure 4-10. Daily average moisture content of plywood sheathing and wood truss at selected locations in three attics of House III (SIP House) measured during the monitoring period from July 2013 to August 2014.

The MC levels varied between 13% and 35% on plywood sheathing and wood trusses for the three attic spaces monitored. The MC profiles at three selected plywood sheathing locations and one truss location are shown in Figure 4-10 for discussion. The initial moisture contents of plywood sheathing and wood truss were higher compared to those in House I and II, at around 16% for North sheathing in Unit B upstairs, about 18% for north truss in Unit B upstairs and north sheathing in Unit A upstairs in July 2013. The MC levels fluctuated with slight increase over the winter time. The MCs of plywood sheathing and wood truss in the attic of Unit B downstairs remained below 20% over the monitoring period, similar to what is shown in Figure 4.10 for "Unit B Downstairs-East sheathing". The MCs of plywood and wood truss in the attics of upstairs, both Unit A and B, all had levels above 20% for four to five months. As shown in Figure 4-10, starting from mid-Jan. 2014, the MC of North truss of Unit B and North sheathing of Unit A gradually increased to above 20%, while a significant increase in MC started from mid-March and MCs peaked at 29% at Unit A North sheathing and 35% at Unit B Upstairs-North truss by early April 2014, respectively. The MC of Unit B Upstairs-North sheathing reached above 20% by early April and peaked at 29% by mid-April. The MCs at these three locations remained at above fiber saturation level until the end of May, then gradually decreased but still remained above 20% until the end of July 2014. The MC profiles of plywood sheathing and wood truss at other locations in these two-upstairs' attics were similar, therefore, not shown in Figure 4-10.



a) Attic air temperature compared to outdoor air temperature.



b) Attic air RH compared to outdoor air RH.

Figure 4-11. Attic air RH/T conditions in Unit B Upstairs in House III (SIP House) compared to outdoor air RH/T conditions.

Figure 4-11 shows the comparison of relative humidity and temperature between attic air in Unit B Upstairs and outdoor air for the monitoring period from August 2012 to June 2014. The attic air temperature followed a similar trend as the outdoor air and typically higher than outdoor air temperature with an average of 5℃ with occasions as high as close to 25℃, especially during summer with high solar radiation. During the summer time, there were also occasions with attic air temperatures being lower than outdoor air temperature due to clear sky radiation. In the winter time, the difference was within 5℃. There were slightly seasonal variations in RH level of outdoor air but generally the outdoor RH was high with an annual average of 86% and the maximum RH can get as high as close to 100% in spring and summer time. In winter period, RH level of attic air remained above 90%, while in the summer time, attic RH remained above 60% with an average of 75% from May to August, which was much higher than the attic RH levels in House I and House II with ventilated attics.

Figure 4-12 shows the monthly average indoor air temperature and relative humidity of Unit B upstairs room as an example. The temperature and relative humidity in other rooms were similar. The room temperatures from July 2012 to Jan. 2013 were low with an average of about 12℃. Most likely this room was not occupied during this period. Starting from the end of Jan. 2014 the room temperature was raised above 20℃. The average room temperature during the period from Jan. to June 2014 was 21.3℃. The corresponding monthly averaged relative humidity fluctuated between 10% and 45%.

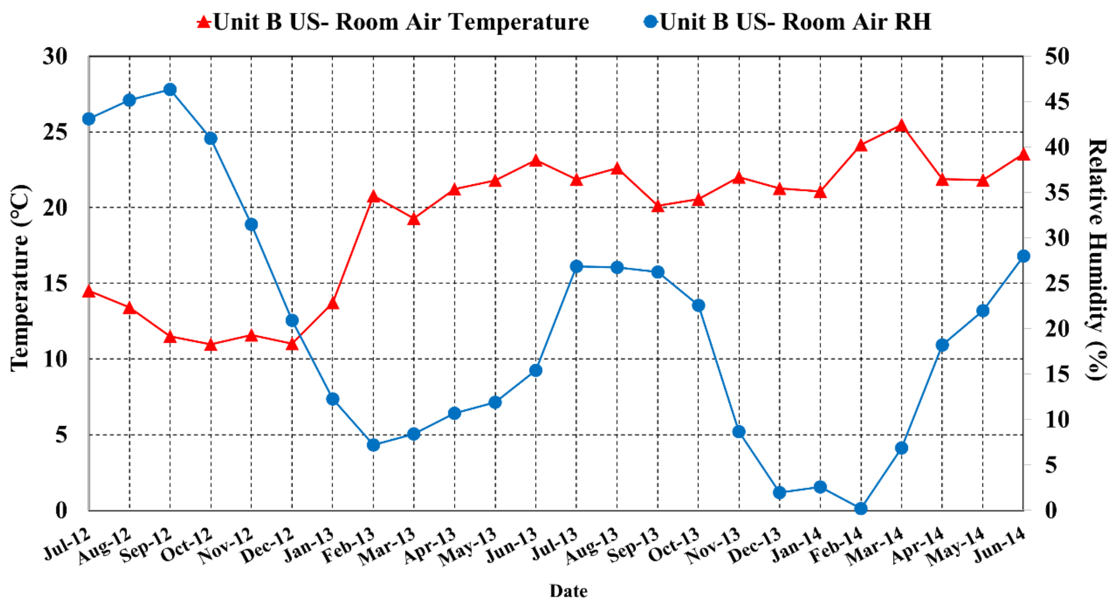


Figure 4-12. Monthly average room air temperature and relative humidity in Unit B Upstairs of House III (SIP House).

Figure 4-13 shows the monthly averaged humidity ratio difference between indoor and attic air, and the humidity ratio difference between indoor and outdoor air for Unit B upstairs. During the period from Oct. to the end of Feb., the indoor humidity ratio was typically higher than attic humidity ratio, which means that indoor air is a moisture source to attic by vapour diffusion or air leakage. In summer period, the elevated humidity ratio in attic means higher vapour pressure, there will be reversed vapour diffusion from attic air to indoors. The average humidity ratio between indoor and attic during the winter time was an average of 0.6g/kg, while during the spring and summer time the humidity ratio between attic and indoor was an average of 2.5g/kg. Similarly, during the winter time, the indoor air humidity ratio is higher than outdoor air with a slightly higher difference compared to the moisture excess between indoor and attic, while during the summer time the humidity ratio of outdoor air is higher than indoor with a much lower magnitude compared to the difference between attic and indoor.

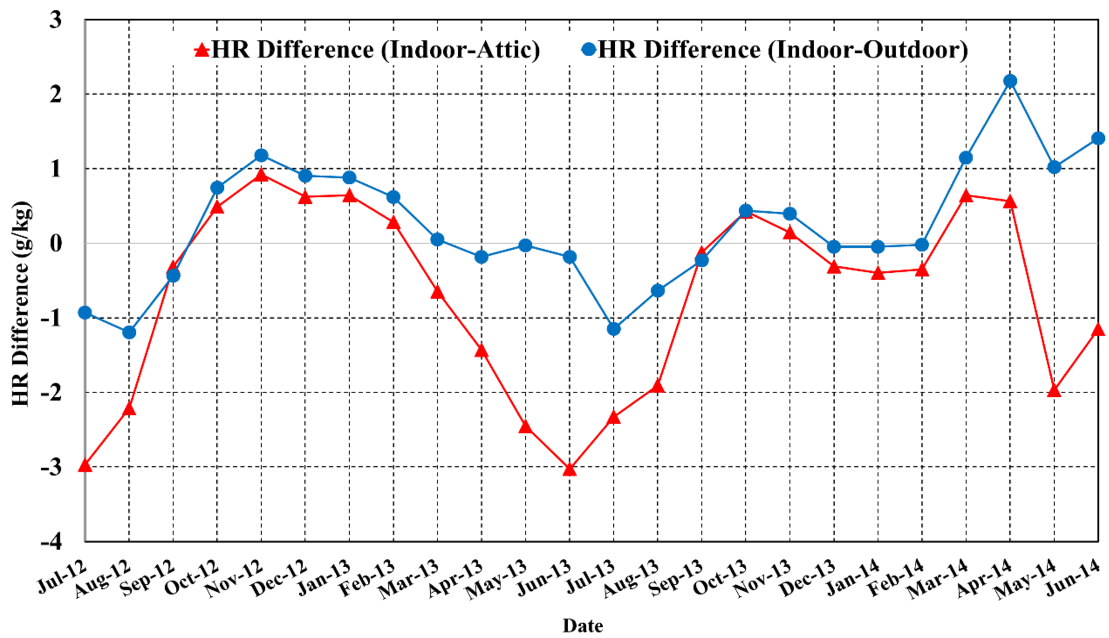
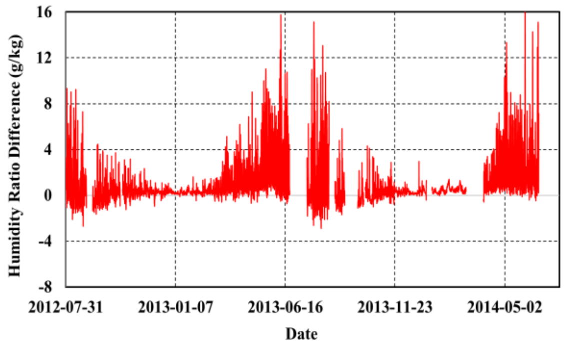
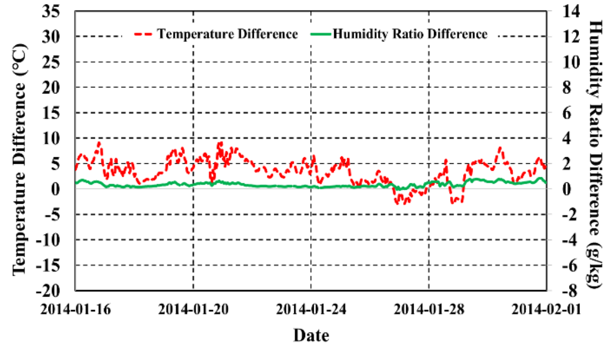


Figure 4-13. Monthly averaged humidity ratio difference between indoor and attic air and indoor and outdoor air for Unit B upstairs.

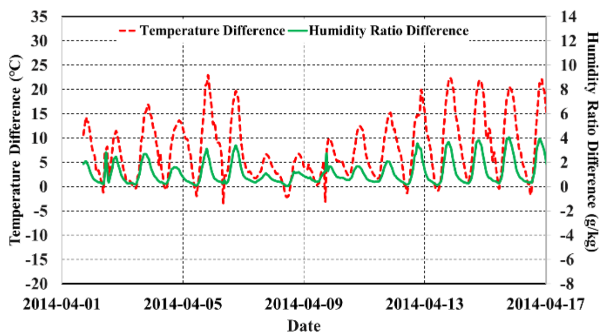
Figure 4-14 shows the comparison of the humidity ratio between attic air and outdoor air. Similarly, the humidity ratio difference between attic air and outdoor air is small during the winter time and higher during the spring and summer time. Compared to House I and House II, this moisture excess in attic air is lower during the winter time but higher during the spring and summer time. During the winter time, the moisture excess was less than 1 g/kg with an average of 0.35 g/kg, while during the spring time the moisture excess was less than 4 g/kg with an average of 1.2 g/kg. During the summer time, the moisture excess fluctuated more but stayed mostly positive, ranging from -2.9 g/kg to 12.3 g/kg, with an average of 3.3 g/kg. This indicates that during the summer time, there are still quite amount of moisture retained in the attic and without ventilation, the excess moisture accumulated through the winter time cannot be effectively removed. This is consistent with the high level of MCs in plywood and wood truss and high level of RH observed in the un-ventilated attic of this SIP house.



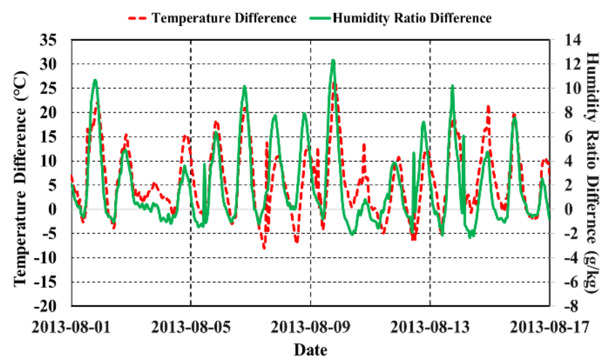
a) Entire monitoring period.



b) Two weeks in winter.



c) Two weeks in spring.



d) Two weeks in summer.

Figure 4-14. Difference is humidity ratio and temperature between attic air and outdoor air in House III (SIP House).

In general, the RH level in attic air and the MC levels of wood structure in the un-ventilated SIP house were higher than that in Houses I and II with ventilated attics. The MCs at most of the sheathing and wood trusses reached levels for risks of mold growth and decay.

4.2 Mold Growth Index

The procedure outlined in ASHRAE 160-2016 (ASHRAE, 2016) is followed for the calculation of mold growth index. The Mold Growth Index developed by Ojanen et al., which is defined based on the mold visual appearance on moisture sensitive materials. It is a numerical value varying from 0 (no mold growth) to 6 (100% visually detected coverage) and can be calculated using transient temperature and relative humidity histories of the subjected material surfaces. A mold growth index of three (M=3) is described as visual findings of mold on the surface with

<10% coverage or <50% coverage of mold under microscope. Mold growth index values less than three correspond with growth visible only under microscope. The mold growth index is a function of temperature, relative humidity and duration, and the material sensitivity class. Material surfaces are classified into four classes, i.e. very sensitive, sensitive, medium resistant and resistant. Wood-based boards and spruce are classified as “sensitive materials”. The mold growth indices on plywood sheathing surface and wood truss were calculated. Given that surface relative humidity was not measured, sorption isotherm is used to calculate surface relative humidity based on moisture content measurements (Ojanen et al., 2010).

In general, the mold growth index values calculated for the two houses with attic ventilation are very small, close to zero in House I and a maximum value of 0.3 in House II, which did not pose risks for mold growth for the monitored periods. For mold growth to sustain, it requires favorable conditions to be maintained for a certain time of period. In the extremely cold climate of Arctic region, the attic temperature is often below zero, although the RH is above 80%, the sub-zero temperature prohibits the growth of mold. During the spring time, when temperature is above zero, often the sheathing and wood truss temperature increases due to the availability of solar radiation, which lowers the surface relative humidity, therefore, the conditions for mold growth becomes unfavorable as well. For the two houses with ventilated attic, the combination of temperature and relative humidity on plywood sheathing and wood truss does not support the sustained growth of mold during the monitoring period, which is consistent with what have been observed on site. For the un-ventilated SIP house though, the RH levels and moisture content of plywood and wood trusses remained high during the spring and summer months. Signs of moisture problems such as wet plywood, rusted nails, black stains (likely mold) and sign of wood decay on wood truss were observed during site visits. The mold growth index calculated on both plywood sheathing and wood truss had a value about 3 at the end of monitoring period although no obvious sign of mold growth was observed on the plywood sheathing.

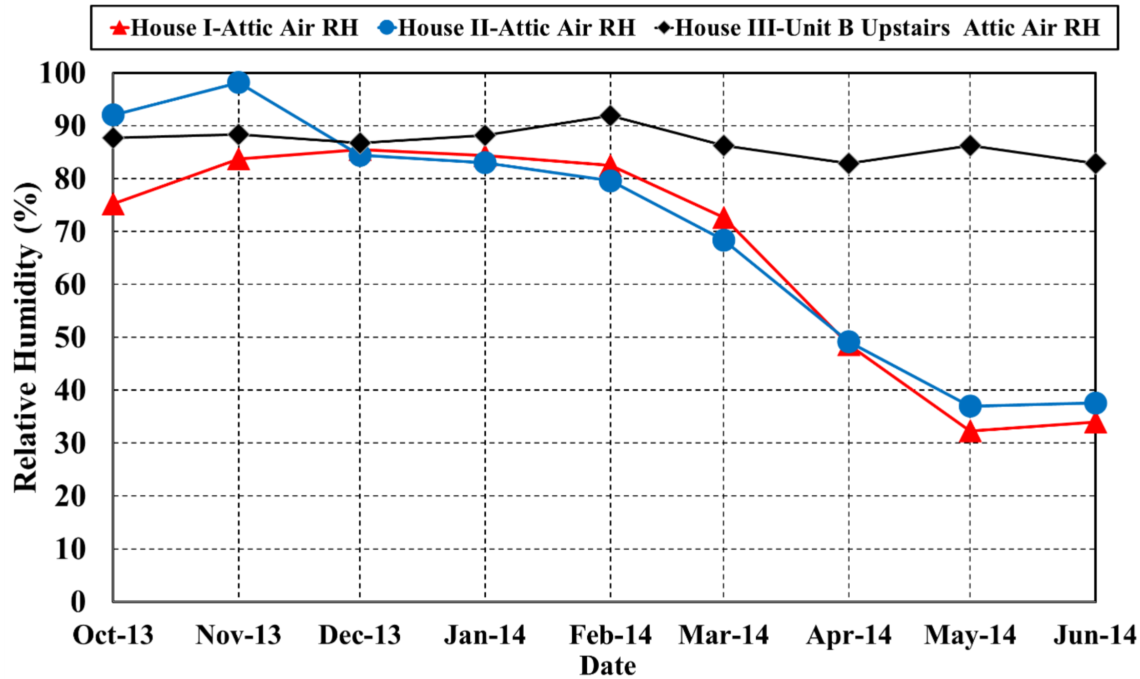
4.3 Performance Comparison

The hygrothermal conditions of three houses with different venting systems in remote Arctic regions were monitored and the hygrothermal performance of these attics were evaluated based on measured relative humidity, temperature, moisture content of plywood sheathing and wood truss, moisture excess in attic spaces, and potential for mold growth. The comparison in hygrothermal performance of these three attics is summarized in Table 4.1 and presented in Figure 4-15.

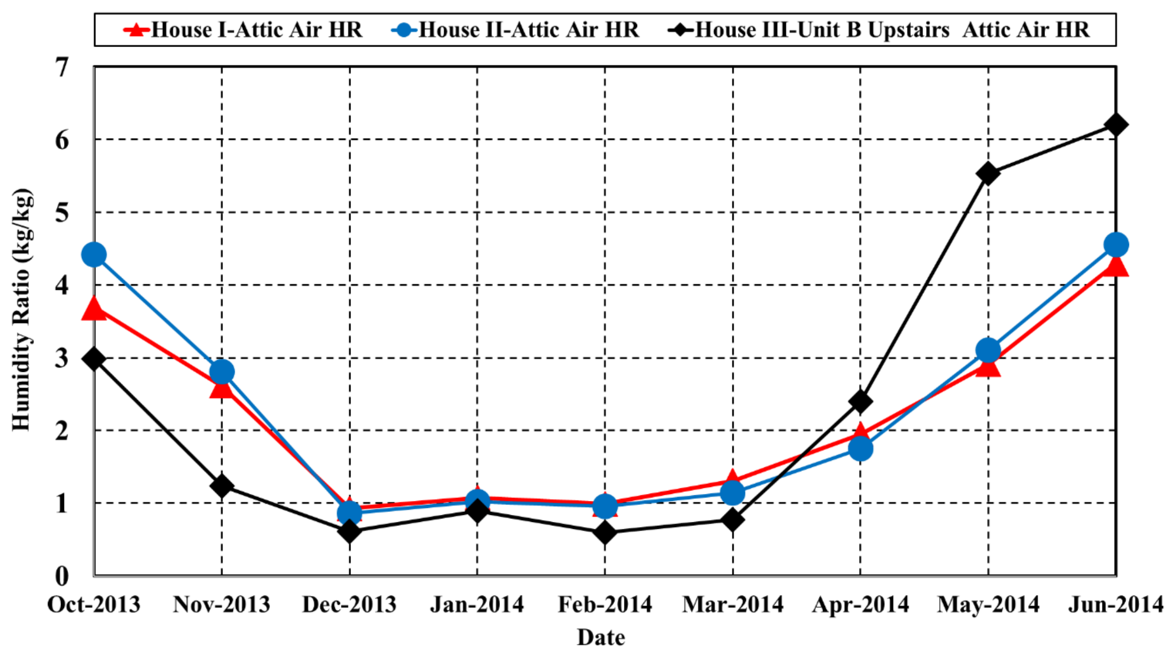
Table 4.1. Comparison of hygrothermal performance of three attics.

	RH (attic air)	**Daily average MC**	**ΔHR (attic-outdoor air)**	**Mold growth index**
House I (ventilated attic with filter membrane	Ave.:65.2% Min: 8.8% Max: 99.5%	NW truss had MC level above 20% for two weeks and dried quickly to 12% during the summer.	Ave.(+,76%):0.79 g/kg Ave.(-,24%):-1.24 g/kg Min: -7.82 g/kg Max: 7.32 g/kg	Negligible, close to zero
House II (ventilated attic with filter membrane)	Ave.:69.9% Min: 12.4% Max: 100%	• All sheathing except for NW sheathing had a short period of MC level above 20% (2-5 weeks); • **SW, SE sheathing & SW truss** peaked at 26-28% toward the end of Feb. 2014, above 20% for 2-2.5 weeks; **NE sheathing** peaked at 24% at end of Mar. 2014, above 20% for 2 weeks; • **West sheathing** peaked at 26%, above 20% for 5 weeks.	Ave.(+,73%):0.97 g/kg Ave.(-,27%):-1.17 g/kg Min: -6.93 g/kg Max:13.70 g/kg	Max. 0.3
House III (un-ventilated attic)	Ave.: 85.7% Min: 64.5% Max: 99.3%	• Higher initial MCs; • Longer period of MCs above 20% (4-5 months); • **Unit B North Truss** peaked at 35% at the end of March 2014; **Unit A North Sheathing** peaked at 29% early April; **Unit B North sheathing** peaked at 29% mid-April; • In summer 2014, MCs at three locations still remained above 20% except for Unit B East sheathing.	Ave.(+,83%):1.22g/kg Ave.(-,17%):-0.47 g/kg Min: -2.88 g/kg Max: 16.39 g/kg	About 3.0 on both plywood sheathing and wood truss at the end of Aug. 2014

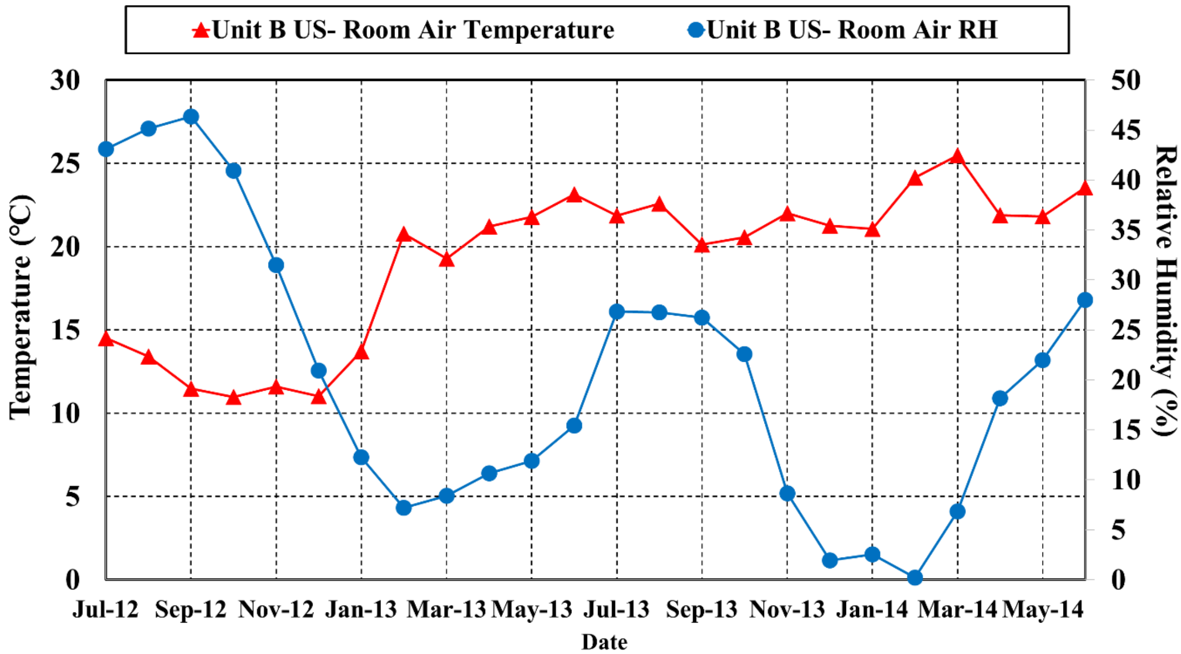
- positive sign (+) refers to attic air HR is higher than outdoor air HR.
- % refers to the proportion of the year, when the humidity ratio is lower (-) or higher (+) than in the outdoor air.



a) Monthly average relative humidity in attic.



b) Monthly average humidity ratio in attic.



(c) Monthly average humidity ratio difference between attic and outdoor air (moisture excess).

Figure 4-15. Comparison among the three attics: (a) monthly average relative humidity in attic; (b) monthly average humidity ratio in attic; (c) monthly average humidity ratio difference between attic and outdoor air (moisture excess).

The analysis shows that in general the ventilated attics with filtering membrane managed to maintain the attics at acceptable conditions. In House I, the daily average MCs at most monitored locations in plywood sheathing and wood truss remained below 20%, except for NW truss with a short period above 20% toward the end of March. In House II, all sheathing except for NW sheathing and wood truss had a short period of daily average MC levels above 20%. The MCs increased abruptly and peaked at 26-28% toward the end of Feb. 2014 and dried quickly within two weeks to below 20% at SW sheathing, SW truss and SE sheathing, while the MC level of West sheathing remained above 20% longer, for about five weeks. The abrupt increase of MC at NE sheathing started about one month later in mid-March with a peak value of 24% and dried quickly within two weeks to below 20%. The MC levels at these locations were able to decrease to around 10% during the summer months. The attic air temperature and humidity ratios were generally higher than that of the outdoor air during the winter, spring and fall times. There were occasions when the attic air temperature and humidity ratio were lower than that of the outdoor air, mainly during the night in the summer due to clear-sky radiation. The time for the attic humidity ratio higher than the outdoor air was 76% for House I and 73% for house II.

In general, the maximum daily averaged MC levels in plywood sheathing and wood truss in House II were higher than those in House I. This trend is consistent with the attic relative humidity and moisture excess, i.e. both the average RH and moisture excess in attic air of House II were slightly higher than that in House I, as shown in Figure 4-15. It is difficult to attribute the slight difference in hygrothermal performance between these two attics to the difference in venting strategies given that many other factors such as the moisture from indoors, the insulation level and airtightness of the ceilings, pressure difference, and local weather conditions also affect the hygrothermal conditions of the attics. The short period of elevated moisture content levels did not result in mold growth risks, as both shown by the mold growth index calculated and site observations.

For the SIP house with the un-ventilated attic, the attic RH levels were higher than those in House I and House II. As shown in Figure 4-15-a), a monthly average of 75% RH remained through the summer, while during the winter and spring time the monthly average RH remained about 90%. 83% of the time the attic humidity ratio was higher than the outdoor air. As shown in Figure 4-15-b), the humidity ratio of attic air in the un-ventilated attic of House III was lower than that in the ventilated attics during the winter time due to its location in a colder climate, while it abruptly increased starting from the spring and became significantly greater than that in the ventilated attics in the summer. Consequently, as shown in Figure 4.15-c), the monthly averaged moisture excess in un-ventilated attic of House III remained positive all year round and significantly higher during the summer months, while the monthly averaged moisture excess in ventilated attics of House I and II became negative during summer months, which is an indication of drier attic in the summer as the result of attic ventilation.

The MC levels remained above 20% at most locations for four to five months from March to July 2014. The MCs peaked at 29-35% at sheathing and wood truss in mid-March and dried much slower compared to House I and II. The initial MC levels of the plywood sheathing in House III were higher at about 16-18% compared to that in House I and House II. The application of weather stripping around the attic hatches may have limited air leakage from indoor space to attic, which did not increase the MC of sheathing significantly as indicated by the slight increase of MC in sheathing over the winter time. However, without active attic ventilation, even slight accumulation of moisture in the attic cannot be effectively removed out of the attic. Although drying occurred during the summer time, the drying rate was much slower than that in House I and II with attic ventilation. The trend with moisture accumulation over time and high MC levels above 20% even during the summer months pose risks for biological degradation for the un-ventilated attic.

Chapter 5 HYGROTHERMAL SIMULATIONS

This chapter presents detailed settings of hygrothermal models created by WUFI Plus 3.1 of House I (ventilated attic) and House III (un-ventilated attic) including model geometry, climate conditions, boundary conditions, initial conditions, envelope assemblies and material properties. Meanwhile, simulation results of relative humidity (RH) and temperature (T) in attic zone and moisture levels (MC) and temperature (T) of attic sheathing are compared with measured results for model validation. Comparison of House I and House III in both Kuujjuaq and Iqaluit under same conditions is also performed for further model validation.

5.1 Introduction of WUFI Plus 3.1

WUFI® Plus is an advanced whole-building simulation tool based on one-dimensional (1-D) hygrothermal calculations on building envelope assemblies (roofs, walls, floors, foundations, etc.) developed by Künzel (Künzel, 1994; Antretter, Sauer, Schöpfer & Holm, 2011). It integrates hygrothermal simulations for all assemblies of building envelope under zonal model (Holm & Künzel, 2003). As a commercial HAM simulation tool, WUFI® Plus can develop holistic model for test house which is able to combine heat, air and moisture simulating in the entire building. This software not only can be used for studying hygrothermal performance across building construction, but also allows for simulating indoor environment through defining separate zones by multi-zone model. It simulates the un-steady transient flows of heat and moisture exchange among assembly surfaces under predefined time step. Meanwhile, internal loads, building envelope structure, ventilation are taken into account as main factors for presenting real-time simulation results based on user-defined outdoor and indoor climate. Besides, WUFI Plus also can generate whole-building energy consumption through defining HVAC system.

WUFI Plus 3.1, the latest version in WUFI Plus family, is selected to create model in this thesis. One of the advantages of WUFI Plus is detailed 3D model can be created or imported to get accurate result. To investigate the dynamic hygrothermal performance of ventilated and un-ventilated attics, each test house is divided into attic zone and indoor zone to setup model.

Boundary conditions, initial conditions and material properties with detailed enclosure constructions need to be input to WUFI Plus to run simulation.

5.2 Model Setup

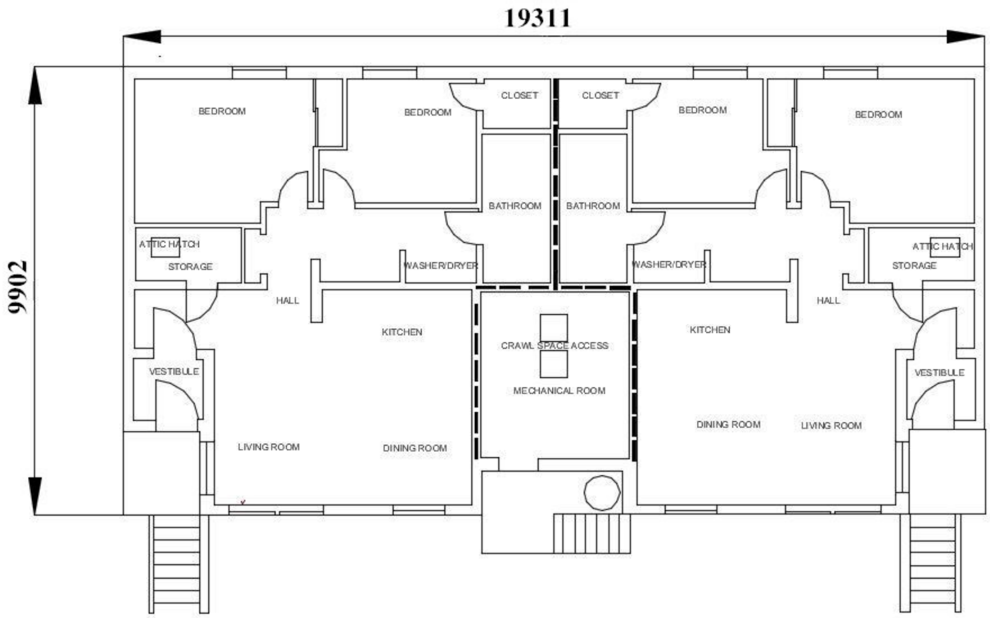
5.2.1 Hygrothermal Model for House I: KMHB House

5.2.1.1 Building Geometry and Zonal Model in WUFI Plus

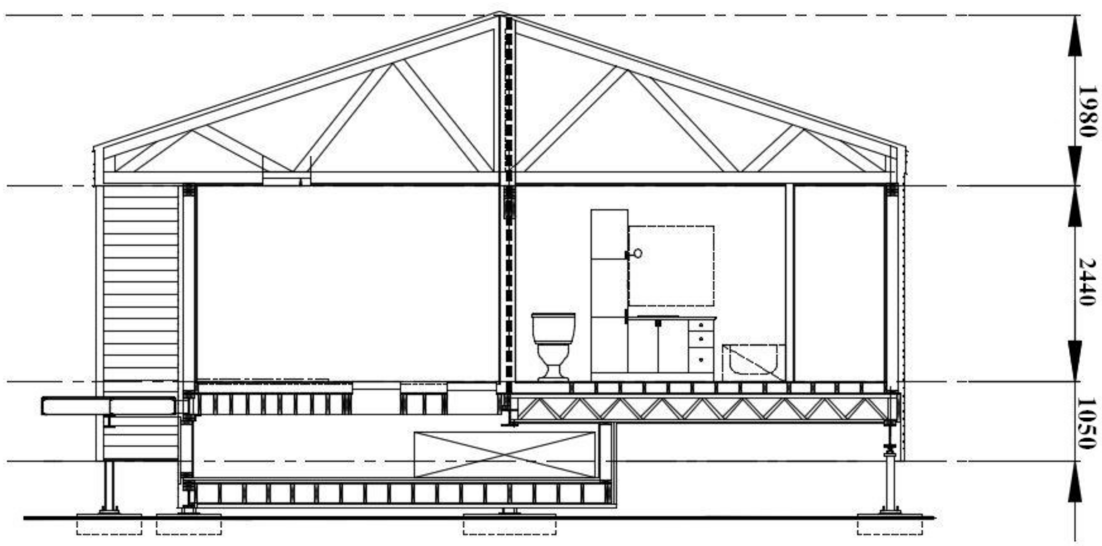
House I is a typical single-story duplex residential house owned by Kativik Municipal Housing Bureau (KMHB) located in Kuujjuaq. This house has a ventilated and unconditioned cold attic and two 1000 ft^2 living units with a shared mechanical room. Figure 5-1 shows the floor plan and elevation plan of House I, meanwhile, the dimension of main house is about 9.9m×19.3m×2.44m (W×L×D), the height of low-sloped attic is 1.98m.

Based on the construction drawing, a detailed model of House I (Figure 5-2) is created by WUFI Plus HAM tool. To simulate hygrothermal conditions in attic area, House I is separated to two simulated zones: attic zone and indoor zone (living space). Crawl space is not included in this model since this portion of the house does not affect hygrothermal conditions of ventilated attic. The indoor zone is simplified to be considered as one area without partition walls. The volume of indoor zone and attic zone are about 440 m^3 and 156 m^3, respectively.

Simulation period is set from October 17th, 2013 to July 18th, 2015 to match the period of field measurements.



a) Floor plan of House I.



b) Elevation plan of House I.

Figure 5-1. Architecture drawing of House I (Dimensions are in millimeters).

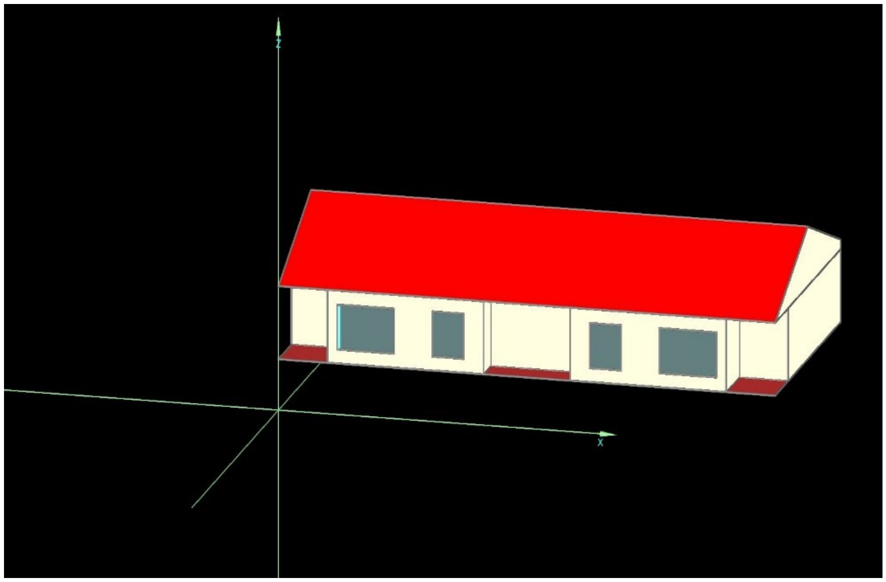


Figure 5-2. Simulation model of House I (KMHB House) created by WUFI Plus.

5.2.1.2 General Setting in WUFI Plus

Selection of calculation methods of WUFI Plus depends on input parameters and expected outcome, which will affect the accuracy of simulation results. Calculation methods activated in WUFI Plus model of House I are listed as follow:

1) Include shading calculation;
2) Explicit radiation balance on external surfaces;
3) Wind dependent heat transfer on exterior surfaces;
4) Include moisture balance and comfort by thermal calculation.

5.2.1.3 Boundary Conditions

Details of boundary conditions are presented in this section including outdoor climate, indoor climate and surface transfer. Outdoor climate elements needed by WUFI Plus including temperature, relative humidity, solar radiation (diffused solar radiation and direct solar radiation), wind speed and wind direction. Indoor climate mainly considers temperature and RH level.

For outdoor climate, WUFI Plus has built-in weather database for a number of cites around the world, but Kuujjuaq is not included. And there is no on-site weather data measured in test houses in Kuujjuaq. Therefore, the weather data from EnergyPlus Weather Format (EPW) is used instead. There are 20 weather data sources for EPW weather file, which can be downloaded from energy plus official website. For Kuujjuaq, weather data source of EPW file is CWEC (Canadian Weather for Energy Calculation). CWEC files are combined with hourly observed weather data for a synthetic one-year period. These files are co-production completed by Numerical Logics and Environment Canada and the National Research Council of Canada and available from Environment Canada official website.

5.2.1.3.1 Outdoor Climate

The detailed weather elements, including temperature, relative humidity, solar radiation (diffused solar radiation and direct solar radiation), wind speed and wind direction, are plotted in the following graphs.

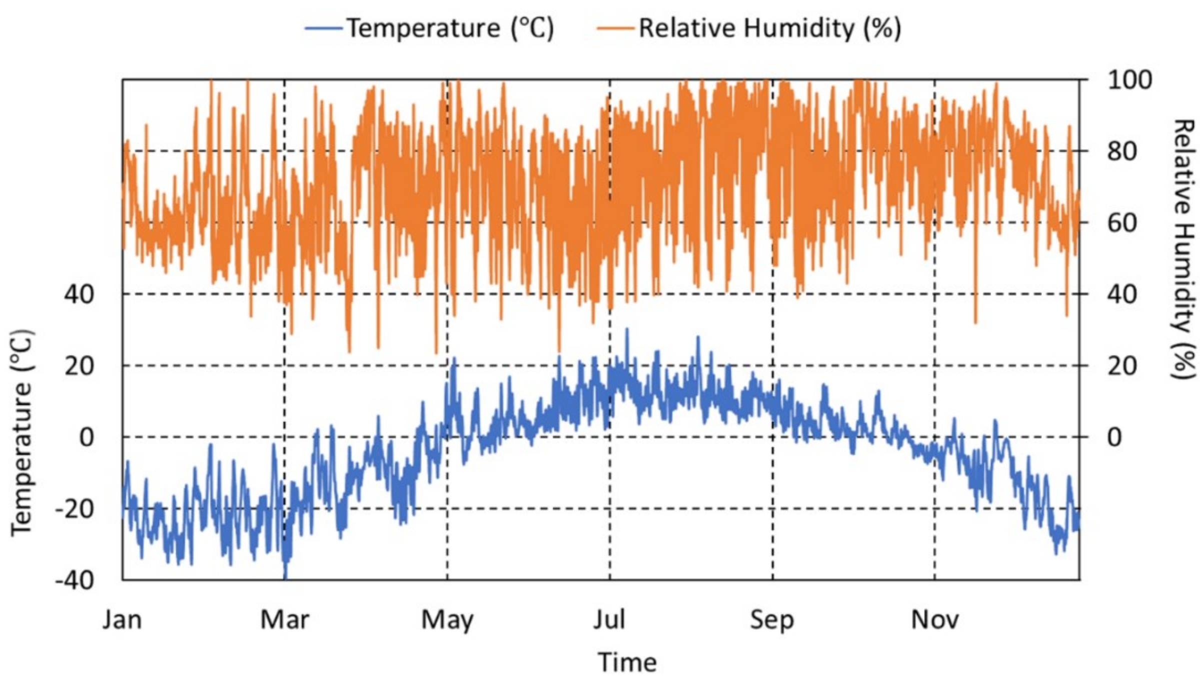


Figure 5-3. Outdoor relative humidity and temperature of CWEC weather file in Kuujjuaq.

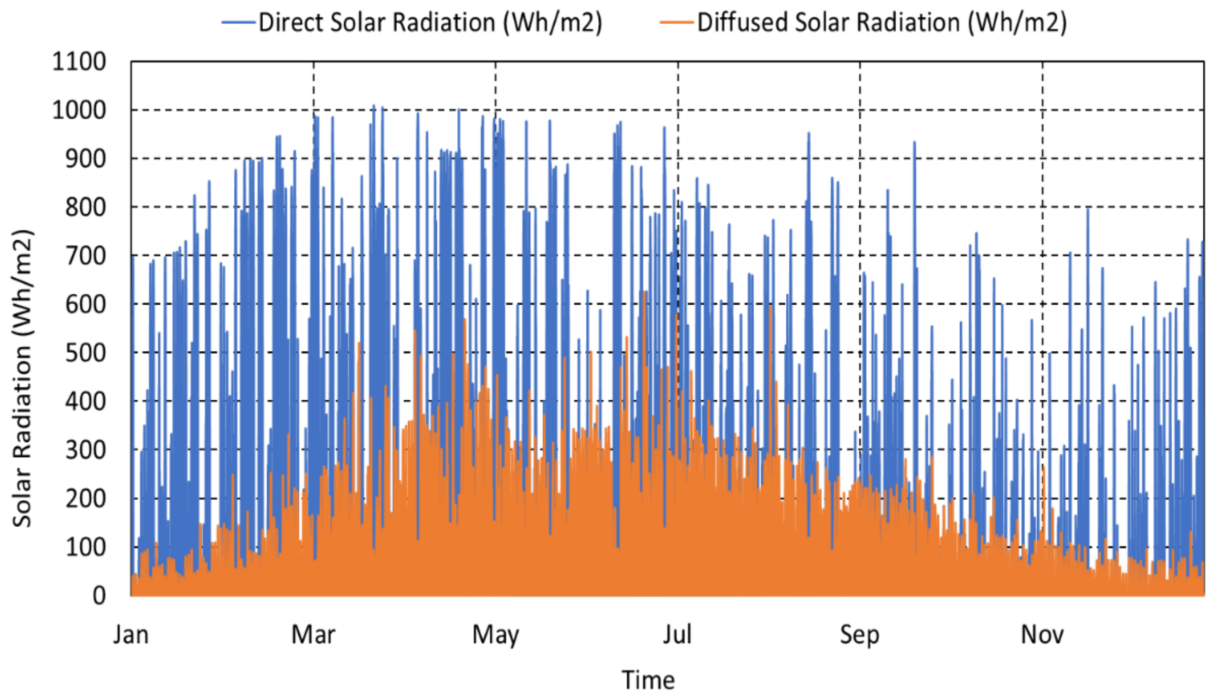
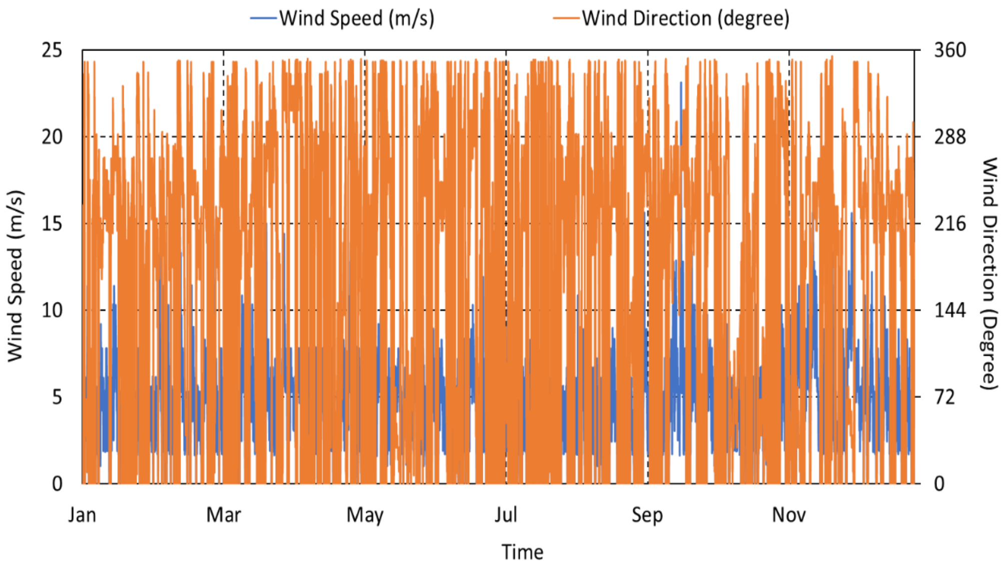
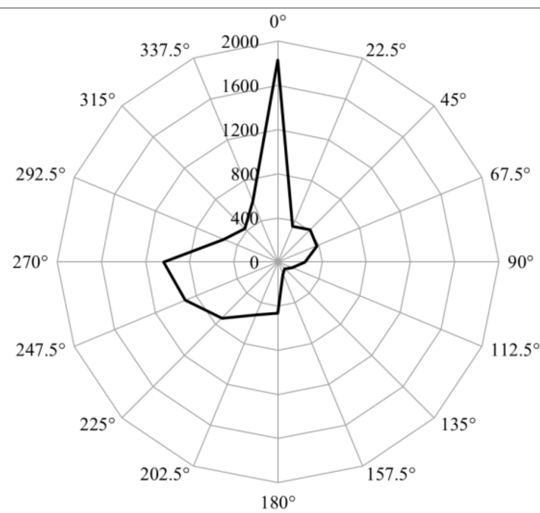


Figure 5-4. Diffused and direct solar radiation of CWEC weather file in Kuujjuaq.

Figure 5-3 and Figure 5-4 show outdoor temperature & relative humidity and diffused & direct solar radiation of CWEC file in Kuujjuaq, respectively. The outdoor temperature in Kuujjuaq varies between a minimum of -39.6 ℃ and a maximum of 30.3 ℃. The annual average temperature is -3.74 °C with the standard deviation of 13.72°C. The relative humidity is generally high in the whole typical year with an obvious fluctuation, sometimes reach as high as 100% and the minimum value is 24%. The annual average is about 72% with the standard deviation of 15.1%. Direct solar radiation varies between 0 to 1009 W/m^2 with the obvious daily fluctuation. The annual average is around 122 W/m^2 with the standard deviation of 235 W/m^2. Diffused solar radiation varies between 0 to 625 W/m^2 with the obvious daily fluctuation. The annual average is around 60 W/m^2 with the standard deviation of 93 W/m^2.



a) Wind speed and wind direction diagram.



b) Wind rose plot.

Figure 5-5. Wind speed and wind direction of CWEC weather file in Kuujjuaq.

As shown in Figure 5-5, hourly wind speed and wind direction of CWEC weather file in Kuujjuaq are both plotted in diagram and wind rose graphs to indicate wind distribution more intuitively. Maximum wind speed is 23.1 m/s and minimum value is 0 m/s with the average speed is 3.85 m/s. Wind direction has obviously hourly change, the main wind distribution is from north and west orientations. Meanwhile, the frequency of the north can reach to 1432 times per year (hourly time per whole year) which presents the North is the main wind in Kuujjuaq. (0°=North; 90°=East; 180°=South; 270°=West)

5.2.1.3.2 Indoor Climate

For indoor climate, measured indoor temperature and RH House I from October 17th, 2013 to July 18th, 2015 are available and used as input.

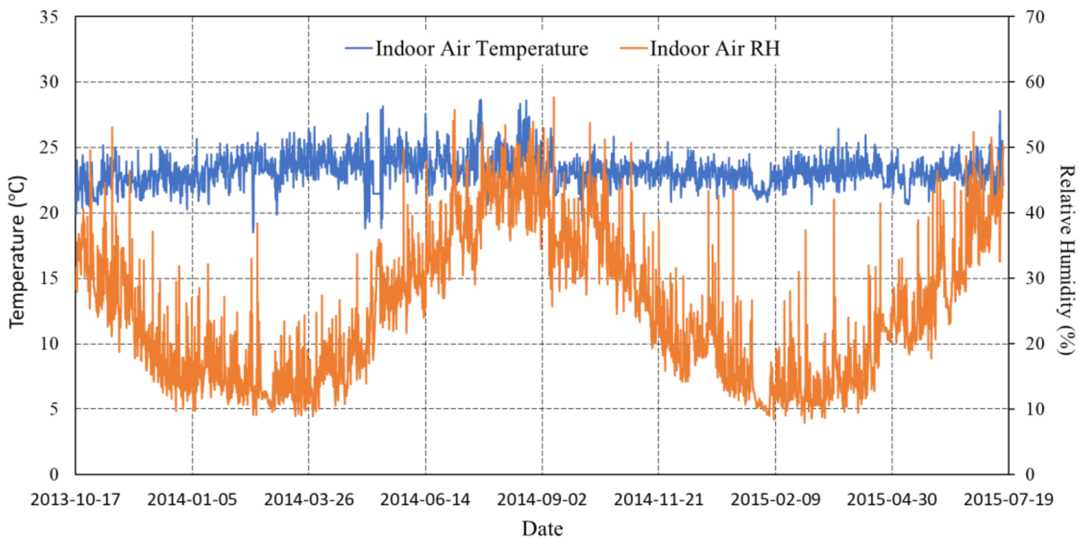


Figure 5-6. Field measured indoor climate (Temperature and Relative Humidity) in House I (KMHB House).

Figure 5-6 presents on-site indoor climate (temperature and relative humidity level) measured in KMHB house from October 17th, 2013 to July 18th, 2015. Indoor temperature ranges from 19 ℃ to 29 ℃ with significant daily fluctuations. The average indoor temperature is around 23℃. Indoor relative humidity (RH) varies between 8% and 58% with a distinct seasonal change. RH curve gradually decreases during winter and spring periods and increases back during summer time. The maximum and minimum RH values can be found in August and March, respectively.

Indoor temperature range could be from 67 to 82 °F (20 to 27℃) for occupancy thermal comfort purposes mentioned from ASHRAE Standard 55-2013 (Thermal Environmental Conditions for Human Occupancy). ASHRAE Standard 62.1-2010 (Ventilation for Acceptable Indoor Air Quality) notes relative humidity in occupied space should be less than 65% under dehumidification condition. Both field measured temperature and relative humidity level remain in this range.

5.2.1.3.3 Surface Transfer of Attic Components

Surface transfer normally includes two aspects which are thermal and moisture transfer in both exterior and interior sides of building envelope components. Surface thermal transfer includes heat transfer resistance, solar absorption/emission on the exterior surface, solar gain in interior distribution and shading. Surface moisture transfer is affected by surface coating. The hygroscopic characteristics of coating material influence moisture diffusion of envelope assemblies. It's recognized that the concept of "surface transfer coefficient" is derived from boundary layer theory which is established by Ludwig Prandtl in 1904 (Anderson, 2005). Surface transfer coefficient is important for the accuracy of hygrothermal simulation results. Unreasonable setting of surface transfer coefficient may cause non-physical results. Default values for the surface transfer coefficients are set in the model for in House I.

5.2.1.4 Initial Conditions

The setting of initial conditions is based on field measured data and weather data of House I. Table 5.1 lists the initial temperature and RH of indoor zone, attic zone and envelope assemblies (from outside to inside). Table 5.2 lists the initial temperature and MC level of plywood sheathing in attic space according to field measured data.

Table 5.1. Initial conditions of Indoor Zone and Attic Zone (House I).

Zone Name	Specific Items	Initial Temperature (℃)	Initial RH (%)
Indoor Zone	Indoor Air	21.52	28.74
	Exterior Wall Assemblies	2.8	83
	Exterior Windows	2.8	83
Attic Zone	Attic Air	3.1	62
	Low-Sloped Roof	2.8	83

Table 5.2. Initial conditions of plywood sheathing (House I).

	Initial Temperature (℃)	Initial MC (%)
South Sheathing	8.46	13.06
North Sheathing	8.39	13.07

5.2.1.5 Envelope Assemblies & Material Properties

Table 5.3 lists the detailed configurations of envelope assemblies in House I. The material properties are taken from WUFI Plus material database under "North America" —— "Generic Materials" category.

Table 5.3. Detailed configurations of envelope assemblies in House I.

Envelope Assembly	Detailed Configurations (Layer by Layer)
Exterior Wall (from exterior to interior)	• Engineered Wood Siding • 19×64mm Vertical Wood Strapping • Air Barrier (Spun-bonded Polyolefin) • 38mm Rigid XPS • 38×140mm Wood Studs (SPF) • 140mm Mineral Wool Insulation • 0.15mm Polyethylene Vapor Barrier • 19×64 mm Horizontal Wood Strapping • 13mm Gypsum Board
Sloped Roof (from exterior to interior)	• Asphalt Shingles • Roofing Membrane • 16mm Plywood Sheathing
Ceiling (from indoor space to attic space)	• 13mm Gypsum Board • 19×64mm Wood Strapping • 0.15mm Polyethylene Vapor Barrier • 280mm Fiberglass Insulation
Floor (from exterior to interior)	• 13mm Exterior Plywood • Air Barrier (Spun-bonded Polyolefin) • 280mm Fiberglass Insulation • 0.15mm Polyethylene Vapor Barrier • 16mm OSB Sheathing • 38×140mm Wood Joists • 16mm Plywood Sheathing • Finished Flooring (PVC)

5.2.1.6 Attic Ventilation Rate & Ceiling Air Leakage Rate

Pitot tubes were installed in attic vent inlet to measure the air pressure drop. According to Bernoulli's equation, air flow speed entering in attic can be calculated based on measured pressure drop. However, there is drift in the pressure differential sensors. Therefore, the collected data is not usable for either analysis or simulation. And a reasonable attic ventilation rate is assumed based on literature review.

To investigate the influence of attic ventilation rates on hygrothermal performance of attics, assumed attic ventilation rate is listed in the following table based on previous experiments and field measurement studies summarized in literature review (Chapter 2).

The blower door test shows, the whole-building airtightness is 1.89 ACH @ 50 Pa (divided by 20 to convert to 0.09 ACH @ 4Pa) tested by depressurization method for House I. According to ASHRAE Fundamental 2013, typically 30% of air leaks through ceiling plane. In this case, ceiling air leakage rate will be 17.79 m^3/h.

Table 5.4 lists the attic ventilation rate and ceiling air leakage rate of House I assigned in WUFI Plus model.

Table 5.4. Setting of attic ventilation rate and ceiling air leakage rate in WUFI Plus model of House I (KMHB House).

Parameter	Detailed Setting
Assumed Attic Ventilation Rate	5 ACH
Assumed Ceiling Air Leakage Rate	17.79 m^3/h (0.09 ACH @ 4 Pa under 30% penetration)

5.2.1.7 Summary of Model Setting

Table 5.5 summaries key information of model setting and boundary conditions of WUFI Plus model of House I (ventilated attic) for model validation.

Table 5.5. Setting of key parameters in WUFI Plus model for House I.

Setting Items	**Detail Setting**
Attic Volume	440 m^3
Indoor Space Volume	156.4 m^3
Attic Ventilation Rate	5 ACH (1/h)
Ceiling Air Leakage Rate	17.79 m^3/h (0.09 ACH @ 4 Pa under 30% penetration)
Un-intentional air infiltration	0.05 ACH
Ceiling Assembly (from indoor space to attic space)	• 13mm Gypsum Board • 19×64mm Wood Strapping • 0.15mm Polyethylene Vapor Barrier • 280mm Fiberglass Insulation

Sloped Roof Assembly (from exterior to interior)	• Asphalt Shingles • Roofing Membrane • 16mm Plywood Sheathing
Outdoor Climate	Kuujjuaq, Nuavik, Quebec Typical Meteorological Year (TMY2) Weather File in EPW format
Indoor Climate	Field Measured Data (RH/T)
Initial Conditions of Attic Air (Temperature and MC)	21.52 ℃; 28.74%
Initial Conditions of Attic Sheathing (Temperature and MC)	South Sheathing—8.46℃; 13.06% North Sheathing—8.39℃;13.07%
Simulation Period	October 17th, 2013 to July 18th, 2015

5.2.2 Hygrothermal Model of House III: SIP House

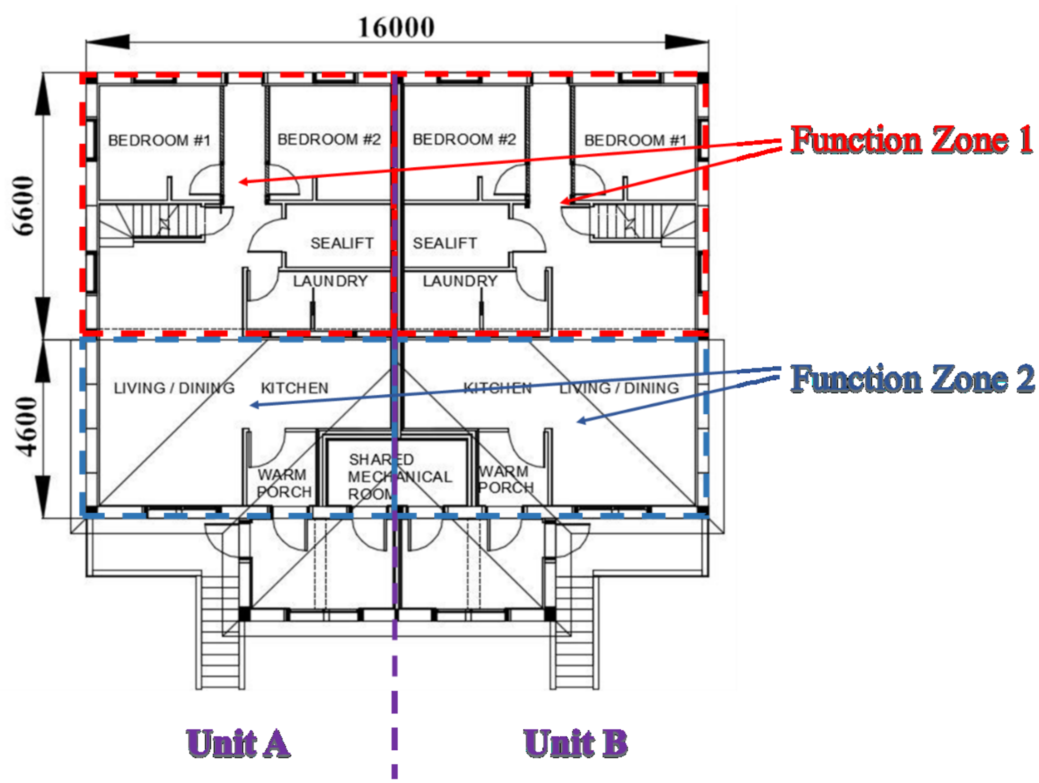
5.2.2.1 Building Geometry and Zonal Model in WUFI Plus

House III (SIP Prototype House) is a two-story duplex house built in Iqaluit in 2012 which is consisting of two 1700 ft^2 units with a shared mechanical room. Two units have totally same constructions, downstairs of the unit is separated to two functional zones, the zone near entrance is designed for living room and kitchen (Function Zone 1) and the other is designed for two bedrooms and laundry room (Function Zone 2). Function Zone 2 has secondary floor (Function Zone 3) which is designed for master bedroom, other bedroom, craft room and bathroom. The detailed floor plans of two stories are shown in Figure 5-7. Figure 5-8-a) and Figure 5-8-b) show front elevation and side elevation of House III, respectively. Mechanical room and room division are not created in WUFI Plus model as these parts will not affect hygrothermal performance of attic any more.

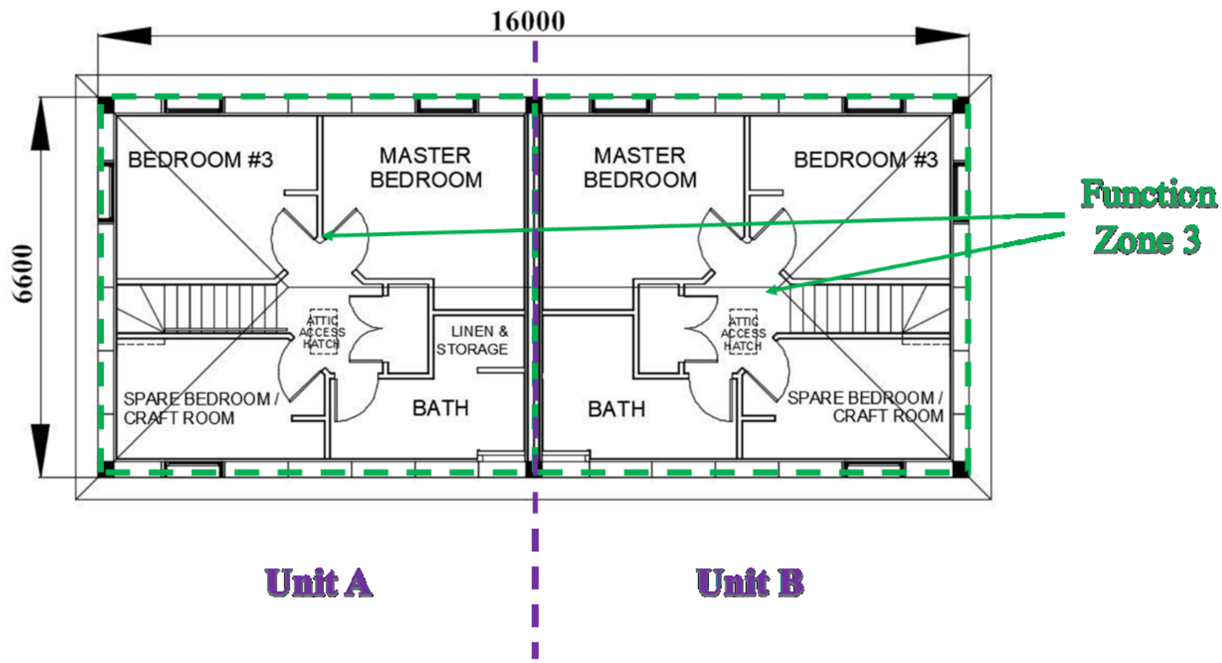
As shown in Figure 5-8-a), front area of House III only has one floor which is used for kitchen and living room spaces (Function Zone 1). The dimension of this area is 16m×4.6m (L×W) with the height of 2.46m. As shown in Figure 5-8-b), back area of House III has two floors which are used for bedrooms, the dimension of this area is 16m×6.6m (L×W) with the height of first floor is 2.46m and which of second floor is 3.04m. Figure 5-7 is elevation plans of House III, it can be seen that the height of sloped roof is 1.6m and the roof slope is 3:12.

Based on building constructions which has two attics in different heights, House III is separated to four simulated zones in WUFI Plus model to run simulation. They are “upstairs attic” zone, “upstairs indoor (living space)” zone, “downstairs attic” zone and “downstairs indoor (living space)” zone. Mechanical room is not established in WUFI Plus model as that is a separate room which doesn’t connect with tested attics. The approximate volume of each simulated zone is 581 m^3 for upstairs indoor zone, 405 m^3 for downstairs indoor zone, 66 m^3 for upstairs attic zone and 59 m^3 for downstairs attic zone, respectively. Figure 5-9 shows the simulation model of House III created by WUFI Plus.

Simulation period is set from August 1st, 2012 to May 31st, 2014 to match the field measured result.

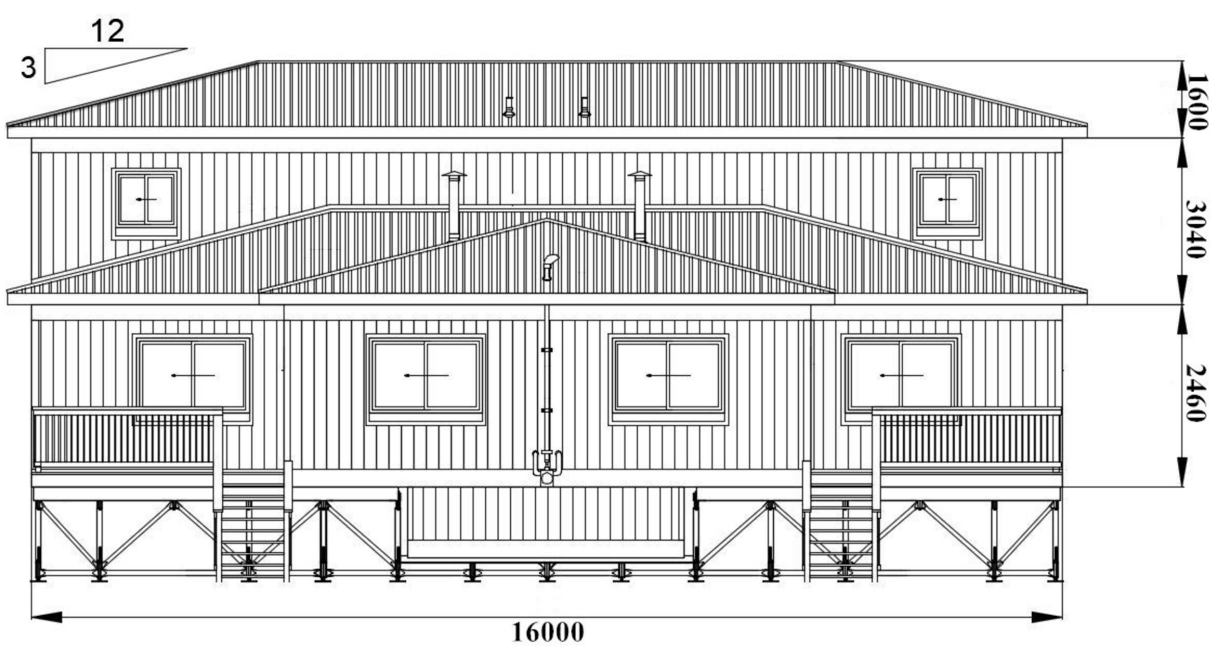


a) First floor plan of House III (SIP House).

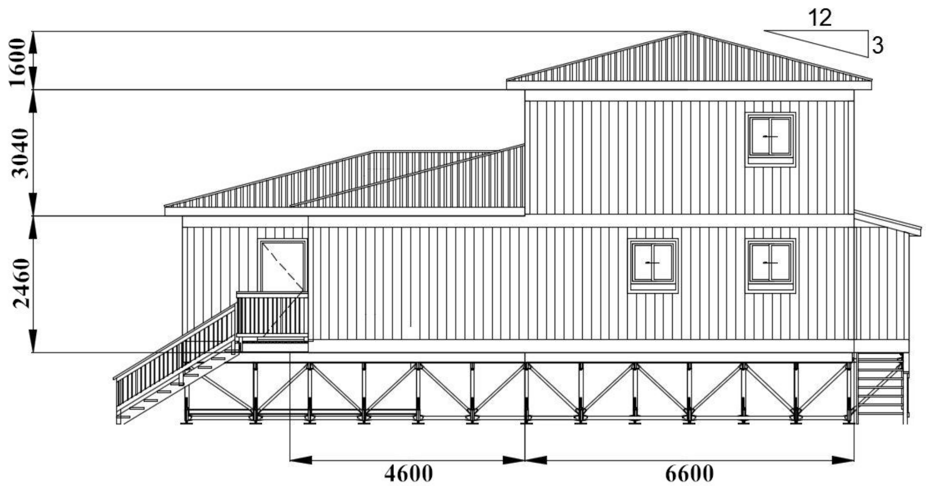


b) Second floor plan of House III (SIP House).

Figure 5-7. Floor plan of House III (SIP House) (Dimensions are in Millimeters).



a) Front elevation plan of House III.



b) Side elevation plan of House III.

Figure 5-8. Elevation plans of House III (SIP House) (Dimensions are in Millimeters).

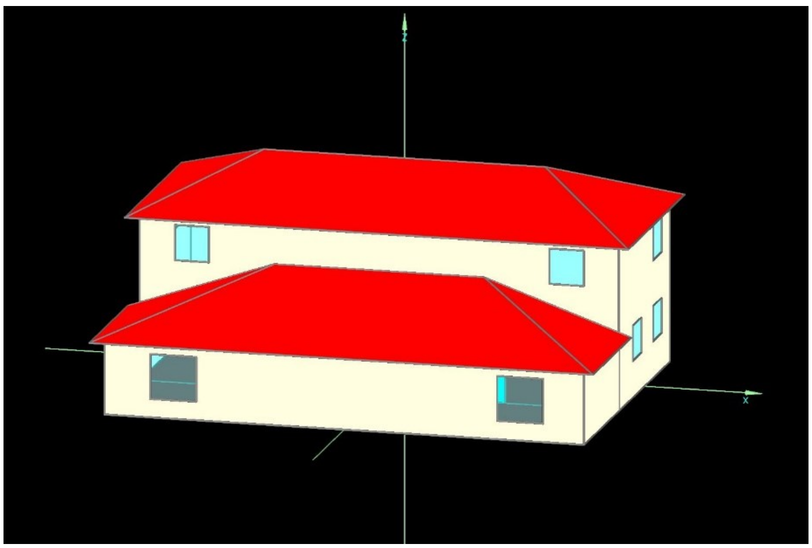


Figure 5-9 Simulation model of House III (SIP House) created by WUFI Plus.

5.2.2.2 General Setting in WUFI Plus

Selection of calculation methods of WUFI Plus depends on input parameters and expected outcome, which will affect the accuracy of simulation results. Calculation methods activated in WUFI Plus model of House III are listed as follow:

1) Include shading calculation;
2) Explicit radiation balance on external surfaces;
3) Wind dependent heat transfer on exterior surfaces;
4) Include moisture balance and comfort by thermal calculation.

5.2.2.3 Boundary Conditions

As same as the introduction of House I, details of boundary conditions of House III are also presented in two aspects: outdoor climate and indoor climate. Outdoor climate elements need to input to WUFI Plus including temperature, relative humidity, solar radiation (diffused solar radiation and direct solar radiation), wind speed and wind direction. Indoor climate mainly considers temperature and RH level.

For outdoor climate, the situation is the same as House I. WUFI Plus database does not include Iqaluit and no on-site weather data is measured for House III. Therefore, EnergyPlus Weather Format (EPW) file is used instead. For Iqaluit, weather data source of EPW file is TMY2 (Typical Meteorological Year Version 2). TMY2 file presents typical weather conditions (solar radiation and other meteorological elements) instead of real-time weather data for one-year period. The source data is from National Renewable Energy Laboratory (NREL) covering the period from 1961 to 1990 for 239 U.S. locations (Marion & Urban, 1995). The design purpose of TMY2 is for energy simulation of different building systems. Same as the CWEC file, there is no rain data included in TMY2. House III has metal roofs that have impermeable surfaces for both upstairs and downstairs, therefore, the impact of rain data on the hygrothermal performance of attic is considered as negligible.

5.2.2.3.1 Outdoor Climate

As introduced above, TMY2 file of Iqaluit under EnergyPlus Weather Format (EWF) is input to WUFI Plus as outdoor climate data. The details of weather elements, including temperature, relative humidity, solar radiation (diffused solar radiation and direct solar radiation), wind speed and wind direction, are plotted in the following graphs.

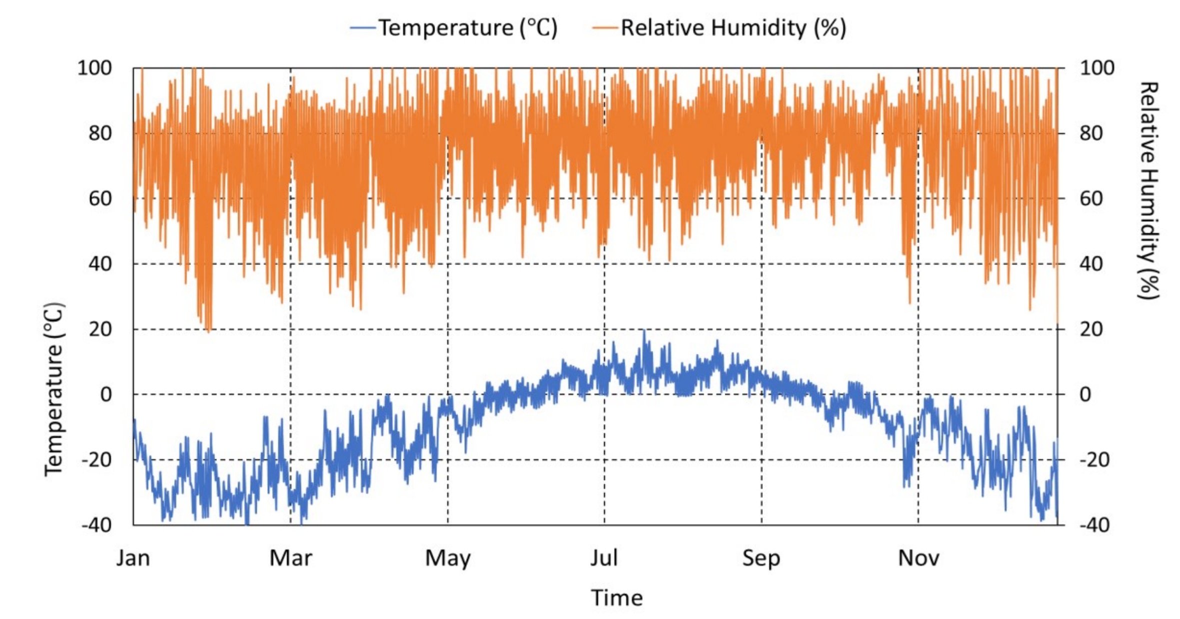


Figure 5-10. Outdoor temperature and relative humidity of TMY2 weather file in Iqaluit.

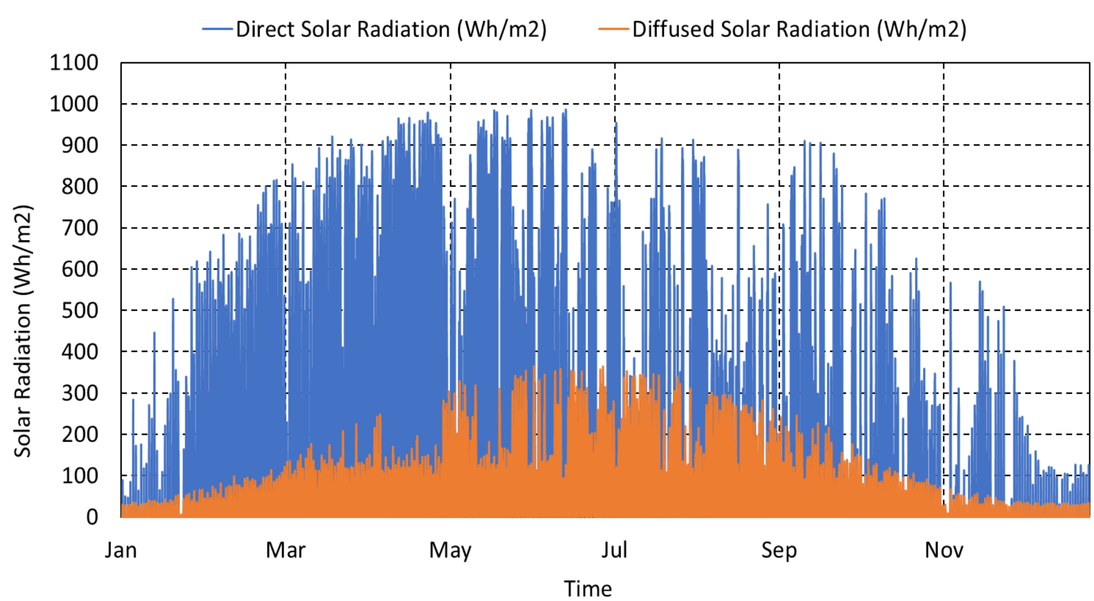
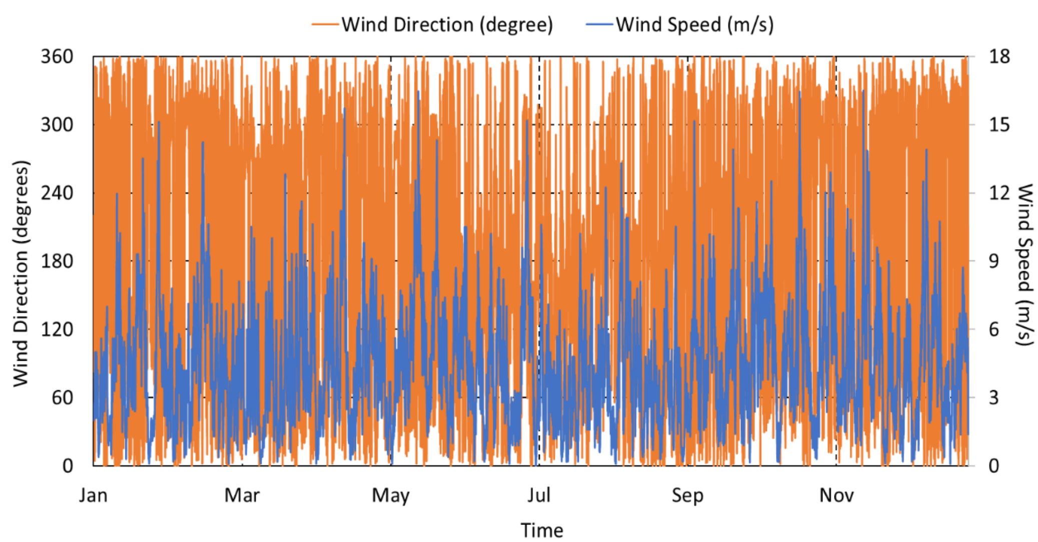


Figure 5-11. Diffused and direct solar radiation of TMY2 weather file in Iqaluit.

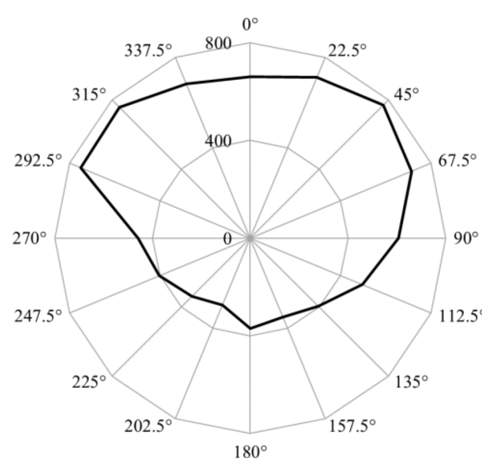
Figure 5-10 shows outdoor temperature and relative humidity of TMY2 file in Iqaluit. Outdoor temperature ranges between a minimum of -40.5 ℃ and a maximum of 19.8 ℃. It can be seen that outdoor temperature is below zero in most of the year except for the period from June to October. The average temperature during winter and spring periods fluctuates around -20℃. And the average temperature in the whole artificial year is -9.36 ℃ with the standard deviation is

13.72℃. Outdoor relative humidity level has a strong daily fluctuation which is ranging from 19% to 100%. The average RH level is 72.7% with the standard deviation is 15%.

Figure 5-11 indicates direct and diffused solar radiation of TMY2 file in Iqaluit. Direct solar radiation varies between 0 to 986 W/m^2 and diffused solar radiation ranges from 0 to 365 W/m^2. It's obvious that curves of direct solar radiation and diffused solar radiation have strong daily variation. The annual average value of direct solar radiation is 162.27 W/m^2 and which of diffused solar radiation is 48.63 W/m^2.



a) Wind speed and wind direction diagram.



a) Wind rose plot.

Figure 5-12. Wind speed and wind direction of TMY2 weather file in Iqaluit.

Figure 5-12-a) shows wind direction and wind speed in diagram format, both wind direction and wind speed indicate dramatically hourly variation. The range of wind speed is between 0 m/s and 16.4 m/s with an average value is 4.4 m/s and the standard deviation is 2.6 m/s. Wind direction changes from 0° to 360° with an obvious fluctuation. Frequency of hourly wind direction is graphed in Figure 5-12-b), the wind blowing from the north is significantly more than in the south. And the wind distribution in the north and south are relatively uniform, respectively. The frequency of each sub-wind direction in the north maintains 700 times per year (hourly time per whole year) approximately and which of the south is less than half that in the North.

5.2.2.3.2 Indoor Climate

For House III, there is no field measured data of indoor conditions available. In this case, EN 15026 from WUFI climate database is selected to generate indoor climate for simulation. EN 15026 is a European Standard issued in 2007 which has two modes: normal moisture load and high moisture load. This standard is normally applied to predict one-dimensional transient heat and mass transfer in multi-layer building constructions based on provided minimum criteria (Barreira, Delgado, Ramos & Freitas, 2010). Moreover, WUFI can derive interior climate according to assigned exterior climate and specific climate.

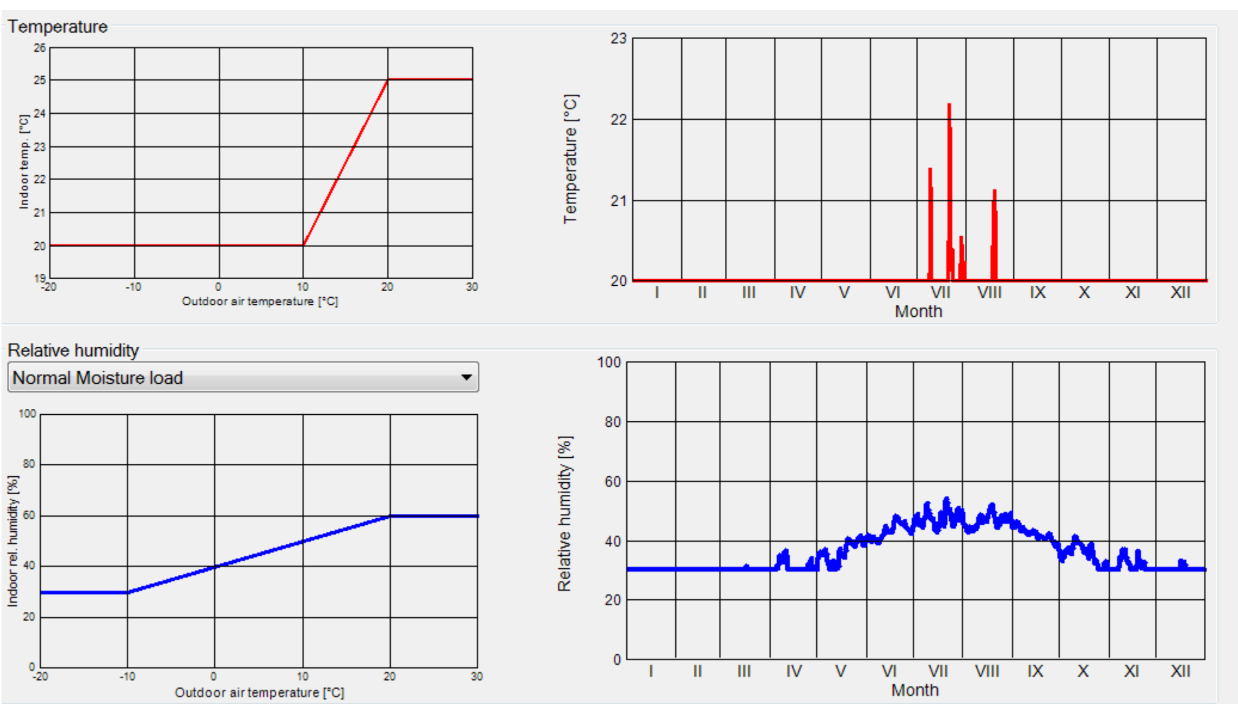


Figure 5-13. Indoor conditions of Standard EN 15026 (Normal Moisture Load).

Figure 5-13 indicates assigned indoor conditions under normal moisture load, temperature and relative humidity, based on Standard EN 15026. It's easy to observe that indoor temperature profile changes between 20℃ and 25℃ and indoor relative humidity changes between 30% and 60% when outdoor temperature ranges from -20℃ to 30℃. Monthly indoor temperatures generally maintain around 20℃ in the whole year, except for on July and August which temperature can reach to 22℃. Monthly indoor relative humidity varies between 30% and 55%, and humidity level maintains around 30% except for the period from May to November.

5.2.2.3.3 Surface Transfer of Attic Components

The detailed introduction can be found in section 5.2.2.3. Most settings of surface transfer coefficient in House III are default values.

5.2.2.4 Initial Conditions

The setting of initial conditions is based on field measured data and weather data of House III. Table 5.6 lists the initial temperature and RH of upstairs and downstairs indoor space, upstairs and downstairs attic spaces and envelope assemblies (from outside to inside). Table 5.7 lists initial temperature and MC levels (after the correction) of plywood sheathing in attic space according to field measured data.

Table 5.6. Initial conditions of Indoor Zone and Attic Zone (House III).

Zone Name	Specific Items	Initial Temperature (℃)	Initial RH (%)
Upstairs Indoor Zone	Indoor Air	14.9	44.3
	Exterior Wall Assemblies	5.4	79
	Exterior Windows	5.4	79
Downstairs Indoor Zone	Indoor Air	15.62	43.67
	Exterior Wall Assemblies	5.4	79
	Exterior Windows	5.4	79
Upstairs Attic Zone	Attic Air	13.83	67.6
	Low-Sloped Roof	5.4	79
Downstairs Attic Zone	Attic Air	15.29	74.79
	Low-Sloped Roof	5.4	79

Table 5.7. Initial conditions of plywood sheathing (House III).

	Initial Temperature (℃)	Initial MC (%)
Upstairs - North Sheathing	19.20	21.35
Upstairs - South Sheathing	8.39	13.07

5.2.2.5 Envelope Assemblies & Material Properties

Table 5.8 lists the detailed configurations of envelope assemblies in House III. The material properties are taken from WUFI Plus material database under "North America" —— "Generic Materials" category.

Table 5.8. Detailed configurations of envelope assemblies in House III.

Envelope Assembly	Detailed Configurations (Layer by Layer)
Exterior Wall (from exterior to interior)	• 15mm Goodstyle panel siding • 19×64mm Vertical Strapping (SPF) @ 400mm c/c • Weather Barrier (Spun-bonded Polyolefin) • 305mm Structural Insulated Panel (SIP) • 38×38mm Vertical Wood Strapping (SPF) @400mm c/c • 13mm Abuse Resistant Gypsum Board
Sloped Roof (from exterior to interior)	• Pre-finished Metal Roofing • 19×64mm Wood Strapping (SPF) @ 400 mm c/c • Weather Barrier (Spun-bonded Polyolefin) • 13mm Square Edge Plywood with H-clips • Engineered Wood Roof Trusses (SPF) @800mm c/c
Ceiling (from exterior to interior)	• 380mm Blown-in Cellulose Insulation RSI 11.1 (R-63) • 38mm Polyisocyanurate Insulation RSI 1.59 (R-9) • 19×64 Wood Strapping (SPF) @ 400mm c/c • 13mm Gypsum Board
Floor (from exterior to interior)	• Floor Finish • 16mm Tongue and Groove Plywood (SPF) Floor Sheathing • 371mm Structural Insulated Panel (SIP)
Partial Wall	• 12.7mm Abuse Resistant Gypsum Board • 152.4mm SPF Wood Stud • 12.7mm Abuse Resistant Gypsum Board

5.2.2.6 Ceiling Air Leakage Rate & Un-intentional air infiltration

Un-ventilated attic is a fully sealed construction without any openings in attic assembly. Therefore, moisture sources are mainly from indoor space. In this case, ceiling air leakage rate and un-intentional air infiltration are set as variables when indoor temperature and relative humidity are assigned.

The bower door test showed that the whole-building airtightness is 1.80 ACH @ 50 Pa (divided by 20 to convert to 0.09 ACH @ 4Pa) tested by depressurization method. According to ASHRAE Fundamental 2013, assume 30% air penetrating through ceiling plane. In this case, ceiling air leakage rate of upstairs and downstairs attics will be 15.66 m^3/h and 10.94 m^3/h, respectively.

For un-intentional air infiltration, which is the air tightness of attic construction itself. Too much leaky air will also introduce excessive moisture, and the selection of accurate value of un-intentional air infiltration should be measured by blower door test set in attic space. In this case, the result of blower door test of whole-building is used instead. As introduced in previous paragraph, 1.80 ACH @ 50 Pa (divided by 20 to convert to 0.09 ACH @ 4Pa) is assigned to WUFI Plus model in House III.

Summary of detailed setting of attic ventilation rate and ceiling air leakage rate is listed in Table 5.9 as follows:

Table 5.9. Setting of un-intentional air infiltration and ceiling air leakage rate in WUFI Plus model of House III.

Setting Items	Detailed Setting
Assumed Ceiling Air Leakage Rate of Upstairs Attic	15.66 m^3/h
Assumed Ceiling Air Leakage Rate of Downstairs Attic	10.94 m^3/h
Assumed Un-intentional air infiltration of Upstairs and Downstairs Attics	0.09 ACH

5.2.2.7 Summary of Model Setting

Table 5.10 summaries key information of model setting and boundary conditions of WUFI Plus model of House III (un-ventilated attic) for model validation.

Table 5.10. Key setting summarization of WUFI Plus model validation for House III.

Setting Items	Detail Setting
Upstairs Attic Volume	581 m^3
Downstairs Attic Volume	405 m^3
Upstairs Indoor Space Volume	66 m^3
Downstairs Indoor Space Volume	59 m^3
Ceiling Air Leakage Rate of Upstairs Attic	15.66 m^3/h (0.09 ACH @ 4 Pa under 30% penetration)
Ceiling Air Leakage Rate of Downstairs Attic	10.94 m^3/h (0.09 ACH @ 4 Pa under 30% penetration)
Un-intentional air infiltration of Upstairs and Downstairs Attics	0.09 ACH
Ceiling Assembly (from indoor space to attic space)	• 13mm Gypsum Board • 19×64mm Wood Strapping @ 406mm O.C. • 380mm Blown-in Cellulose Insulation (R-63)
Sloped Roof Assembly (from exterior to interior)	• Pre-finished Metal Roofing • 19×64mm Wood Strapping @ 406mm O.C. • Weather Barrier Membrane • 13mm Square Edge Plywood with Clips
Outdoor Climate	Iqaluit, Nunavut, Canada Typical Meteorological Year (TMY2) Weather File in EPW format
Indoor Climate	EN 15026 (RH/T)
Initial Conditions of Upstairs Attic Air	14.9℃ ; 44.3%
Initial Conditions of Downstairs Attic Air	15.62℃ ; 43.67%
Simulation Period	August 1st, 2012 to May 31st, 2014

5.3 Parametric Study of Ventilated and Un-Ventilated Attics for Model Validation

This section investigates the effect of variables on hygrothermal performance of attic space through parametric study. Investigated variables are parameters which aren't measured but important for the attic performance. Based on different moisture sources, ventilated and un-ventilated attics are set in different variables. For ventilated attic (House I), attic ventilation rate and ceiling air leakage rate are selected as variables when indoor conditions are determined by on-site measured data. For un-ventilated, the fully sealed construction, ceiling air leakage rate and indoor moisture level are chosen as variables when background ventilation (un-intentional air infiltration rate) is assumed. Analysis of parametric study results of House I and House III are presented in the following sub-sections.

The purpose of parametric study is to validate WUFI Plus models through combining different scenarios of uncertainty parameters under the premise of certainty parameters. The scenario that best match the field measured data will be used in validated WUFI Plus models.

Root-mean-square deviation of atomic positions (or simply root-mean-square deviation, RMSD) is selected as calibration criteria to evaluate the accuracy of WUFI Plus models. In this thesis, RMSD is used to measure the difference between simulation results and field measurements, the calculation formula is shown in Equation 5.1 as follows:

$$RMSD = \sqrt{\frac{\sum_{t=1}^{N}(s_t - m_t)^2}{N}} \tag{5.1}$$

Where, $RMSD$ —— root-mean-square deviation of atomic positions (or simply root-mean-square deviation);

t —— time (hourly, daily or monthly);

N —— number of data points;

s_t —— simulation result at time t;

m_t —— measured data at time t.

5.3.1 House I: KMHB House with Ventilated Attic

For ventilated attic, there are two main moisture sources which are not measured by field measurements, while will affect the hygothermal performance of attic zone. One source is from outdoor through attic ventilation and the other is from indoor through air leakage across ceiling plane. Additionally, the air tightness of attic construction itself, also called as un-intentional air infiltration, will also have influence on moisture accumulation within attic space to a certain extent as well. Therefore, attic ventilation rate and ceiling air leakage rate are selected as variables to investigate their effects on hygrothermal performance in attic space. RH/T of attic air and MC/T of plywood sheathing are selected as indicators of hygrothermal performance of attic.

Based on literature review in chapter 2, selected attic ventilation rates chosen are 1 ACH, 5ACH and 10 ACH. And according to blower door test results and ASHRAE standard, three ceiling leakage rates are chosen, they are low rate —10% penetration (air leakage rate is 5.93 m^3/h), medium rate—30% penetration (air leakage rate is 17.79 m^3/h) and high rate—60% penetration (air leakage rate is 35.58 m^3/h).

For un-intentional air infiltration, it's difficult to find out a certain value unless blower door test is setup for attic space. Un-intentional air infiltration of 0.05 ACH is assumed in this model.

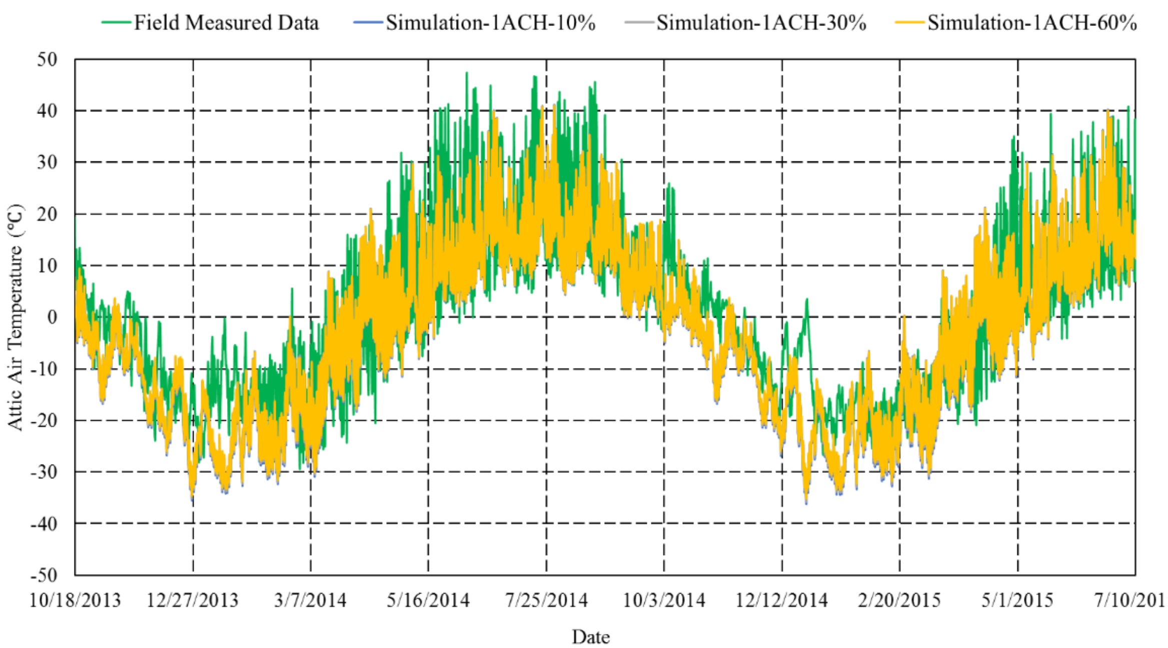
Table 5.11 summarizes variables and their values assigned in the parametric study in WUFI Plus model of House I.

Table 5.11. Parametric study setting of House I in WUFI Plus.

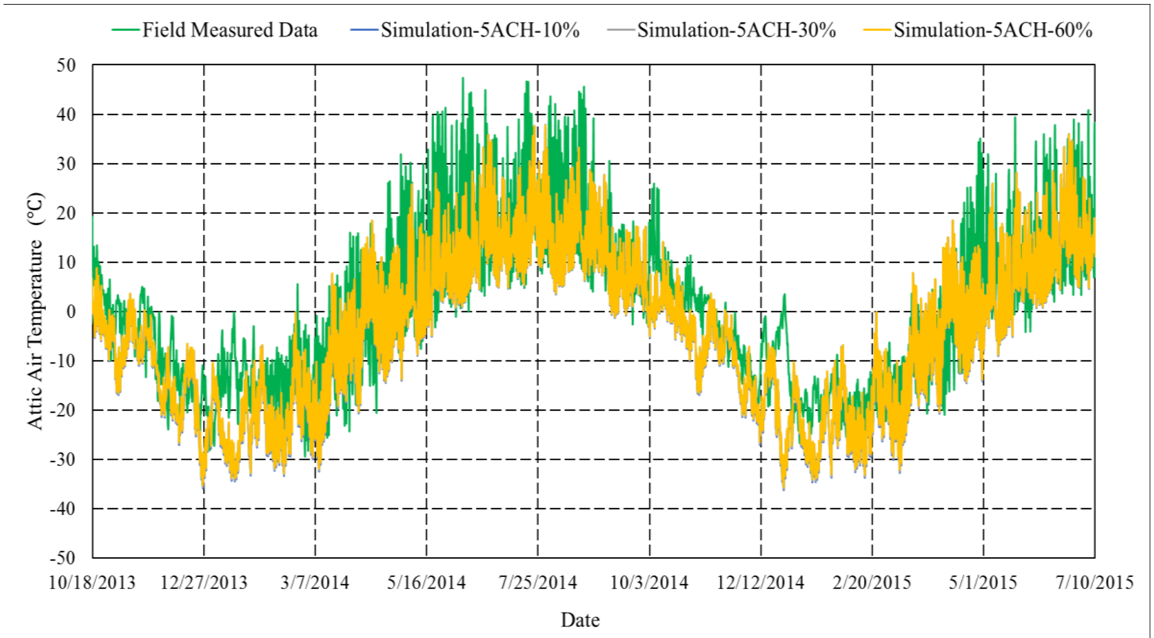
Parametric Items	**Specific Parameter**	**Detailed Setting**
Determined Parameter	Indoor Conditions	Hourly field measured data (collected by on-site sensors)
Assumed Uncertain Parameter	Un-intentional air infiltration	0.05 ACH
Variable Parameter	Ceiling Air Leakage Rate	1) Low Rate — 10% penetration
		2) Medium Rate — 30% penetration
		3) High Rate — 60% penetration
	Ventilation Rate	1 ACH; 5ACH; 10ACH

5.3.1.1 Effect of Ceiling Air Leakage Rate

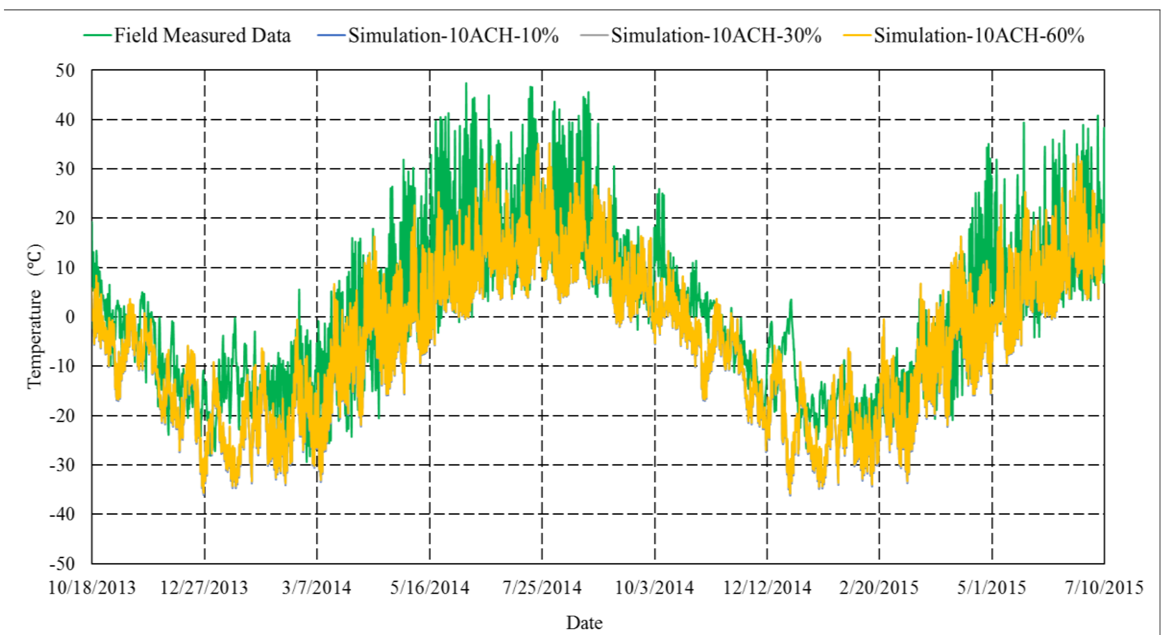
As stated at the beginning of this section, ceiling air leakage rate will affect moisture transfer from indoor space to the attic space. In this sub-section, different ceiling air leakage rates (indicated as penetration percentage) as variables under different constant attic ventilation rates are input to WUFI Plus model to investigate their effect on hygrothermal performance of attic space. Indoor RH/T conditions (field measured data) and un-intentional air infiltration rate (assumption value) are as constant input values. The comparison between simulation results and field measurements are shown in Figure 5-14 and Figure 5-15:



a) Attic air temperature (simulation results compared to field measurements) under 1 ACH attic ventilation rate.



b) Attic air temperature (simulation results compared to field measurements) under 5 ACH attic ventilation rate.



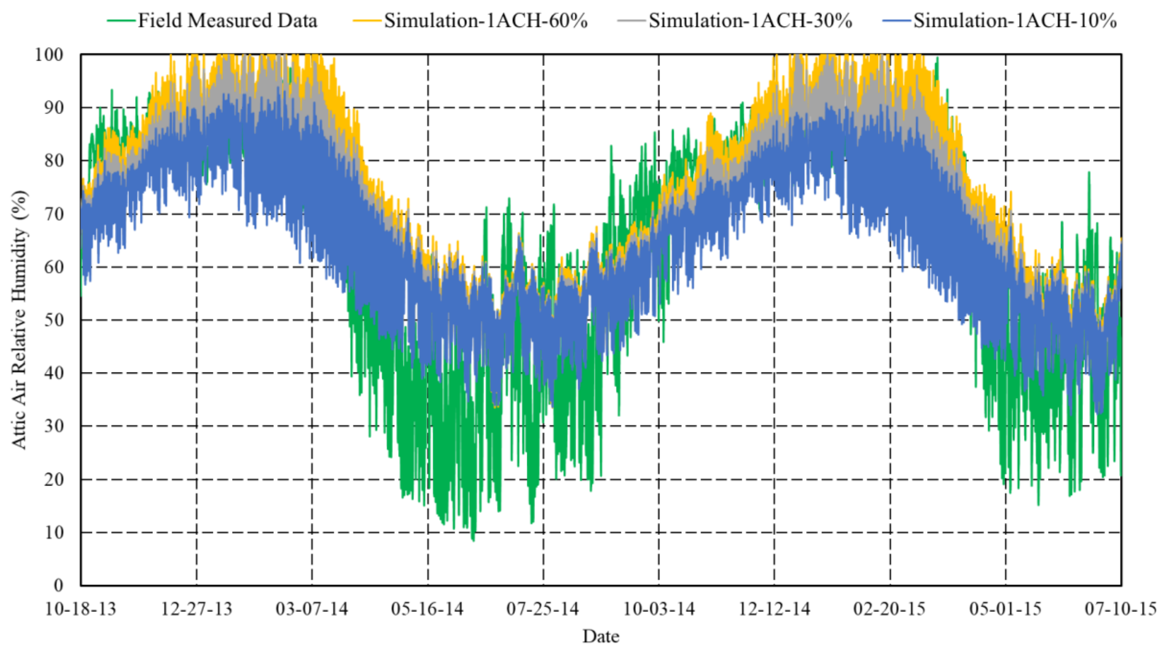
c) Attic air temperature (simulation results compared to field measurements) under 10 ACH attic ventilation rate.

Figure 5-14. The effect of ceiling air leakage rate on the attic air temperature (hourly data): comparison between simulation and field measurements under different attic ventilation rates of House I (KMHB House).

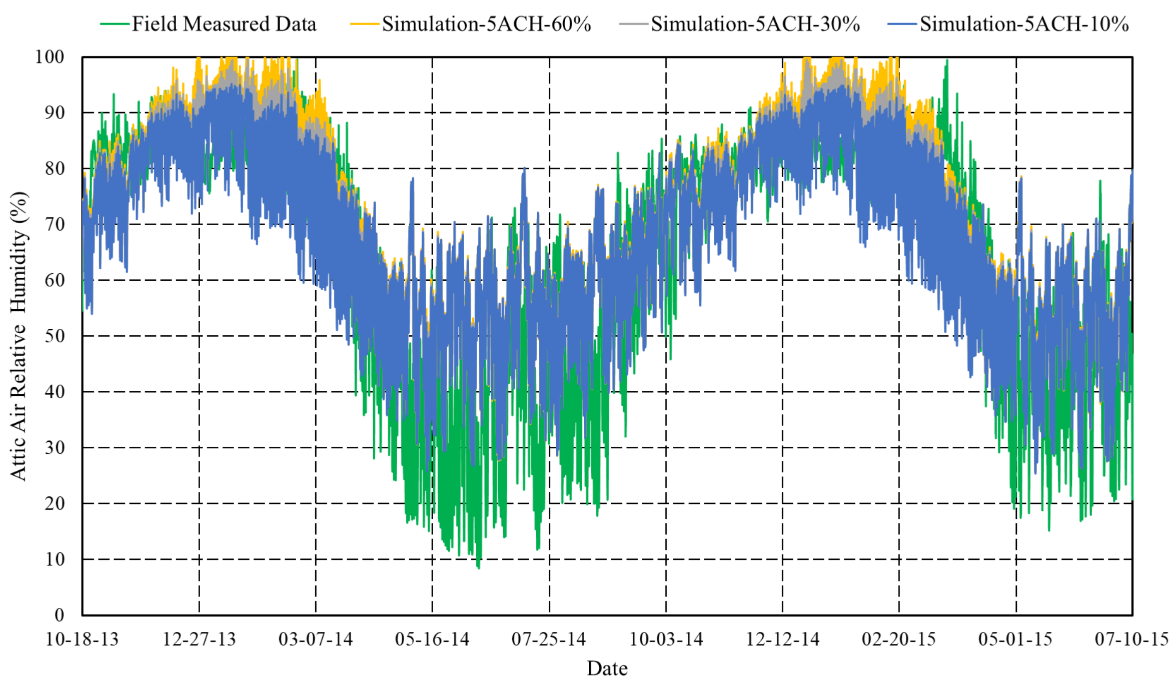
Figure 5-14 shows simulated attic temperature profiles with different ceiling leakage rates (10%, 30%, 60%) under constant attic ventilation rates (1ACH, 5ACH, 10ACH) compared with field measured data during the period from mid-Oct. 2013 to July 2015, respectively. Average temperature differences (also called as ADT) and RMSD values between simulation and field measured results are listed in Table 5.12 to indicate parametric study results and models' accuracy. RMSD and ADT values are main indicators to show the accuracy of simulation results compared to field measured data. As shown in Figure 5-14, all simulation curves follow the same trends with field measured data under all scenarios. Among three ceiling leakage rates under constant attic ventilation rate, there are only slight difference of RMSD and ADT values, both of them are around 0.07, and simulated temperature profiles almost the same. When attic ventilation rate is constant, RMSD and ADT values decrease with ceiling leakage rates increasing (from 10% to 60%), which means ceiling leakage rate at 60% is the best result matching the field measured data. Overall, RMSD and ADT values increase with the increase of attic ventilation rates (from 1ACH to 10ACH), which means simulation results under 1ACH that best matches the field measured data. As listed in the table below, average temperature RMSD under 1ACH, 5ACH and 10ACH are 10.15℃, 10.31℃ and 10.53℃, respectively. ADT values show there are around 36%, 32% and 29% simulation data higher than field measured data under 1ACH, 5ACH and 10ACH, respectively.

Table 5.12. Average Temperature Difference (ADT) and RMSD values between simulation and field measurements under different ceiling leakage rates and attic ventilation rates.

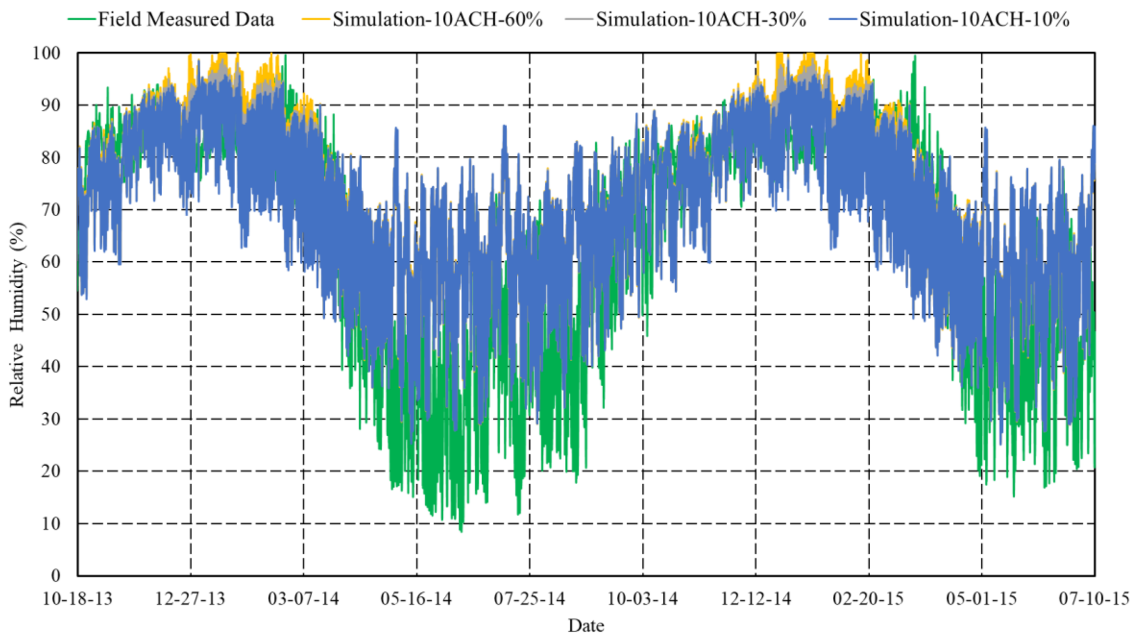
	Temperature RMSD (Simulation Result-Field Data)	**Average Temperature RMSD under constant ventilation rate**	**ADT (℃) (Simulation Result-Field Data)**	
1 ACH-10%	10.27	10.15	(+,35%) 6.88	(-,65%) -8.81
1 ACH-30%	10.17		(+,36%) 7.20	(-,64%) -8.67
1 ACH-60%	10.02		(+,36%) 6.83	(-,64%) -8.50
5 ACH-10%	10.39	10.31	(+,32%) 6.19	(-,68%) -9.14
5 ACH-30%	10.32		(+,32%) 6.20	(-,68%) -9.05
5 ACH-60%	10.21		(+,33%) 6.20	(-,67%) -8.93
10 ACH-10%	10.60	10.53	(+,29%) 5.76	(-,71%) -9.40
10 ACH-30%	10.54		(+,29%) 5.77	(-,71%) -9.33
10 ACH-60%	10.46		(+,30%) 5.79	(-,70%) -9.24



a) Attic air RH (simulation results compared to field measurements) under 1 ACH attic ventilation rate.



b) Attic air RH (simulation results compared to field measurements) under 5 ACH attic ventilation rate.



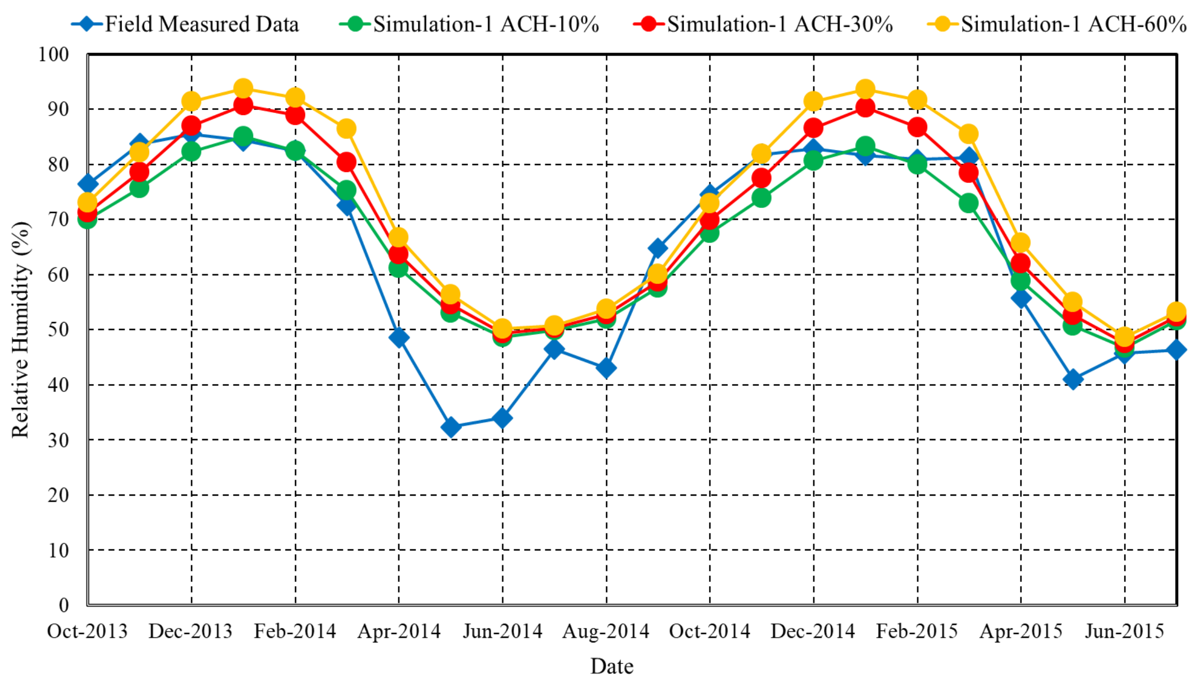
c) Attic air RH (simulation results compared to field measurements) under 10 ACH attic ventilation rate.

Figure 5-15. The effect of ceiling air leakage rate on the attic air RH (hourly data): comparison between simulation and field measurements under different attic ventilation rates of House I (KMHB House).

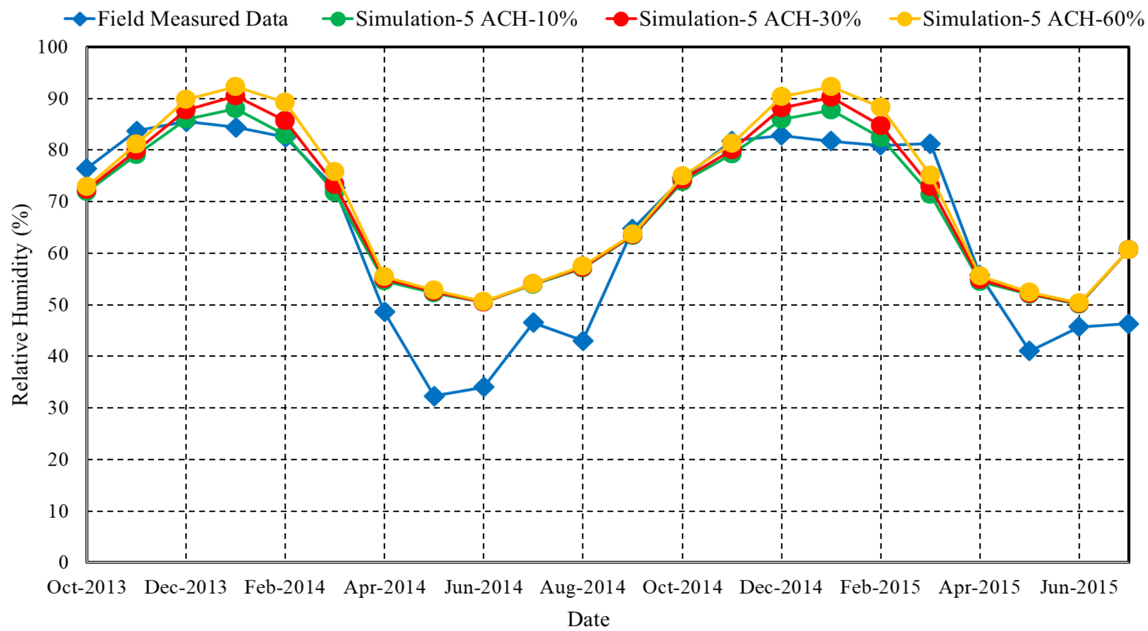
Figure 5-15 shows simulated attic relative humidity (RH) profiles with different ceiling leakage rates (10%, 30%, 60%) under constant attic ventilation rates (1ACH, 5ACH, 10ACH) compared with field measured data from mid-Oct. 2013 to July 2015, respectively. Similar to temperature profiles shown in Figure 5-14, simulation results of RH profiles follow the same trends of field measurements for all parametric situations. However, simulation curves under different ceiling leakage rates have different degrees of fluctuations. As shown in Figure 5-14-a), simulation curves are smooth without strong daily variation when attic ventilation rate is 1ACH. While the difference among RH profiles are obvious in the rest of the year, RH values increase with the increase of ceiling leakage rate. Compared to simulation result under 1ACH, simulation profiles under 5ACH and 10ACH have stronger fluctuations indicated in Figure 5-14-b) and Figure 5-14-c). Table 5-13 lists average relative humidity differences (also called as ADRH) and RMSD values between simulation and field measured results. Consistent with temperature data, RMSD of RH values have the same tendency, i.e. the difference increases with the increase of attic ventilation rate. ADRH values show there are around 60%, 64% and 66% simulation data higher than field measured data under 1ACH, 5ACH and 10ACH, respectively.

Table 5.13. Average Relative Humidity Difference (ADRH) and RMSD values between simulation and field measurements with different ceiling leakage rates under different constant attic ventilation rates.

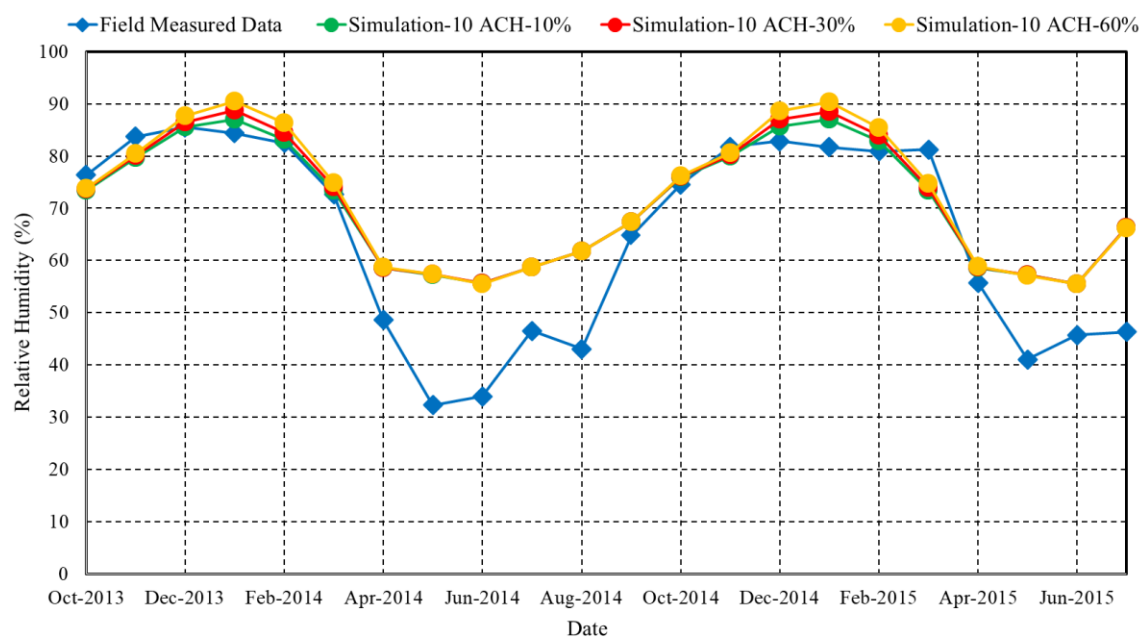
	RH RMSD (Simulation Result-Field Data)	Average RH RMSD under constant ventilation rate	ADRH (%) (Simulation Result-Field Data)	
1 ACH-10%	13.77	14.69	(+,50%) 12.20	(-,50%) -8.50
1 ACH-30%	14.49		(+,61%) 13.18	(-,39%) -8.07
1 ACH-60%	15.80		(+,71%) 9.91	(-,29%) -7.65
5 ACH-10%	14.64	14.90	(+,60%) 12.19	(-,40%) -9.02
5 ACH-30%	14.85		(+,64%) 12.53	(-,36%) -9.08
5 ACH-60%	15.22		(+,67%) 13.16	(-,33%) -8.96
10 ACH-10%	16.93	17.4	(+,65%) 14.40	(-,35%) -9.06
10 ACH-30%	17.02		(+,66%) 14.55	(-,34%) -9.09
10 ACH-60%	17.17		(+,68%) 14.82	(-,58%) -9.07



a) Attic air RH (simulation results compared to field measurements) under 1 ACH attic ventilation rate.



b) Attic air RH (simulation results compared to field measurements) under 5 ACH attic ventilation rate.



c) Attic air RH (simulation results compared to field measurements) under 10 ACH attic ventilation rate.

Figure 5-16. The effect of ceiling air leakage rate on the attic air RH (monthly average): comparison between simulation and field measurements under different attic ventilation rates of House I (KMHB House).

Figure 5-15 indicates ceiling air leakage rates have no significant effect on attic air temperature, but have significant impact on relative humidity levels of attic air. To present RH difference more clearly, Figure 5-16 shows monthly average results among simulated attic relative humidity (RH) profiles with different ceiling leakage rates (10%, 30%, 60%) under constant attic ventilation rates (1ACH, 5ACH, 10ACH) compared with field measured data during the period from mid-Oct. 2013 to July 2015, respectively. It's obvious that all simulation results follow the trends of field measured data and generally higher than field measurements during the whole monitoring period. Simulation results show attic RH levels will increase with the increase of ceiling air leakage rates under constant attic ventilation rate. And this phenomenon is more obvious when attic ventilation rate is at low value. Table 5.14 lists the RH difference simulated (monthly average) among different ceiling air leakage rates under different constant attic ventilation rates. The average RH difference among 10%, 30% and 60% ceiling air leakage rates under constant attic ventilation rates (1ACH, 5ACH, 10ACH) range from 0.45% to 3.23%. The maximum RH difference normally can be found in Jan. and March 2015, RH difference values are around 7%, 3% and 1.7% under 1ACH, 5ACH and 10ACH, respectively. And the minimum RH difference normally can be found in July 2014, RH difference values are about 0.35%, 0.03% and -0.05% under 1ACH, 5ACH and 10ACH, respectively.

Table 5.14. Simulation RH difference (monthly average) among different ceiling air leakage rates under different constant attic ventilation rates.

	Maximum RH Difference (Monthly Average)	**Minimum RH Difference (Monthly Average)**	**Average RH Difference (Monthly Average)**
1 ACH (Simulation 30%-10%)	7.00%	0.35%	3.23%
1 ACH (Simulation 60%-30%)	6.98%	0.39%	2.98%
5 ACH (Simulation 30%-10%)	2.73%	0.03%	0.97%
5 ACH (Simulation 60%-30%)	3.57%	0.04%	1.17%
10 ACH (Simulation 30%-10%)	1.64%	-0.04%	0.45%
10 ACH (Simulation 60%-30%)	1.83%	-0.07%	0.57%

Table 5.15 summarizes monthly average ADRH and RMSD values between simulation and field measurements with different ceiling leakage rates under constant attic ventilation rates during the period from mid-Oct. 2013 to July 2015. Compared to hourly data listed in Table 5.13, monthly average data is easier to show the difference between field measurements and simulation results. RMSD values between simulation results and field measurements increase with the increase of ceiling leakage rates under constant attic ventilation rate. The maximum RMSD values can be found when ceiling air leakage rate is 60% which are 10.55%, 9.00% and 11.09% under 1ACH, 5ACH and 10ACH, respectively. Average RMSD values are 9.09%, 8.61% and 10.97% under 1ACH, 5ACH and 10ACH, respectively. And ADRH values show more than 50% of field measured data is larger than simulation results.

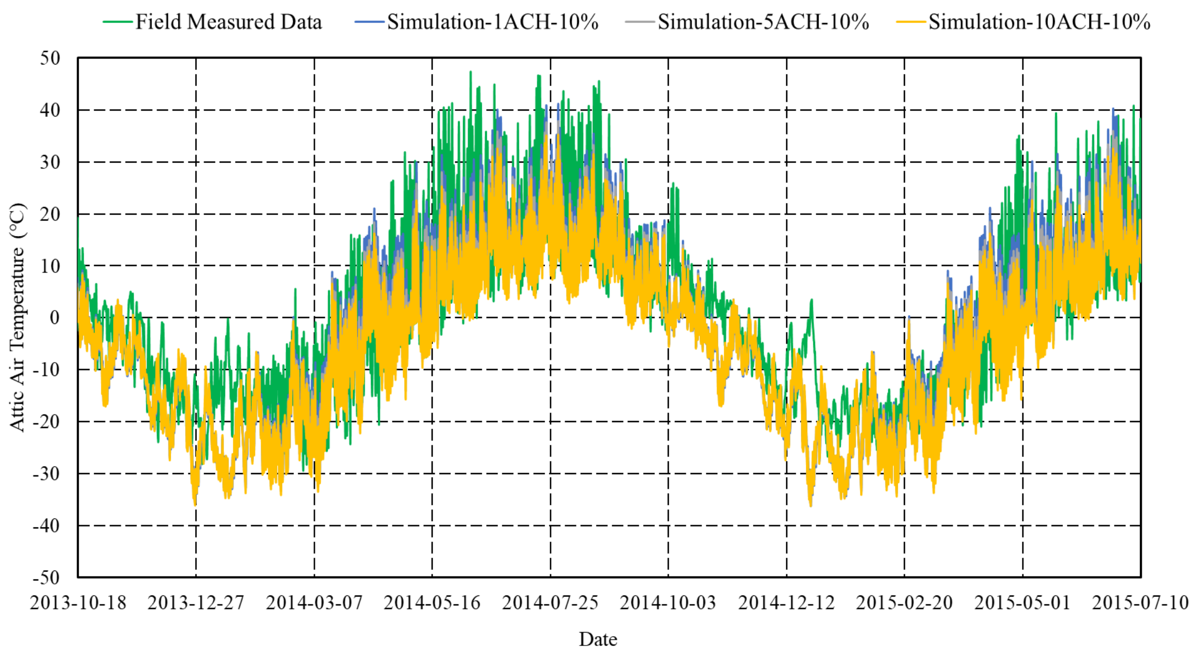
Table 5.15. Average Relative Humidity Difference (ADRH) and RMSD values (monthly average) between simulation and field measured results with different ceiling leakage rates under constant attic ventilation rates.

	RH RMSD (Simulation Result-Field Data)	Average RH RMSD under constant attic ventilation rate	ADRH (%) (Simulation Result-Field Data)	
1 ACH-10%	7.96	9.09	(+,55%) 7.04	(-,45%) -5.09
1 ACH-30%	8.76		(+,73%) 8.28	(-,27%) -4.64
1 ACH-60%	10.55		(+,82%) 10.08	(-,18%) -2.81
5 ACH-10%	8.29	8.61	(+,64%) 7.77	(-,40%) -3.22
5 ACH-30%	8.53		(+,68%) 8.31	(-,32%) -2.89
5 ACH-60%	9.00		(+,73%) 9.01	(-,27%) -2.34
10 ACH-10%	10.87	10.97	(+,77%) 9.65	(-,23%) -3.38
10 ACH-30%	10.95		(+,77%) 9.06	(-,23%) -3.85
10 ACH-60%	11.09		(+,77%) 8.59	(-,23%) -4.19

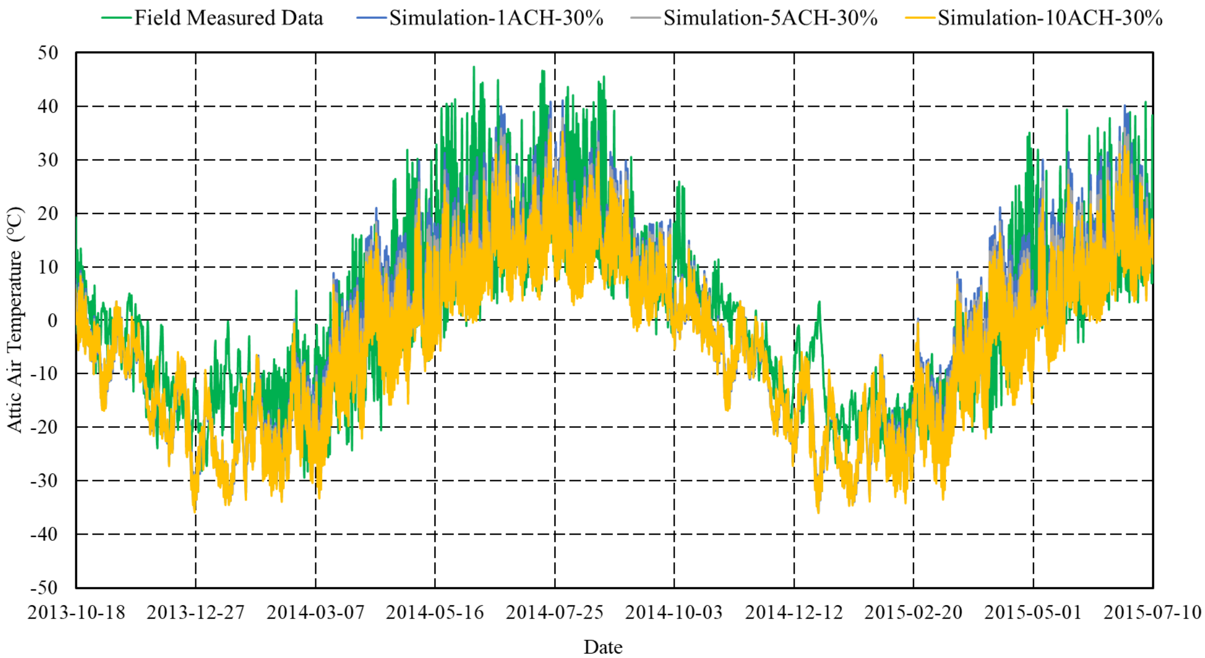
In summary, the ceiling air leakage rate has negligible influence on the RMSD values of attic air temperature but considerable influence on the RMSD value of attic air RH under constant ventilation rate assumed (1ACH, 5ACH or 10ACH). The difference in RH difference in RH between simulation and field measurement increases with the increase of ventilation rate and increase of ceiling air leakage rate. Therefore, the best case is ceiling air leakage rate at 10% with attic ventilation rate at 1ACH.

5.3.1.2 Effect of Attic Ventilation Rate

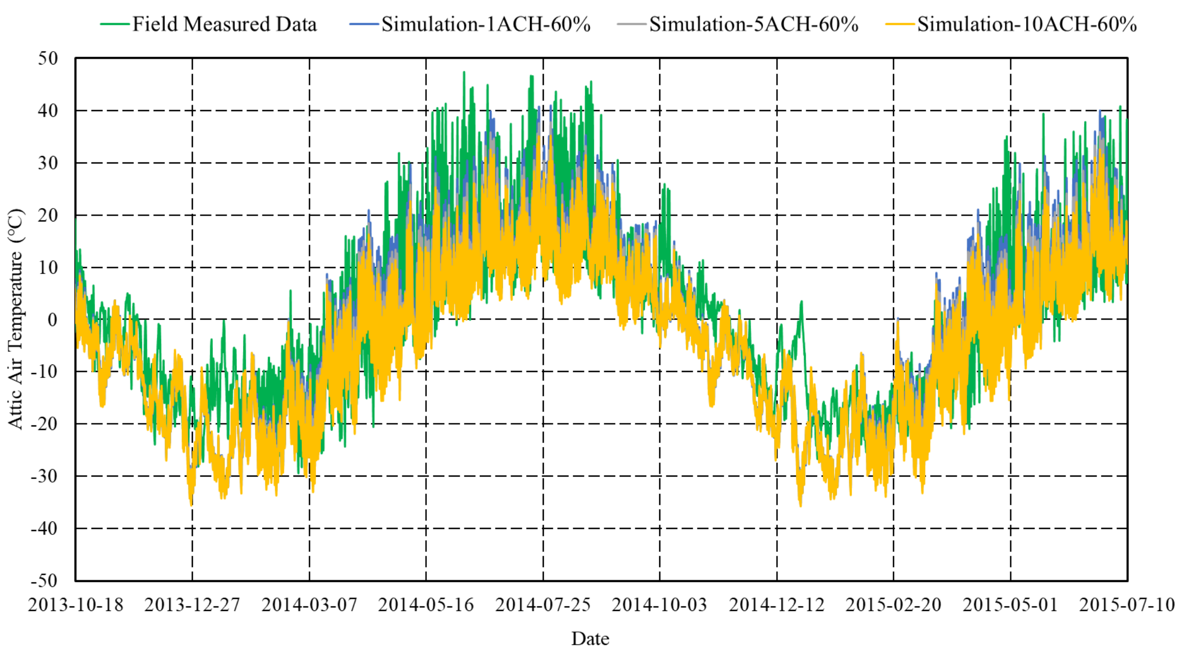
As stated at the beginning of this section, attic ventilation rates have influence on moisture induced through outdoor air. In this sub-section, different attic ventilation rates as a variable under different ceiling air leakage rates (indicated as penetration percentage) are input to WUFI Plus model to investigate its effect on hygrothermal performance of attic space. Indoor RH/T conditions (field measured data) and un-intentional air infiltration (assumption value) are as constant input values. The comparison results between simulation result and field measurements under the setting above are shown in the following figures.



a) Attic air temperature (simulated results compares to field measured data) under 10% ceiling air leakage rate.



b) Attic air temperature (simulated results compares to field measured data) under 30% ceiling air leakage rate.



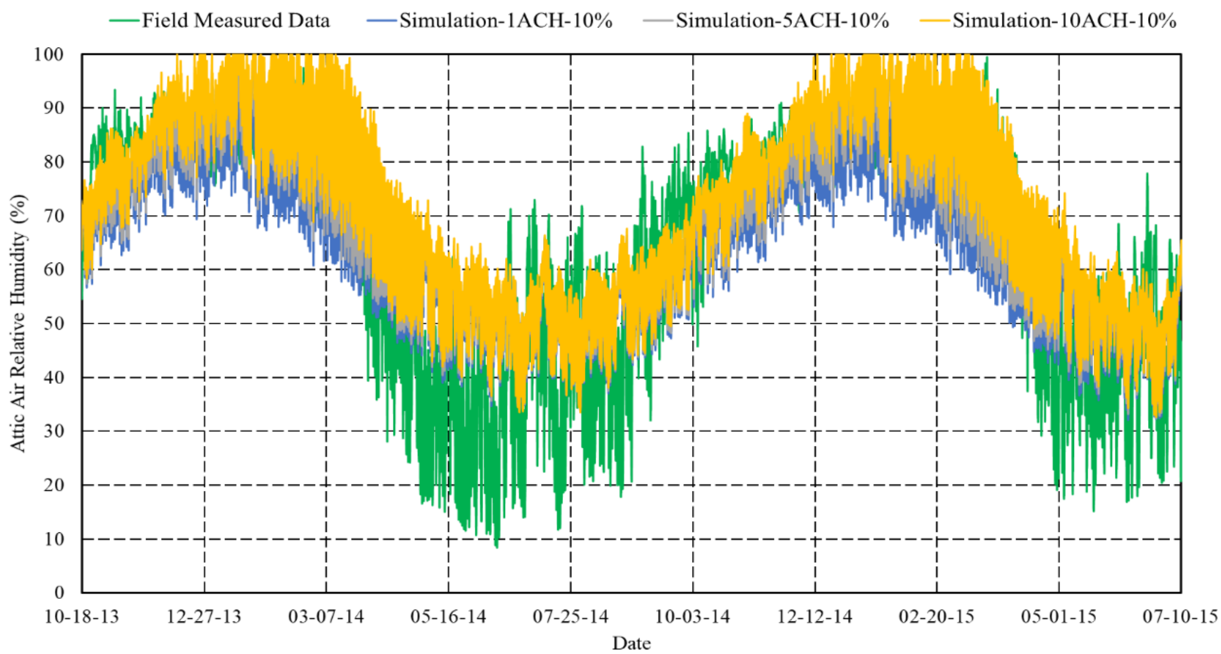
c) Attic air temperature (simulated results compares to field measured data) under 60% ceiling air leakage rate.

Figure 5-17. The effect of attic ventilation rate on the attic air temperature (hourly data): comparison between simulation and field measurements under different ceiling air leakage rates of House I (KMHB House).

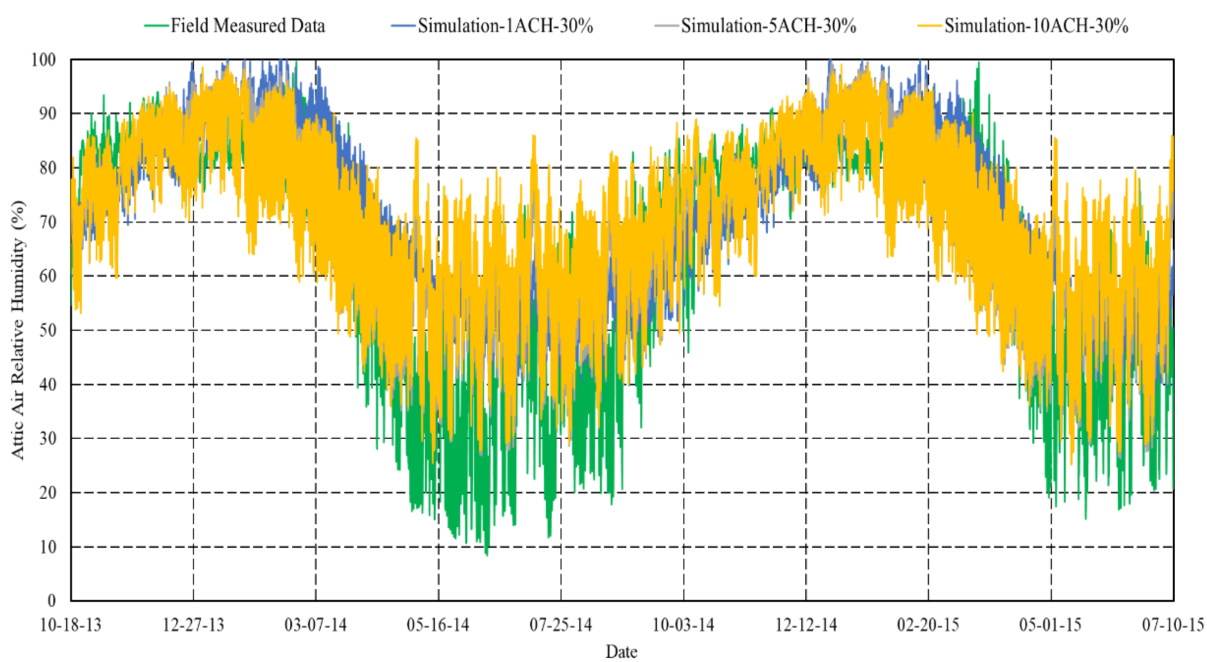
Figure 5-17 shows simulated attic air temperature profiles with different attic ventilation rates (1ACH, 5ACH, 10ACH) under constant ceiling air leakage rates (10%, 30%, 60%) compared with field measured data during the period from mid-Oct. 2013 to July 2015, respectively. Average temperature differences (also called as ADT) and RMSD values between simulation and field measured results are listed in Table 5.16 to indicate parametric study result and models' accuracy. RMSD and ADT values are the main indicators to show the accuracy of comparison result. It's obvious that all simulation curves follow the same trends with field measured data under all scenarios. When ceiling air leakage rates are under constant values, whether it's 10%, 30% or 60%, simulation profiles almost overlap which have no significant difference among three attic ventilation rates (1ACH, 5ACH, 10ACH). Average RMSD temperatures are 10.42 ℃, 10.34℃ and 10.23℃ when ceiling air leakage rates are 10%, 30% and 60%, respectively. RMSD temperature values have little changes with the increase of attic ventilation rates from 1ACH to 10ACH under ceiling air leakage rates are 10%, 30% or 60%.

Table 5.16. Difference among simulated temperature RMSD values with different attic ventilation rates under different ceiling air leakage rates.

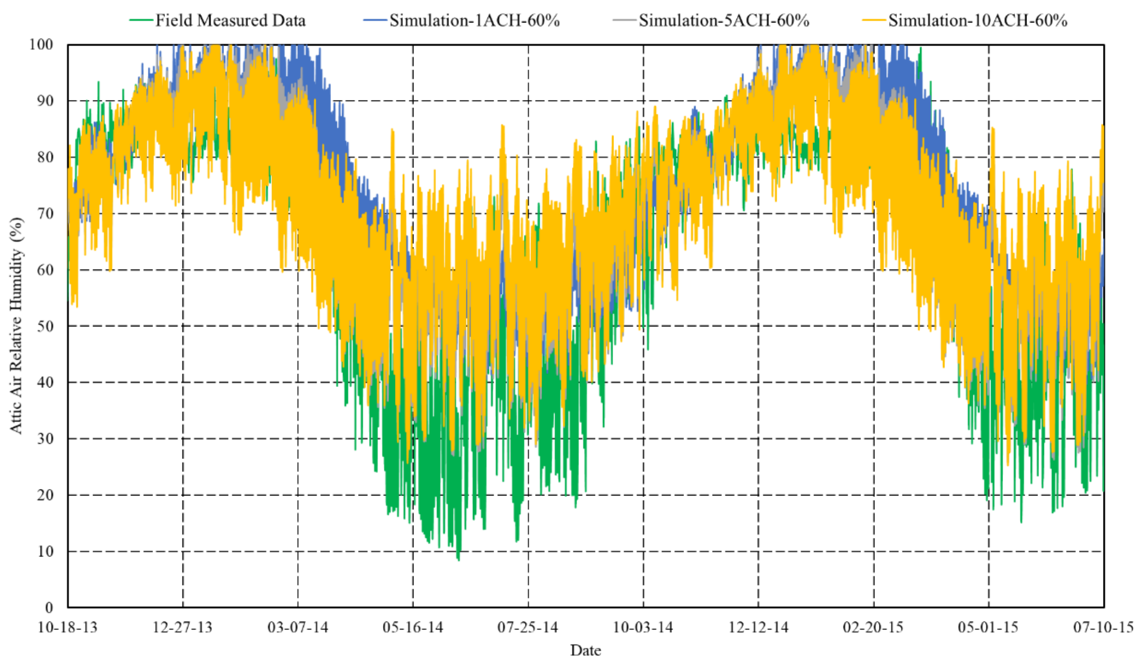
	RMSD Temperature Difference
10% (5 ACH – 1ACH)	0.08℃
10% (10 ACH – 1ACH)	0.33℃
30% (5 ACH – 1ACH)	-0.37℃
30% (10 ACH – 1ACH)	-0.22℃
60% (5 ACH – 1ACH)	-0.06℃
60% (10 ACH – 1ACH)	-0.14℃



a) Attic air RH (simulated results compares to field measured data) under 10% ceiling air leakage rate.



b) Attic air RH (simulated results compares to field measured data) under 30% ceiling air leakage rate.



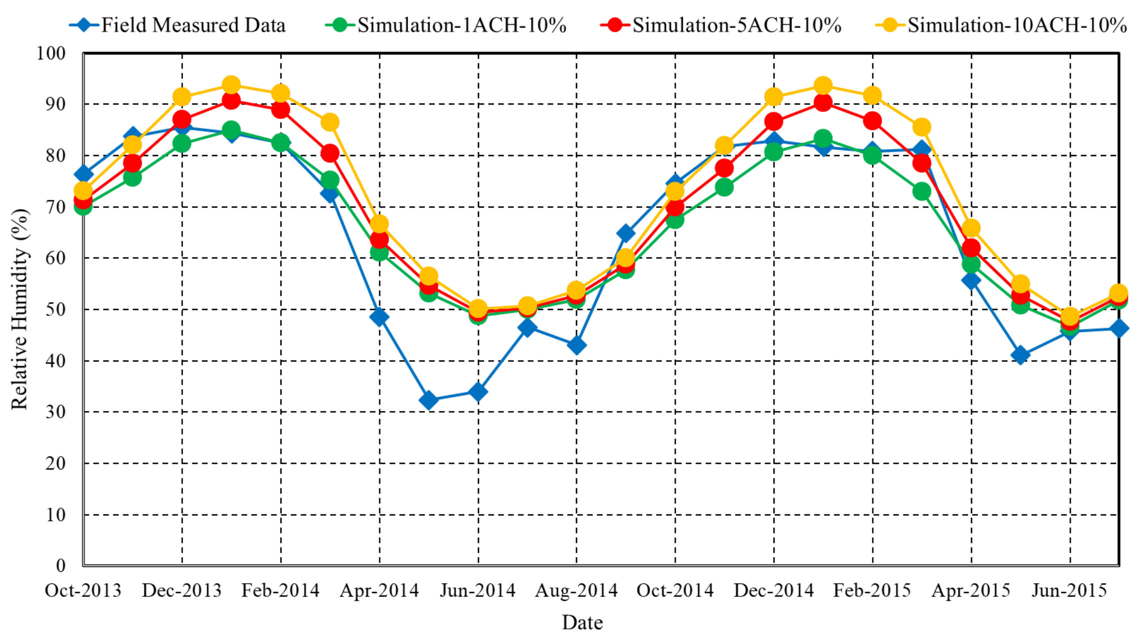
c) Attic air RH (simulated results compares to field measured data) under 60% ceiling air leakage rate.

Figure 5-18. The effect of attic ventilation rate on the attic air RH (hourly data): comparison between simulation and field measurements under different ceiling air leakage rates of House I (KMHB House).

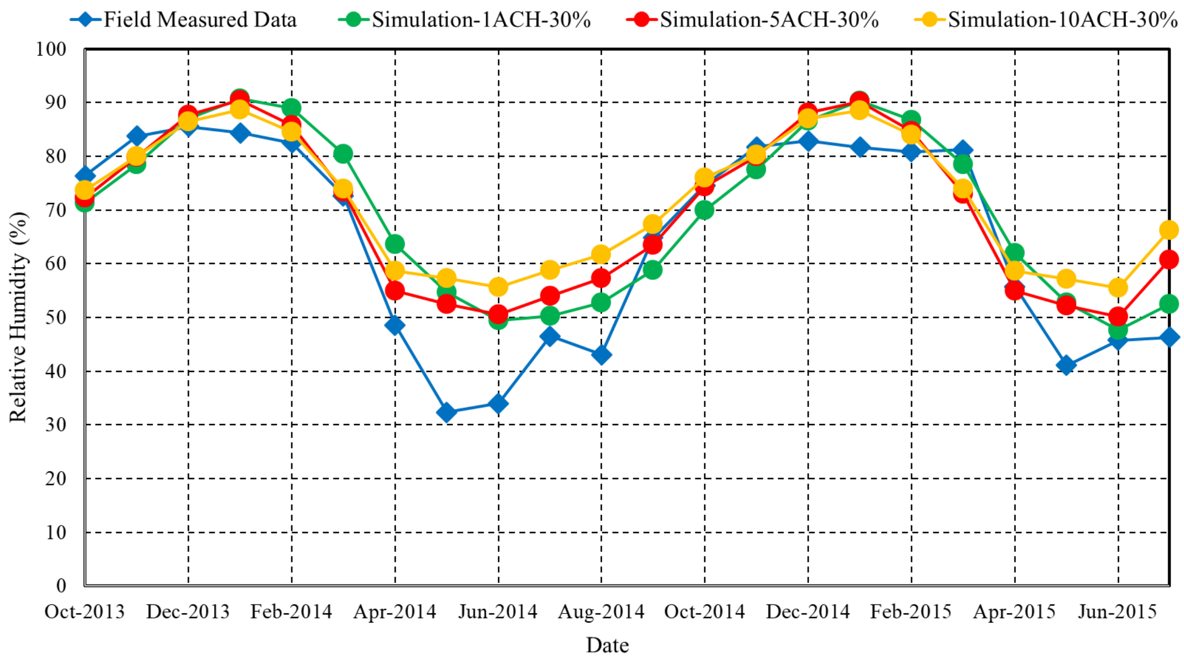
Figure 5-18 shows simulated attic RH profiles with different attic ventilation rates (1ACH, 5ACH, 10ACH) under constant ceiling air leakage rates (10%, 30%, 60%) compared with field measured data from mid-Oct. 2013 to July 2015, respectively. Average RH differences (also called as ADRH) and RMSD values between simulation and field measured results are listed in Table 5.13 to indicate parametric study result and models' accuracy. It's obvious that all simulation curves follow the same trends with field measured data under all scenarios. When ceiling air leakage rates are under constant values, whether it's 10%, 30% or 60%, simulation profiles follow the same trends as field measured data. However, RH profiles have some slight differences among different attic ventilation rates when ceiling air leakage rates maintain constant. For example, when ceiling air leakage rate is 10%, simulation curve of 10ACH is higher than that of 5ACH and 1ACH, and simulation curve of 1 ACH is in the lowest place, while fluctuations of these three curves are nearly the same. Average RH RMSD are 14.69%, 15.45% and 16.06% when ceiling air leakage rates are 10%, 30% and 60%, respectively. The difference in RH between simulation and field measurements increases with the increase of ceiling air leakage rate and the increase of attic ventilation rate. As shown in Table 5.17, difference among RH RMSD values under 10%, 30% and 60% ceiling air leakage rate range from -0.58% to 2.58%.

Table 5.17. Difference among simulated RH RMSD values with different attic ventilation rates under different ceiling air leakage rates.

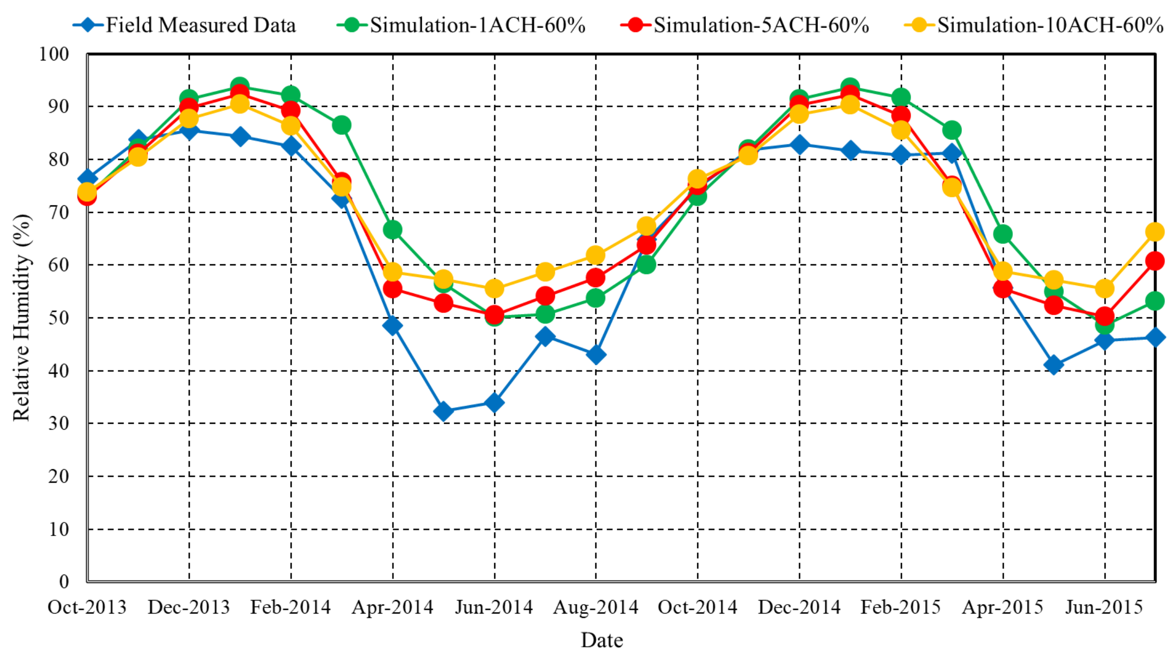
	RMSD RH Difference
10% (5 ACH – 1ACH)	0.72%
10% (10 ACH – 1ACH)	2.03%
30% (5 ACH – 1ACH)	0.36%
30% (10 ACH – 1ACH)	2.58%
60% (5 ACH – 1ACH)	-0.58%
60% (10 ACH – 1ACH)	1.37%



a) Attic air RH (simulation results compared to field measurements) under 10% ceiling air leakage rate.



b) Attic air RH (simulation results compared to field measurements) under 30% ceiling air leakage rate.



c) Attic air RH (simulation results compared to field measurements) under 60% ceiling air leakage rate.

Figure 5-19. The effect of attic ventilation rate on the attic air temperature (monthly average): comparison between simulation and field measurements under different ceiling air leakage rates of House I (KMHB House).

Figure 5-17 shows attic ventilation rates have no significant effect on attic air temperature, but have considerable impact on relative humidity levels of attic air. To present RH difference more clearly, Figure 5-19 shows monthly average results among simulated attic relative humidity (RH) profiles with different attic ventilation rates (1ACH, 5ACH, 10ACH) under constant ceiling air leakage rates (10%, 30%, 60%) compared with field measured data from mid-Oct. 2013 to July 2015, respectively. When ceiling air leakage rate is 10%, simulation RH results increase with the decrease of attic ventilation rate. Simulation RH profiles almost overlap when ceiling air leakage rates are 30% and 60%. Table 5.19 lists simulation RH difference (monthly average) among different attic ventilation rates under different constant ceiling air leakage rates. Average simulation RH difference among 1ACH, 5ACH and 10ACH attic ventilation rates under constant ceiling air leakage rates (10%, 30%, 60%) are 3.23% & 2.98%, -0.01% & 1.97% and -1.83% & 1.37%.

Table 5.18. RH difference simulated (monthly average) among different attic ventilation rates under constant ceiling air leakage rates.

	Maximum RH Difference (Monthly Average)	**Minimum RH Difference (Monthly Average)**	**Average RH Difference (Monthly Average)**
10% (Simulation 5ACH-1ACH)	7.00%	0.35%	3.23%
10% (Simulation 10ACH-5ACH)	6.98%	0.39%	2.98%
30% (Simulation 5ACH-1ACH)	8.25%	-8.68%	-0.01%
30% (Simulation 10ACH-5ACH)	5.60%	-1.70%	1.97%
60% (Simulation 5ACH-1ACH)	7.49%	-11.24%	-1.83%
60% (Simulation 10ACH-5ACH)	5.48%	-2.97%	1.37%

Table 5.18 summarizes monthly average ADRH and RMSD values between simulation results and field measurements with different attic ventilation rates under ceiling air leakage rates during the period from mid-Oct. 2013 to July 2015. RMSD values between simulation results and field measurements increase with the increase of ceiling leakage rates under constant attic ventilation rate. The maximum RMSD values can be found when attic ventilation rate is 10ACH which are 10.55%, 10.94% and 11.09% under 10%, 30% and 60% ceiling air leakage rates, respectively.

Average RMSD values are 9.09%, 8.61% and 10.97% under 10%, 30% and 60%, respectively. And ADRH values show more than 50% of field measured data is larger than simulation results. As shown in Table 5.19, difference among RH RMSD values under 10%, 30% and 60% ceiling air leakage rates range from -0.23% to 2.59%.

Table 5.19. Difference among simulated RH RMSD (monthly average) values with different attic ventilation rates under different ceiling air leakage rates.

	RMSD RH Difference
10% (5 ACH – 1ACH)	0.8%
10% (10 ACH – 1ACH)	2.59%
30% (5 ACH – 1ACH)	-0.23%
30% (10 ACH – 1ACH)	2.18%
60% (5 ACH – 1ACH)	-1.55%
60% (10 ACH – 1ACH)	0.54%

The difference in RH between simulation and field measurements increases with the increase of ventilation rate and increase of ceiling air leakage rate. Therefore, the best case is 10% ceiling air leakage rate with 1ACH attic ventilation.

5.3.2 House III: SIP House with Un-Ventilated Attic

For un-ventilated attic, two parameters, ceiling leakage rate and un-intentional background infiltration are chosen as variables. Based on ASHRAE Fundamental 2013, three ceiling leakage rates are selected, they are low rate —10% penetration (air leakage rate of upstairs attic is 5.22 m^3/h and which of downstairs attic is 3.65 m^3/h), medium rate—30% penetration (air leakage rate of upstairs attic is 15.66 m^3/h and which of downstairs attic is 10.94 m^3/h) and high rate—60% penetration (air leakage rate of upstairs attic is 31.32 m^3/h and which of downstairs attic is 21.88 m^3/h).

Based on blower door test and passive house standard, there are three un-intentional air infiltration values are assigned in WUFI Plus model to run parametric study which are low infiltration—0.05 ACH; medium infiltration—0.09 ACH; high infiltration—0.18 ACH.

For indoor condition, there is no field measured data available, therefore, Standard EN 15026 (normal moisture load) is assigned in WUFI Plus model to run simulation.

Table 5.20 summarizes the variables and their values assigned in the parametric study in WUFI Plus model of House III.

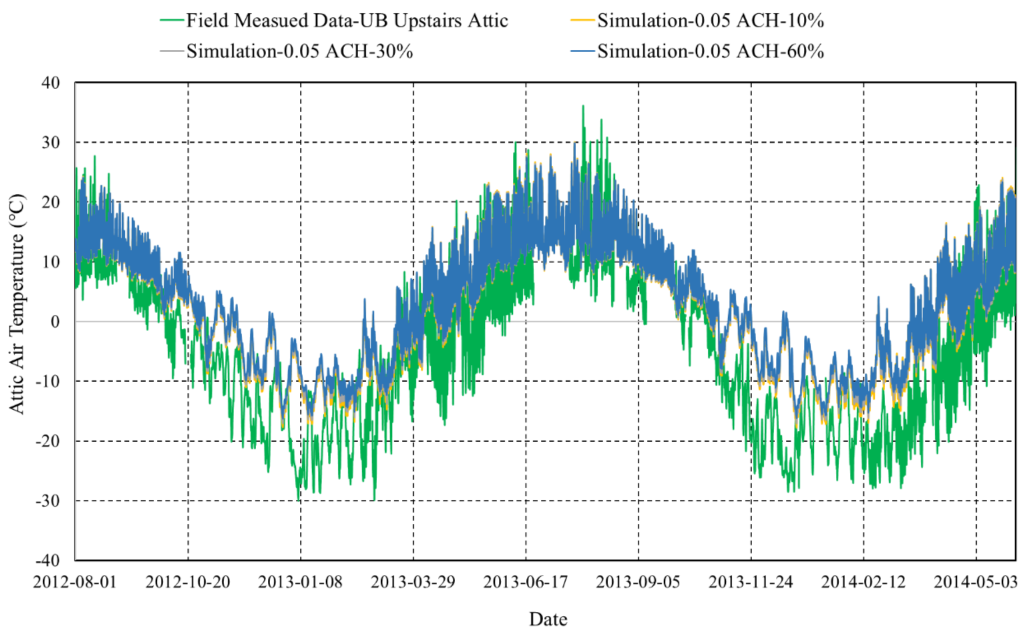
Table 5.20. Parametric study setting of House III (SIP House) in WUFI Plus.

Parametric Items	**Specific Parameter**	**Detail Setting**
Determined Parameter	Indoor Conditions	Standard EN 15026 (normal moisture load)
Variable Parameter	Ceiling Air Leakage Rate	1) Low Rate — 10% penetration (Upstairs—5.22 m^3/h; Downstairs—3.65 m^3/h)
		2) Medium Rate — 30% penetration (Upstairs—15.66 m^3/h; Downstairs—10.94 m^3/h)
		3) High Rate — 60% penetration (Upstairs—31.32 m^3/h; Upstairs—21.88 m^3/h)
	Un-Intentional Air Infiltration	1) 0.05 ACH
		2) 0.09 ACH
		3) 0.18 ACH

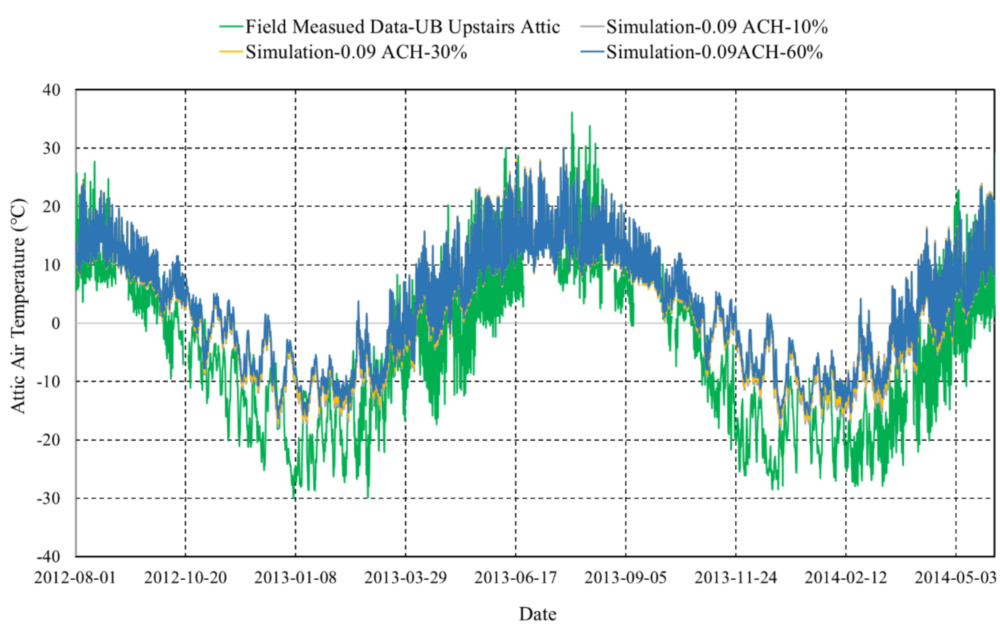
As described in sub-Section 5.2.2.1, un-ventilated attic of House III is set as one assembly without separating units. Therefore, parametric results of attic temperature and relative humidity present simulation result of the whole attic. Because there is no significant difference of field measured hygrothermal performance (attic air temperature and RH) among Unit A Upstairs (UA-US), Unit A Downstairs (UA-DS), Unit B Upstairs (UB-US) and Unit B Downstairs (UB-DS), field measured hygrothermal performance of UB-US is used for the comparison with simulation results.

5.3.2.1 Effect of Ceiling Air Leakage Rate

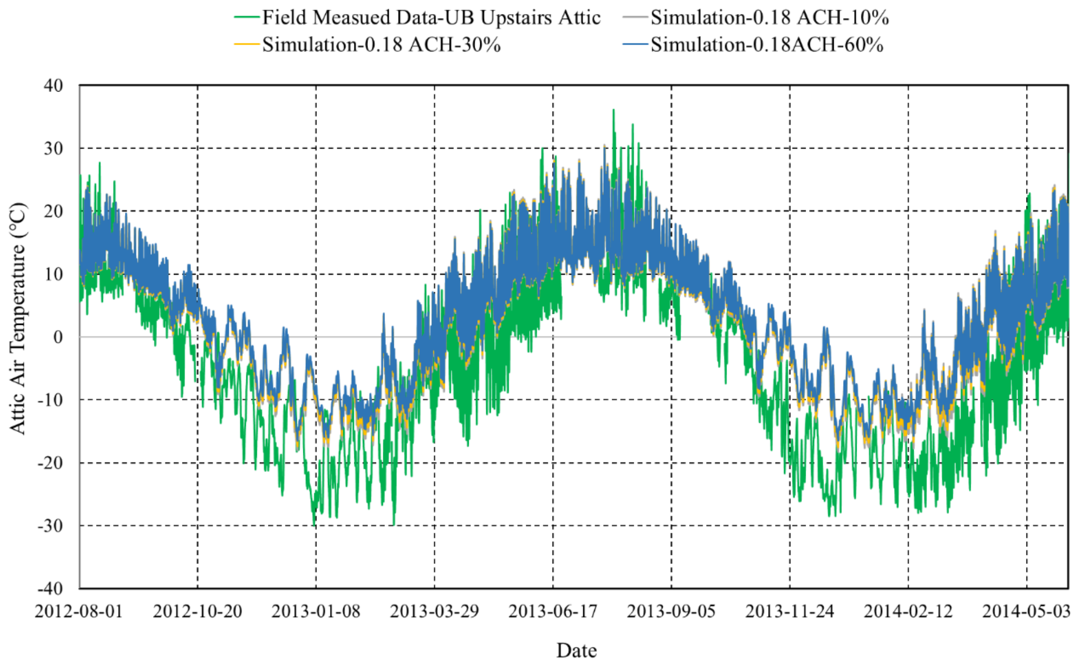
In this section, different ceiling air leakage rates (indicated as penetration percentage) as variables under different constant attic ventilation rates are input to WUFI Plus model to investigate their effect on hygrothermal performance of attic space. Indoor RH/T conditions (Standard EN15026, normal moisture load) from WUFI Plus weather database are assigned to run simulation model. The comparison between simulation results (Upstairs Attic Zone) and field measurements (UB-US) are shown in Figure 5-20 and Figure 5-21.



a) Attic air temperature (simulation results compared to field measurements) under 0.05 ACH unintentional air infiltration.



b) Attic air temperature (simulation results compared to field measurements) under 0.09 ACH unintentional air infiltration.



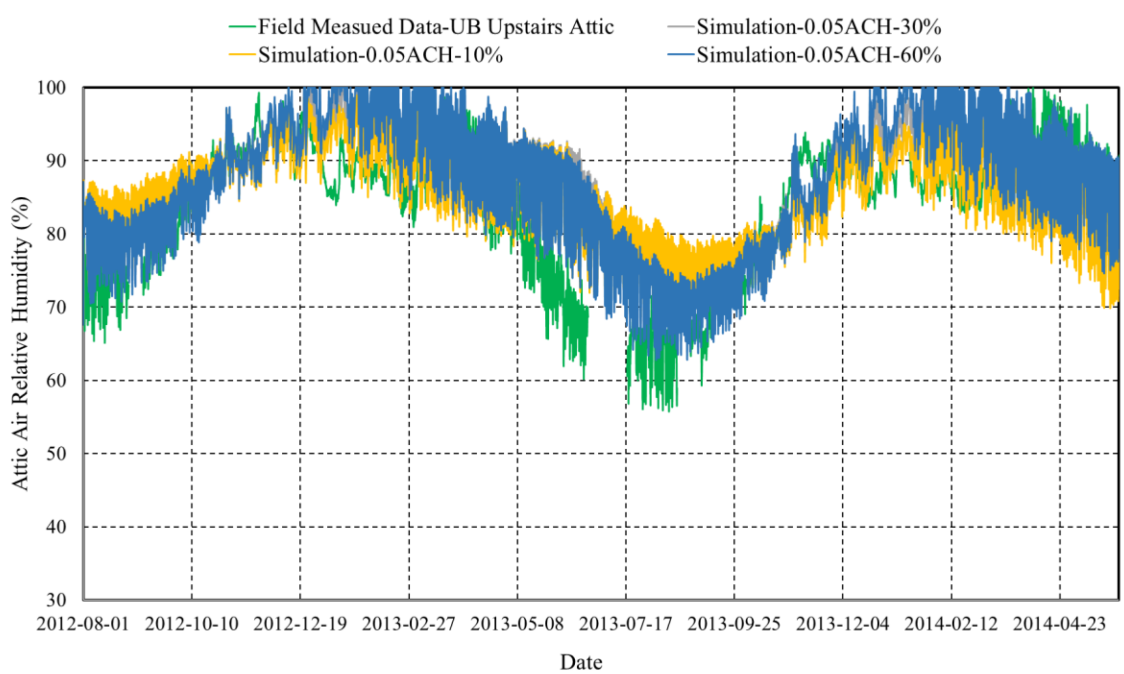
c) Attic air temperature (simulation results compared to field measurements) under 0.18 ACH un-intentional air infiltration.

Figure 5-20. The effect of ceiling air leakage rate on the attic air temperature (hourly data): comparison between simulation and field measurements under different un-intentional air infiltration rates of House III (SIP House).

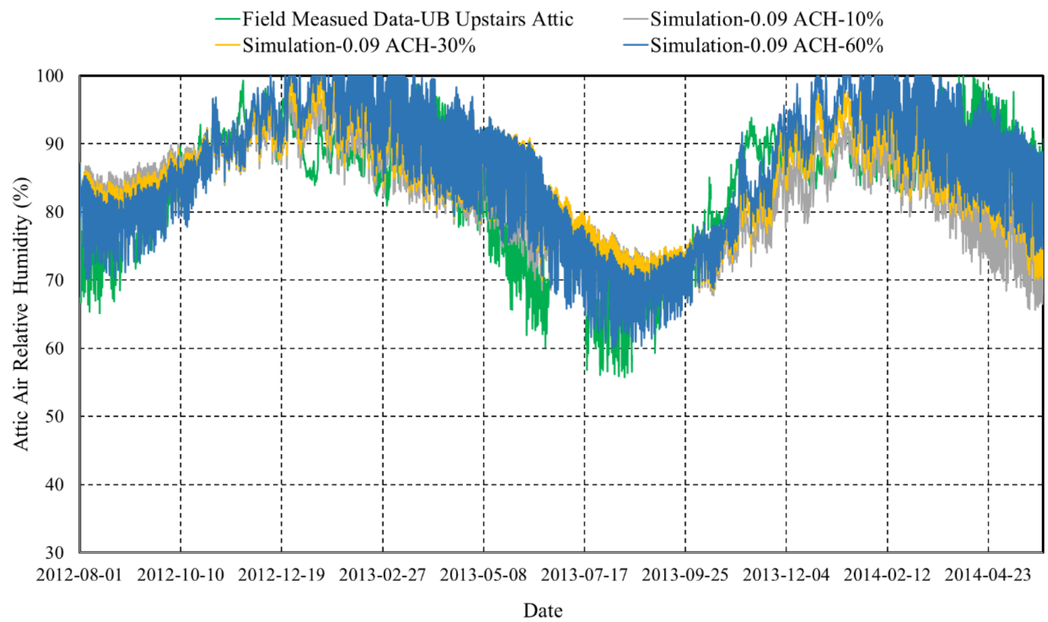
Figure 5-20 shows simulated attic temperature profiles with different ceiling leakage rates (10%, 30%, 60%) under constant un-intentional air infiltration (0.05 ACH, 0.09 ACH, 0.18 ACH) compared with field measured data from Aug. 2012 to June 2014, respectively. Average temperature differences (also called as ADT) and RMSD values between simulation and field measured results are listed in Table 5.21 to indicate parametric study results and models' accuracy. It's obvious that simulation curves almost overlap among different ceiling air leakage rates are 10%, 30% or 60% when un-intentional air infiltration is under constant value (0.05ACH, 0.09ACH, 0.18ACH). Average temperature RMSD values among three air leakage rates are 9.86℃, 10.06℃ and 10.37℃. It's obvious that RMSD values slightly increase with the increase of air leakage rates under constant un-intentional air infiltration rate. According to ADT, about 85% to 88% simulation results are higher than field measurements.

Table 5.21. Average temperature difference (ADT) and RMSD values between simulation and field measured results under different ceiling leakage rates and un-intentional air infiltration rates.

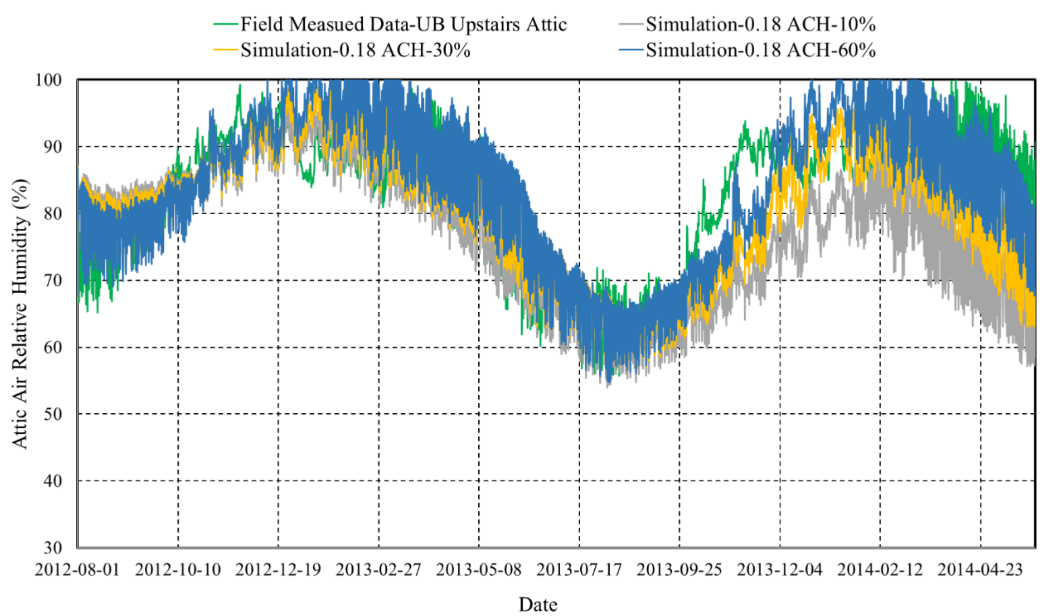
	RMSD Temperature (Simulation Result-Field Data)	Average RMSD Temperature under constant ceiling air leakage rate	ADT (℃) (Simulation Result-Field Data)	
0.05 ACH-10%	9.89	10.14	(+,86%) 8.83	(-,14%) -3.57
0.05 ACH-30%	10.11		(+,87%) 9.01	(-,13%) -3.59
0.05 ACH-60%	10.42		(+,88%) 9.26	(-,12%) -3.65
0.09 ACH-10%	9.87	10.11	(+,85%) 8.80	(-,15%) -3.59
0.09 ACH-30%	10.07		(+,87%) 8.97	(-,13%) -3.60
0.09 ACH-60%	10.39		(+,88%) 9.24	(-,12%) -3.64
0.18 ACH-10%	9.82	10.03	(+,85%) 8.75	(-,15%) -3.66
0.18 ACH-30%	9.99		(+,86%) 8.90	(-,14%) -3.63
0.18 ACH-60%	10.29		(+,88%) 9.16	(-,12%) -3.63



a) Attic air RH (simulated results compare to field measured data) under 0.05 ACH un-intentional air infiltration.



b) Attic air RH (simulated results compare to field measured data) under 0.09 ACH un-intentional air infiltration.



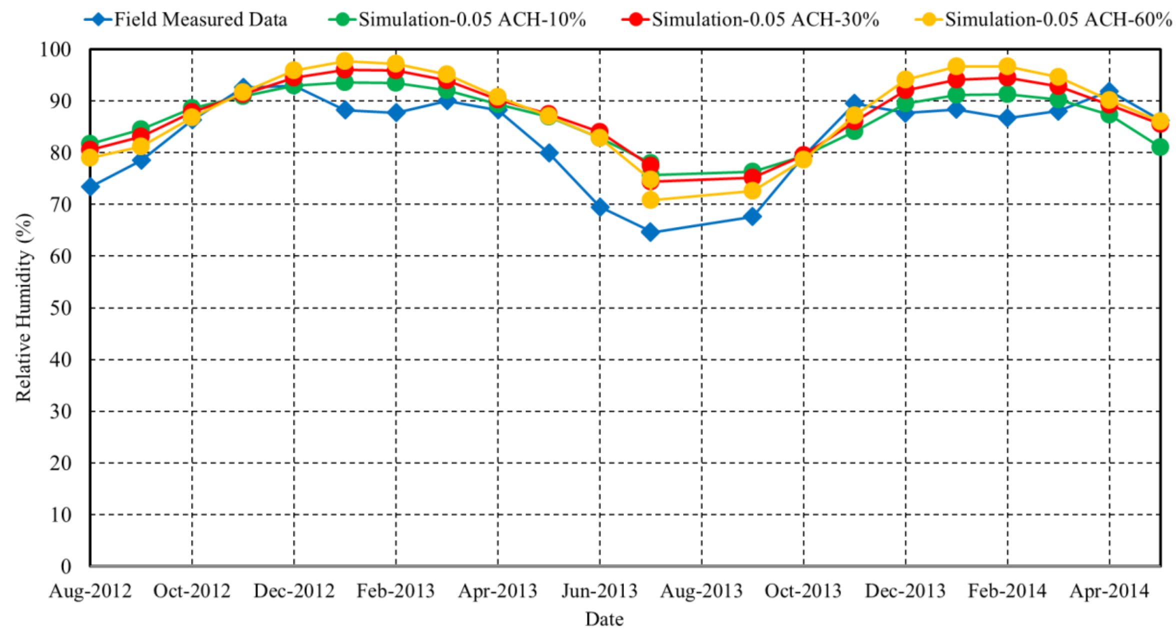
c) Attic air RH (simulated results compare to field measured data) under 0.18 ACH un-intentional air infiltration.

Figure 5-21. The effect of ceiling air leakage rate on the attic air RH (hourly data): comparison between simulation and field measurements under different un-intentional air infiltration rates of House III (SIP House).

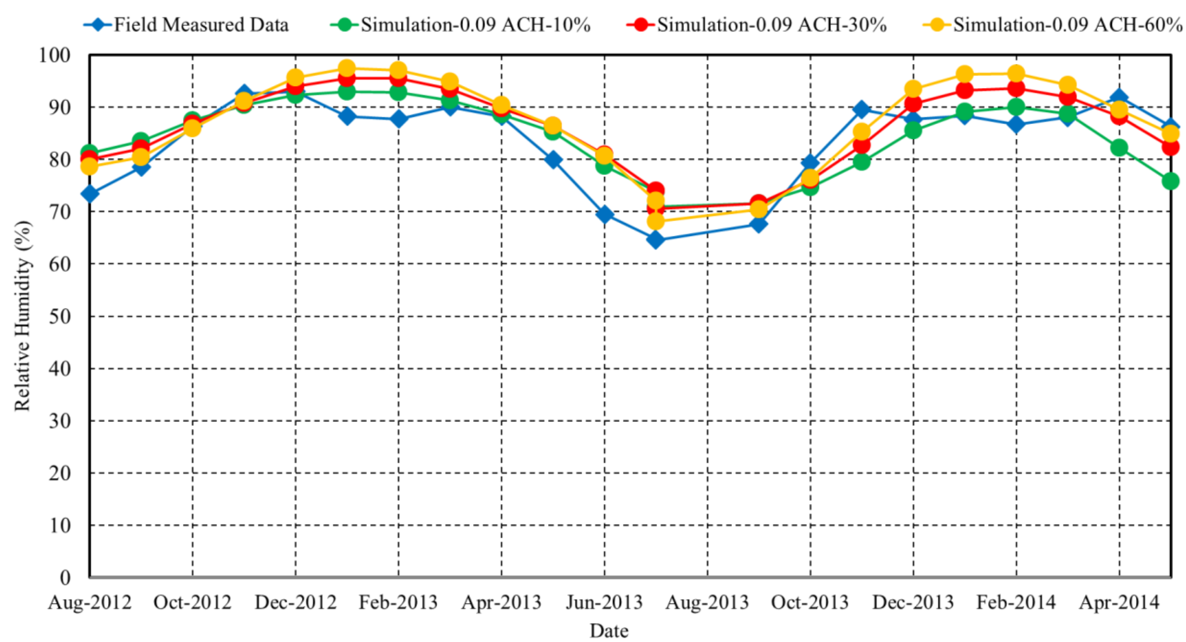
Figure 5-21 shows simulated attic RH profiles with different ceiling leakage rates (10%, 30%, 60%) under constant un-intentional air infiltration (0.05 ACH, 0.09 ACH, 0.18 ACH) compared with field measured data during the period from Aug. 2012 to June 2014, respectively. Average RH differences (also called as ADRH) and RMSD values between simulation and field measured results are listed in Table 5.22 to indicate parametric study results and models' accuracy. It's obvious that all simulation results follow the trend of field measurements. When un-intentional air infiltration is controlled at constant value, difference among RH simulation results increase with the increase of ceiling air leakage rates. Average RH RMSD values with different ceiling leakage rates (10%, 30%, 60%) under constant ceiling air leakage rates (0.05ACH, 0.09ACH, 0.18ACH) are 7.97%, 7.47% and 7.84%, respectively. When un-intentional air infiltration is under 0.05 ACH and 0.09 ACH, there are around 66% to 89% simulation results higher than field measured data. When un-intentional air infiltration is 0.18 ACH, amounts of simulation results which is higher than field measured data increase with the increase of ceiling air leakage rates, they are 32%, 48% and 59%.

Table 5.22. Average relative humidity difference (ADRH) and RMSD values between simulation and field measured results under different ceiling leakage rates and un-intentional air infiltration rates.

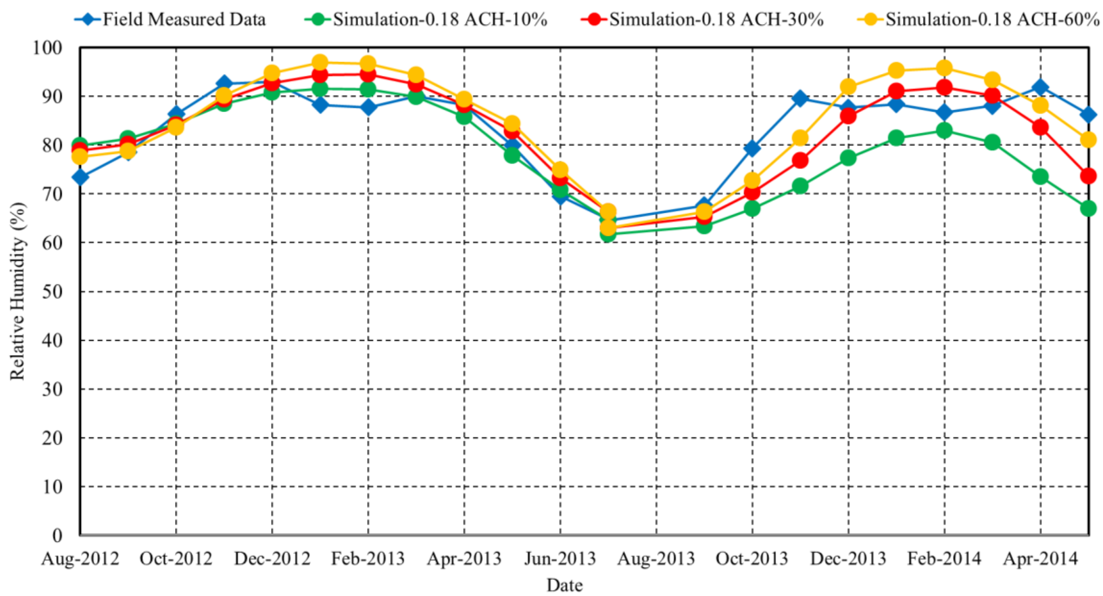
	RMSD (Simulation Result-Field Data)	**Average RMSD under constant ceiling air leakage rate**	**ADRH (%) (Simulation Result-Field Data)**	
0.05 ACH-10%	7.68	7.97	(+,68%) 6.59	(-,32%) -4.88
0.05 ACH-30%	8.09		(+,74%) 7.19	(-,26%) -4.39
0.05 ACH-60%	8.15		(+,75%) 7.42	(-,25%) -4.17
0.09 ACH-10%	7.19	7.47	(+,89%) 6.02	(-,11%) -6.01
0.09 ACH-30%	7.43		(+,66%) 6.59	(-,34%) -4.95
0.09 ACH-60%	7.80		(+,69%) 7.19	(-,31%) -4.51
0.18 ACH-10%	9.00	7.84	(+,32%) 4.64	(-,68%) -9.27
0.18 ACH-30%	7.15		(+,48%) 5.62	(-,52%) -6.78
0.18 ACH-60%	7.38		(+,59%) 6.56	(-,41%) -5.56



a) Attic air RH (simulation results compared to field measurements) under 0.05 ACH un-intentional air infiltration.



b) Attic air RH (simulation results compared to field measurements) under 0.09 ACH un-intentional air infiltration.



c) Attic air RH (simulation results compared to field measurements) under 0.18 ACH un-intentional air infiltration.

Figure 5-22 The effect of ceiling air leakage rate on the attic air RH (monthly average): comparison between simulation and field measurements under different un-intentional air infiltration rates of House III (SIP House).

Figure 5-21 and Figure 5-22 indicate ceiling air leakage rates have no significant effect on attic temperature, but have considerable impact on relative humidity levels of attic air. To present RH difference more clearly, Figure 5-22 shows monthly average among simulated attic relative humidity (RH) profiles with different ceiling leakage rates (10%, 30%, 60%) under constant un-intentional air infiltration rates (0.05ACH, 0.09ACH, 0.18ACH) compared with field measured data during the period from mid-Oct. 2013 to July 2015, respectively. RH simulation results under different ceiling air leakage rates from high to low follow the order: 60%, 30%, 10%. And RH differences are more and more significant with the increase of un-intentional air infiltration (0.05 ACH, 0.09 ACH, 0.18 ACH). Table 5.23 lists simulation RH difference (monthly average) among different ceiling air leakage rates under different constant un-intentional air infiltration rates. Average simulation RH difference among 10%, 30% and 60% ceiling air leakage rates under constant attic ventilation rates (1ACH, 5ACH, 10ACH) are 1.10% & 0.10%, 1.98% & 0.70% and 3.89% & 2.18%. The maximum RH difference always can be found in spring period and the minimum values are in summer period no matter un-intentional air infiltration rates are 0.05 ACH, 0.09 ACH or 0.18 ACH. And there is a larger difference can be found between 30% and 10% than that between 60% and 30%. The maximum RH differences appear in 0.18 ACH which are 10.17% (simulation 30%-10%) and 7.43% (simulation 60%-30%). And the minimum RH differences appear in 0.05 ACH which -1.52% (simulation 30%-10%) and -3.54% (simulation 60%-30%).

Table 5.23. Simulation RH difference (monthly average) among different ceiling air leakage rates under different constant un-intentional air infiltration rates.

	Maximum RH Difference (Monthly Average)	**Minimum RH Difference (Monthly Average)**	**Average RH Difference (Monthly Average)**
0.05 ACH (Simulation 30%-10%)	4.45%	-1.52%	1.10%
0.05 ACH (Simulation 60%-30%)	2.60%	-3.54%	0.10%
0.09 ACH (Simulation 30%-10%)	6.47%	-1.38%	1.98%
0.09 ACH (Simulation 60%-30%)	3.11%	-2.43%	0.70%
0.18 ACH (Simulation 30%-10%)	10.17%	-1.10%	3.89%
0.18 ACH (Simulation 60%-30%)	7.43%	-1.43%	2.18%

Table 5.24 summarizes monthly average ADRH and RMSD values between simulation and field measurements with different ceiling leakage rates under constant un-intentional air infiltration rate during the period from mid-Oct. 2013 to July 2015. Compared to hourly data listed in Table 5.22, monthly average data is easier to show the difference between field measurements and simulation results. RMSD values between simulation results and field measurements increase with the increase of ceiling leakage rates under different constant un-intentional air infiltration rate. Average RMSD values are 6.48%, 5.72% and 6.38% under 0.05 ACH, 0.09 ACH and 0.18 ACH, respectively. When un-intentional air infiltration is under 0.05ACH and 0.09ACH, according to ADRH values, there are 68% to 82% simulation results higher than field measured data and no big RH differences among different ceiling leakage rates. However, when un-intentional air infiltration is 0.18 ACH, the amount of positive values (simulation results higher than field measured data) increase with the increase of ceiling air leakage rates which are 23%, 50%, 64%.

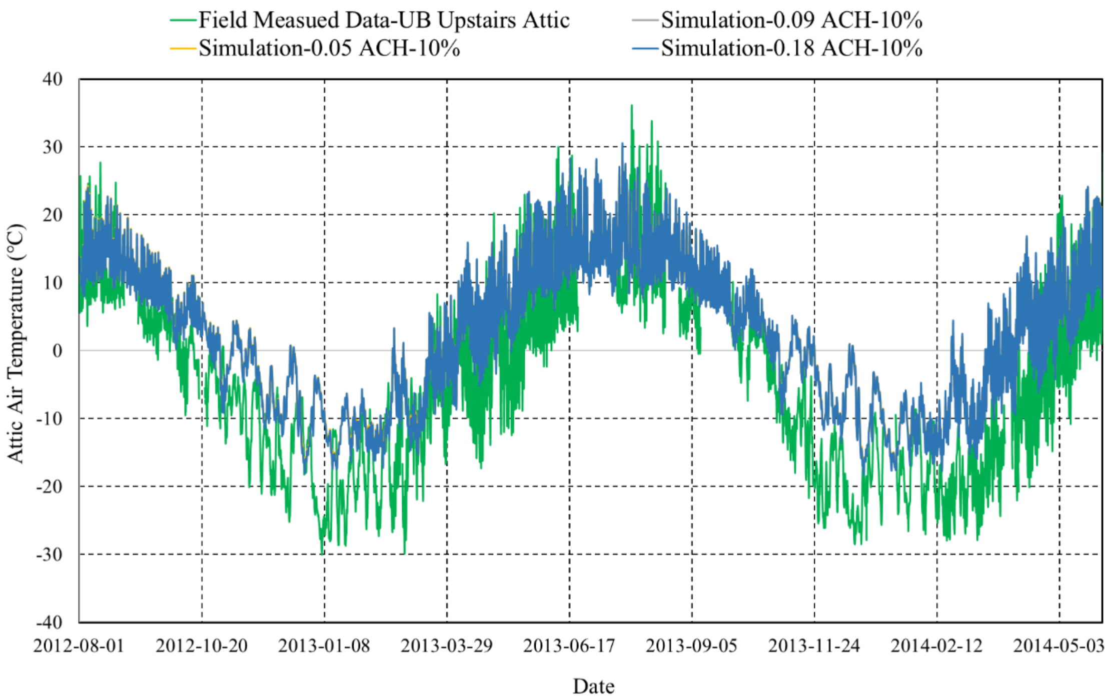
Table 5.24. Average Relative Humidity Difference (ADRH) and RMSD values (monthly average) between simulation and field measured results with different ceiling leakage rates under different constant un-intentional air infiltration rates.

	RMSD (Simulation Result-Field Data)	Average RMSD under constant attic ventilation rate	ADRH (%) (Simulation Result-Field Data)	
0.05 ACH-10%	6.38	6.48	(+,77%) 5.62	(-,23%) -3.37
0.05 ACH-30%	6.60		(+,82%) 6.18	(-,18%) -2.05
0.05 ACH-60%	6.46		(+,77%) 6.55	(-,23%) -1.20
0.09 ACH-10%	5.78	5.72	(+,68%) 4.26	(-,32%) -5.69
0.09 ACH-30%	5.56		(+,77%) 5.13	(-,23%) -3.92
0.09 ACH-60%	5.81		(+,73%) 5.99	(-,27%) -2.12
0.18 ACH-10%	8.40	6.38	(+,23%) 3.53	(-,77%) -6.87
0.18 ACH-30%	5.56		(+,50%) 3.68	(-,50%) -4.92
0.18 ACH-60%	5.18		(+,64%) 4.72	(-,36%) -3.95

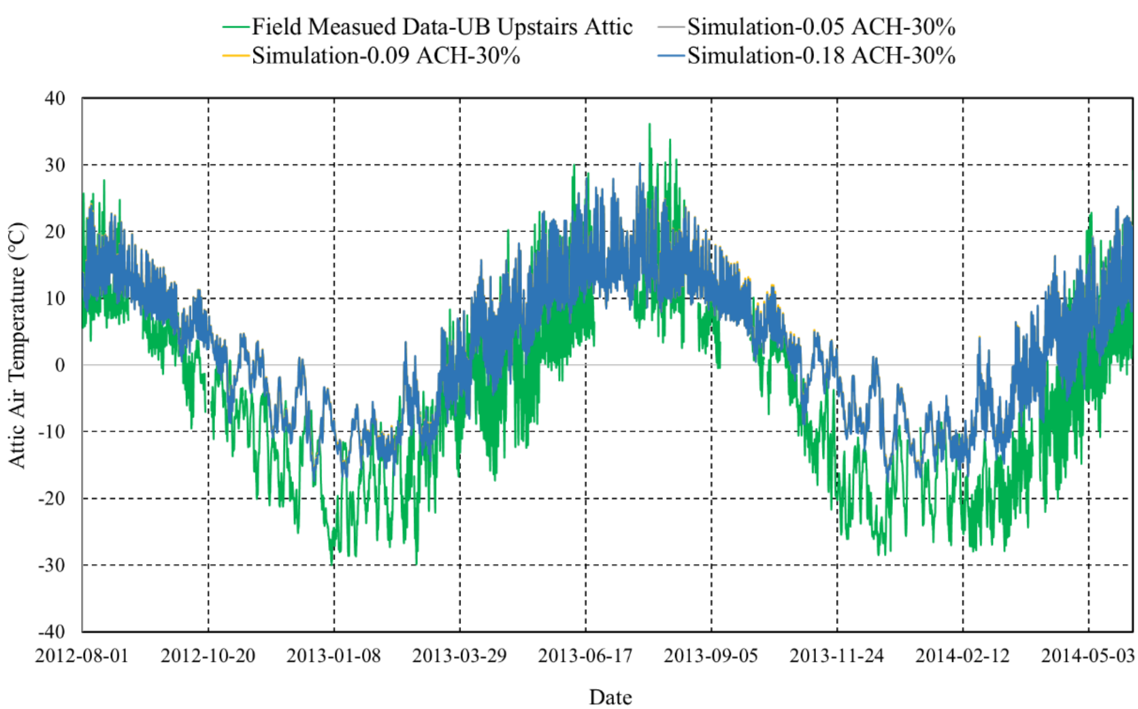
In summary, ceiling air leakage rate has negligible influence on the RMSD values of attic air temperature but considerable influence on the RMSD value of attic air RH under constant un-intentional air infiltration rates (1ACH, 5ACH or 10ACH). The difference in RH between simulation and field measurements increases with the increase of ceiling air leakage rates and un-intentional air infiltration rates.

5.3.2.2 Effect of Un-Intentional Air Infiltration Rate

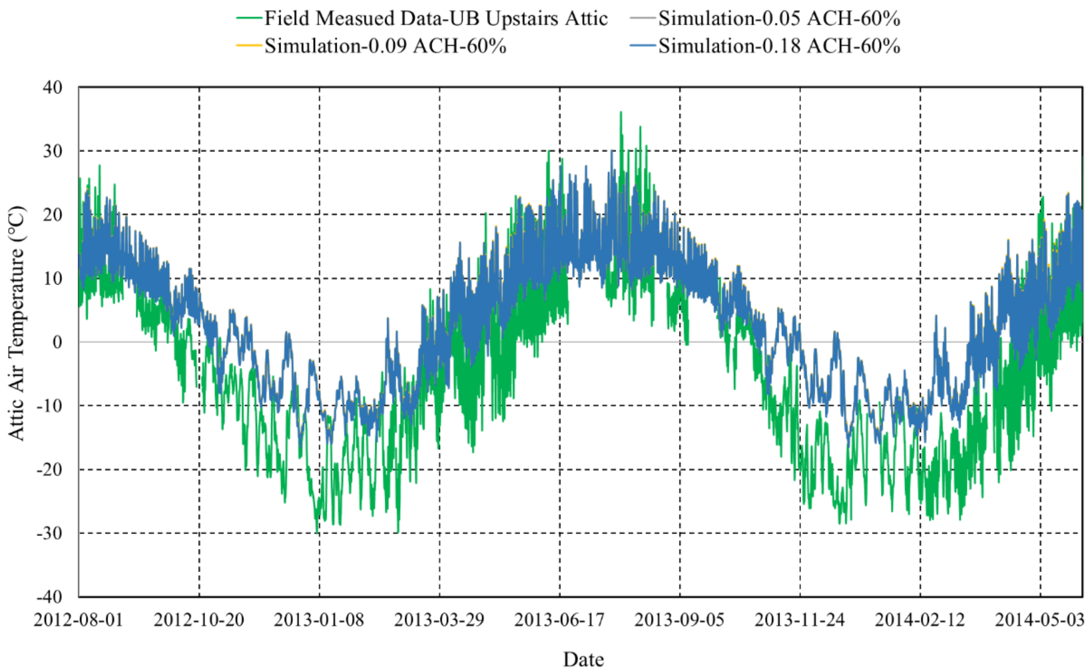
As stated at the beginning of this section, un-ventilated attic is a fully-sealed construction. Except for ceiling air leakage rate, un-intentional air infiltration rate is other moisture source which depends on attic construction itself. In this sub-section, parametric studies are performed to investigate the effect of un-intentional air infiltration rate (0.05ACH, 0.09ACH, 0.18ACH) under different ceiling air leakage rates (10%, 30%, 60%). And the comparative results between simulated results (Upstairs) and field measurements data (UB-US) under the setting above are shown as follows:



a) Attic air temperature (simulation results compared to field measurements) under 10% ceiling air leakage rate.



b) Attic air temperature (simulation results compared to field measurements) under 30% ceiling air leakage rate.



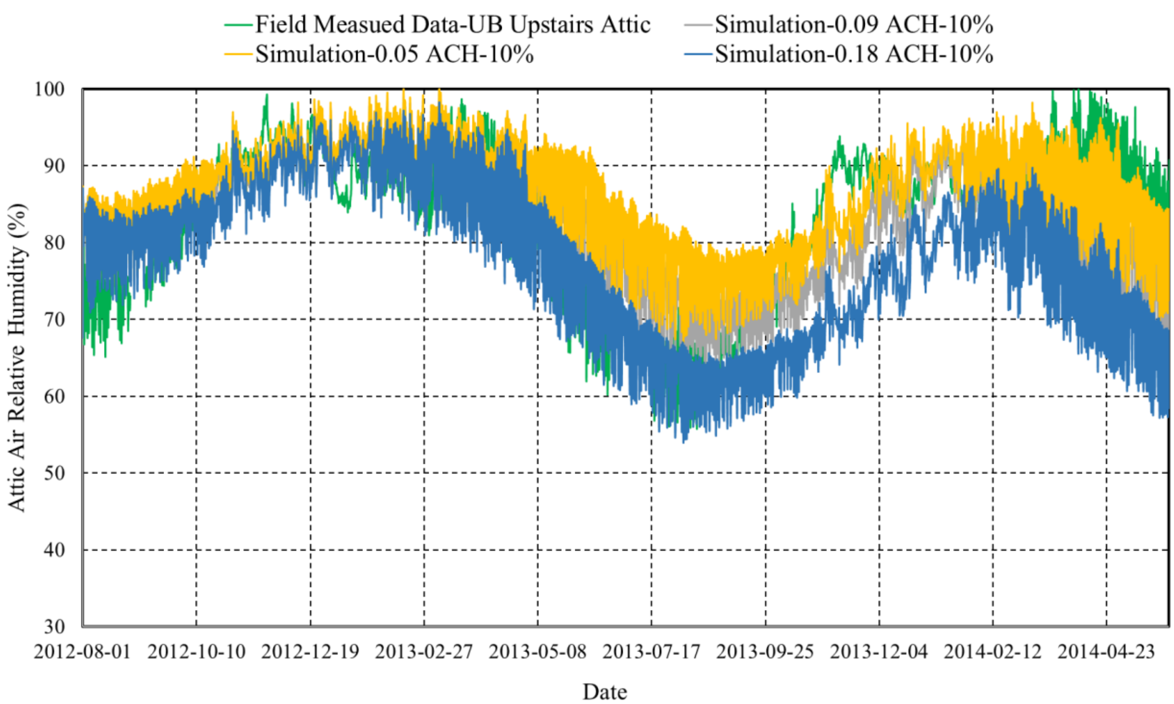
c) Attic air temperature (simulation results compared to field measurements) under 60% ceiling air leakage rate.

Figure 5-23 The effect of un-intentional air infiltration on the attic air temperature (hourly data): comparison between simulation and field measurements under different ceiling air leakage rates of House III (SIP House).

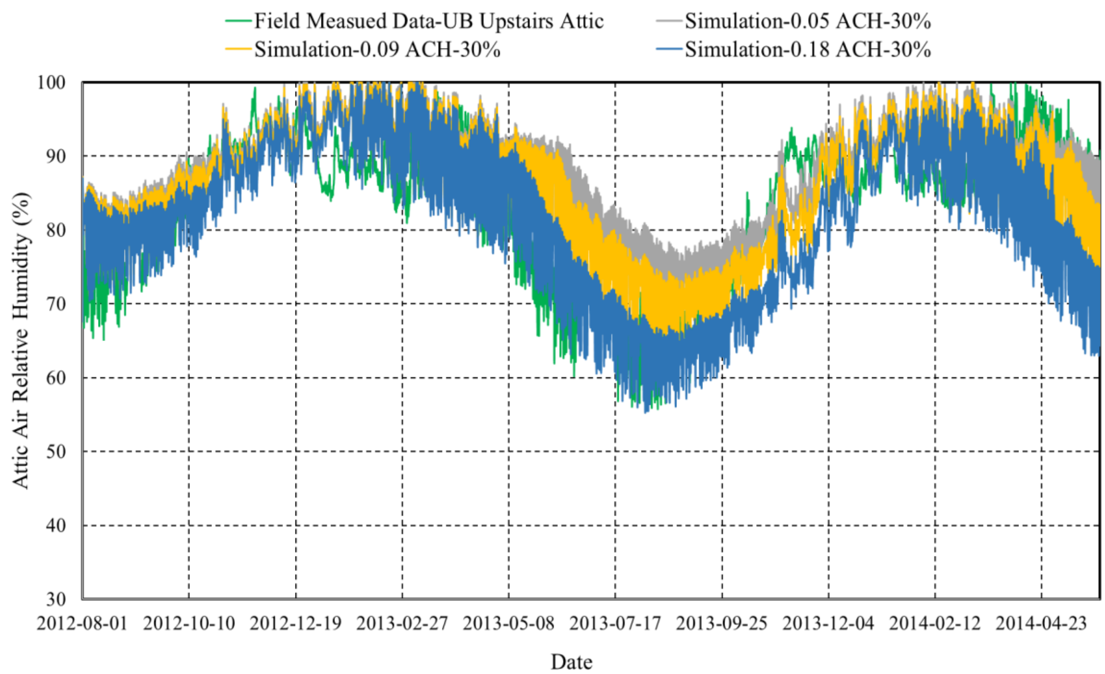
Figure 5-23 shows simulated attic temperature profiles with different attic ventilation rates (1ACH, 5ACH, 10ACH) under constant ceiling air leakage rates (10%, 30%, 60%) compared with field measured data during the period from mid-Aug. 2013 to June 2014, respectively. Average temperature differences (also called as ADT) and RMSD values between simulation and field measured results are listed in Table 5.25 to indicate parametric study result and models' accuracy. It's obvious that all simulation curves follow the same trend of field measured data under all scenarios. When un-intentional air infiltration rate is under constant value, whether it's 0.05 ACH, 0.09 ACH and 0.18 ACH, simulation profiles almost overlap which have no significant difference among three ceiling air leakage rates (10%, 30%, 60%). Average temperature RMSD values are 10.14 ℃, 10.11℃ and 10.03℃ when ceiling air leakage rates are 10%, 30% and 60%, respectively. Temperature RMSD values have slightly changes with the increase of un-intentional air infiltration rates from 0.05 ACH to 0.18 ACH whether ceiling air leakage rates are 10%, 30% or 60%.

Table 5.25. Difference among simulated temperature RMSD values with different un-intentional air infiltration under different ceiling air leakage rates.

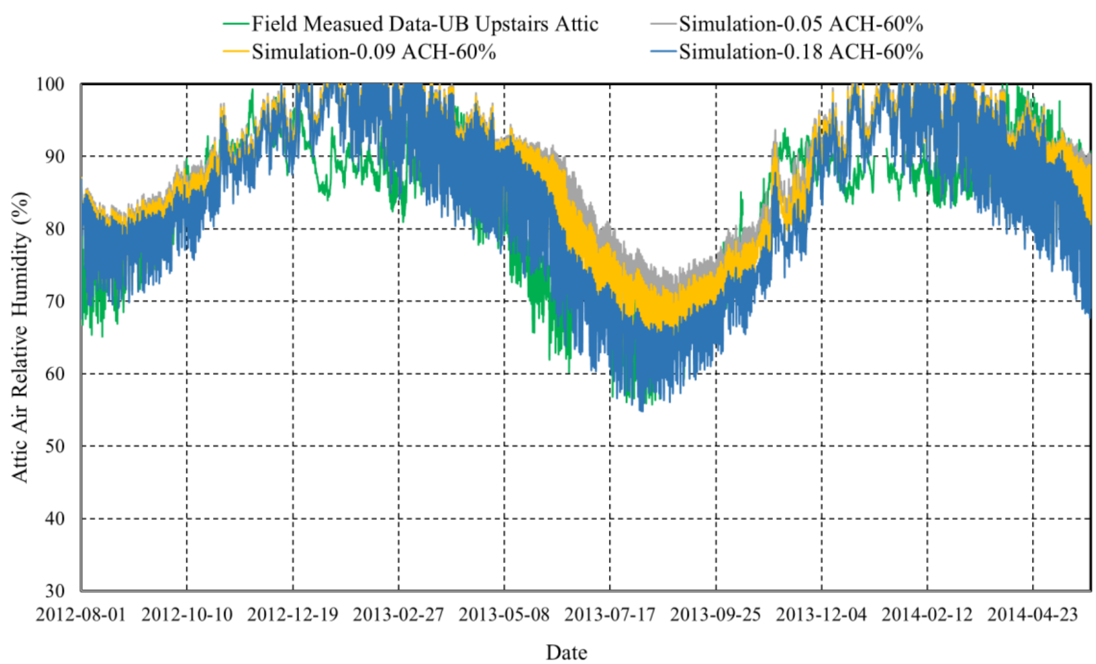
	RMSD Temperature Difference
10% (0.09 ACH – 0.05 ACH)	-0.02℃
10% (0.18 ACH – 0.09 ACH)	-0.04℃
30% (0.09 ACH – 0.05 ACH)	-0.04℃
30% (0.18 ACH – 0.09 ACH)	-0.08℃
60% (0.09 ACH – 0.05 ACH)	0.04℃
60% (0.18 ACH – 0.09 ACH)	-0.1℃



a) Attic air RH (simulation results compared to field measurements) under 10% ceiling air leakage rate.



b) Attic air RH (simulation results compared to field measurements) under 30% ceiling air leakage rate.



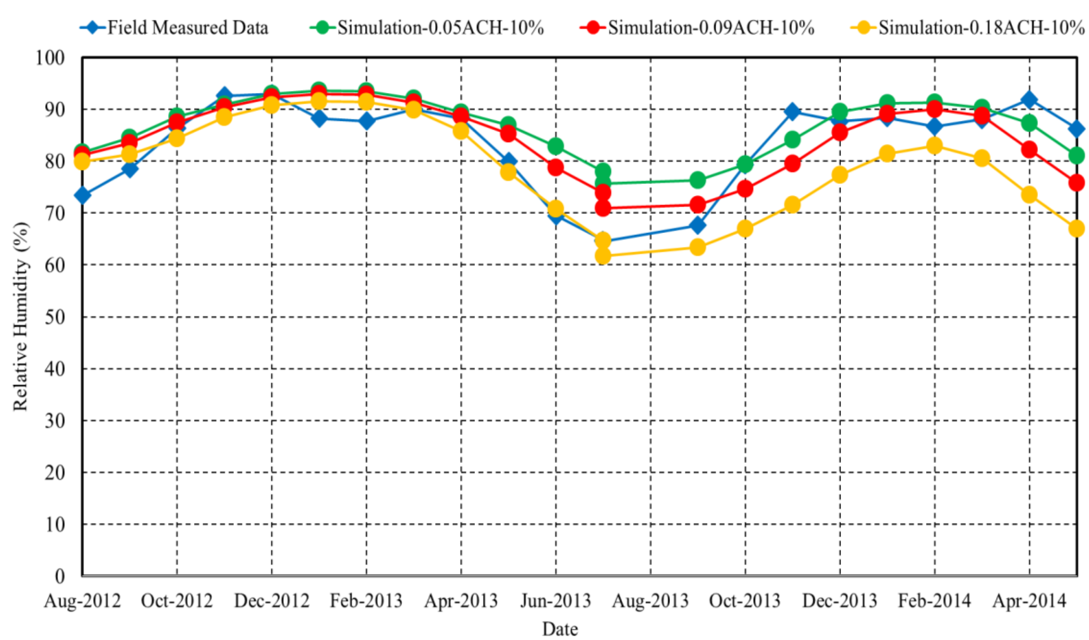
c) Attic air RH (simulation results compared to field measurements) under 60% ceiling air leakage rate.

Figure 5-24. The effect of un-intentional air infiltration on the attic air RH (hourly data): comparison between simulation and field measurements under different ceiling air leakage rates of House III (SIP House).

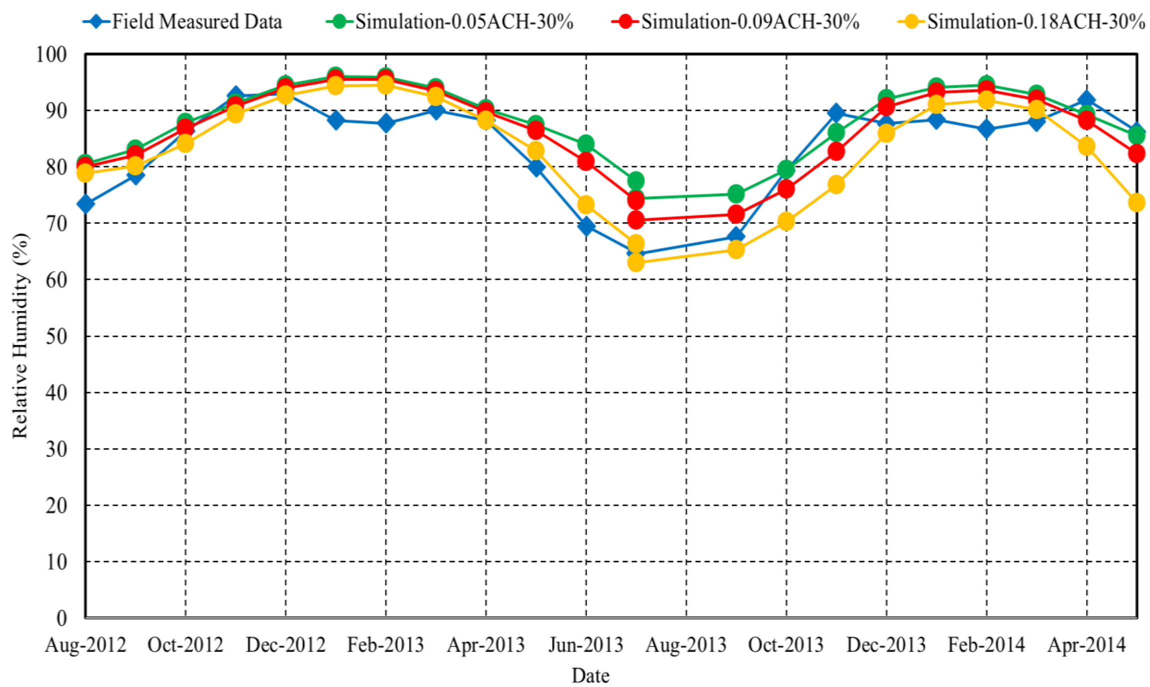
Figure 5-24 shows simulated attic RH profiles with different un-intentional air infiltration rates (0.05 ACH, 0.09 ACH, 0.18 ACH) under different constant ceiling air leakage rates (10%, 30%, 60%) compared with field measured data from Aug. 2012 to June 2014, respectively. Average RH differences (also called as ADRH) and RMSD values between simulation and field measured results are listed in Table 5.26 to indicate parametric study results and models' accuracy. RMSD and ADRH values are the main indicators to show the accuracy of comparison result. It's obvious that all simulation curves follow the trends of field measured data. Differences among simulation results are more obvious when ceiling air leakage rate is 10%, while simulation profiles almost overlap when ceiling air leakage rates are 30% and 60%. As shown in Table 5.26, difference of RH RMSD values under 10%, 30% and 60% ceiling air leakage rate range from -0.55% to 2.48%.

Table 5.26. Difference among simulated RH RMSD values with different un-intentional air infiltration under different ceiling air leakage rates.

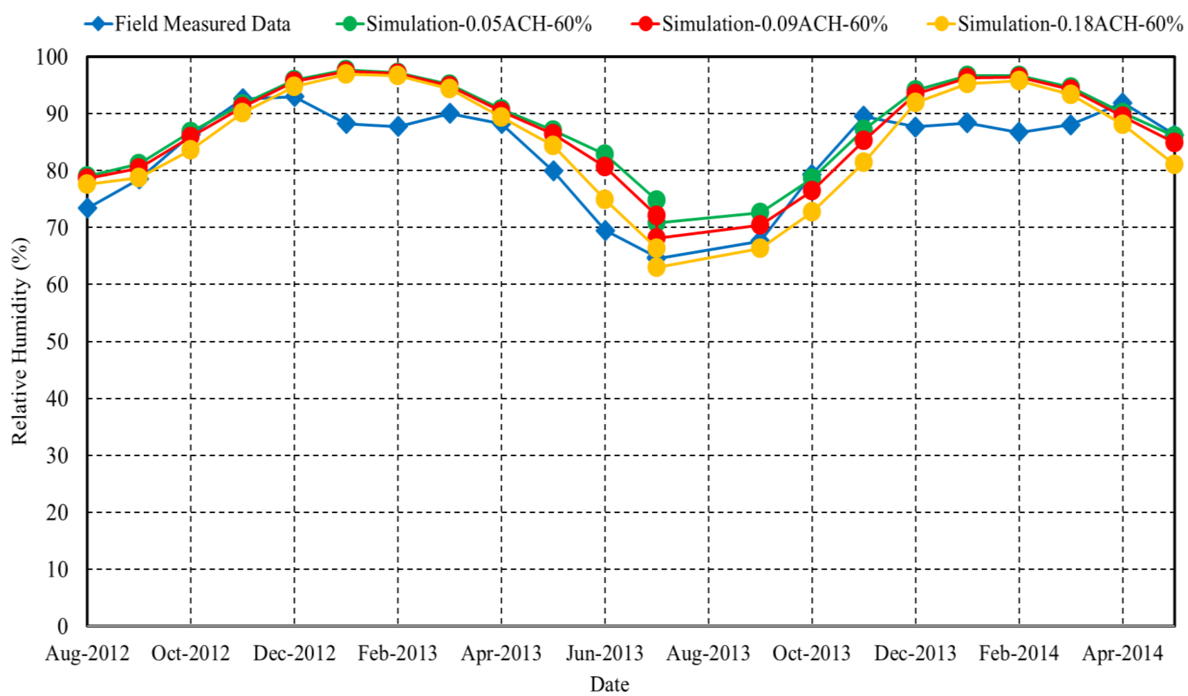
	RMSD Temperature Difference
10% (0.09 ACH – 0.05 ACH)	-0.10℃
10% (0.18 ACH – 0.09 ACH)	2.48℃
30% (0.09 ACH – 0.05 ACH)	-0.55℃
30% (0.18 ACH – 0.09 ACH)	0.29℃
60% (0.09 ACH – 0.05 ACH)	-0.31℃
60% (0.18 ACH – 0.09 ACH)	-0.30℃



a) Attic air RH (simulation results compared to field measurements) under 10% ceiling air leakage rate.



b) Attic air RH (simulation results compared to field measurements) under 30% ceiling air leakage rate.



c) Attic air RH (simulation results compared to field measurements) under 60% ceiling air leakage rate.

Figure 5-25. The effect of un-intentional air infiltration rates on the attic air RH (monthly average): comparison between simulation and field measurements under different ceiling air leakage rates of House III (SIP House).

Figure 5-24 and Figure 5-25 indicate un-intentional air infiltration rate has no significant effect on attic temperature, but have significant impact on relative humidity levels of attic air. To present RH difference more clearly, Figure 5-25 indicates monthly average results among simulated attic relative humidity (RH) profiles with different un-intentional air infiltration (0.05 ACH, 0.09 ACH, 0.18 ACH) under different constant ceiling air leakage rates (10%, 30%, 60%) compared with field measured data during the period from mid-Oct. 2013 to July 2015, respectively. It's obvious that all simulation results follow the trends of field measured data and are generally higher than field measurements during the whole monitoring period. RH in attic air increase with the increase of ceiling air leakage rates and the difference in attic RH due to un-intentional air infiltration rate decreases with the increase of ceiling air leakage rates. Table 5.27 lists simulated RH difference (monthly average) among different un-intentional air infiltration rates under different constant ceiling air leakage rates. Average simulation RH difference of 0.05 ACH, 0.09 ACH and 0.18 ACH un-intentional air infiltration rate under constant ceiling air leakage rates (0.05 ACH, 0.09 ACH, 0.18ACH) range from -5.60% to -1.01%.

Table 5.27. Simulated RH difference (monthly average) among different un-intentional air infiltration under different ceiling air leakage rates.

	Maximum RH Difference (Monthly Average)	**Minimum RH Difference (Monthly Average)**	**Average RH Difference (Monthly Average)**
10% (Simulation 0.09 ACH-0.05 ACH)	-0.57%	-5.30%	-2.49%
10% (Simulation 0.18 ACH-0.09 ACH)	-1.24%	-9.27%	-5.60%
30% (Simulation 0.09 ACH-0.05 ACH)	-0.40%	-3.84%	-1.61%
30% (Simulation 0.18 ACH-0.09 ACH)	-1.02%	-8.63%	-3.69%
60% (Simulation 0.09 ACH-0.05 ACH)	-0.14%	-2.77%	-1.01%
60% (Simulation 0.18 ACH-0.09 ACH)	-0.37%	-5.74%	-2.21%

Table 5.28 summarizes monthly average ADRH and RMSD values between simulation and field measurements with un-intentional air infiltration under different constant ceiling air leakage rates during the period from mid-Oct. 2013 to July 2015. Compare to hourly data listed in Table 5.24, monthly average data is easier to show the difference between field measurements and

simulation results. RMSD values between simulation results and field measurements increase with the increase of ceiling leakage rates under different constant un-intentional air infiltration. Average RMSD values are 6.85%, 5.91% and 5.82% under 0.05 ACH, 0.09 ACH and 0.18 ACH, respectively. The amount of simulation results which are higher than field measured data decrease with the increase of un-intentional air infiltration rates.

Table 5.28. Average relative humidity difference (ADRH) and RMSD values (Monthly Average) between simulation and field measured results with different un-intentional air infiltration rates under different constant ceiling air leakage rates.

	RMSD (Simulation Result-Field Data) (%)	**Average RMSD under constant attic ventilation rate (%)**	**ADRH (%) (Simulation Result-Field Data)**	
0.05 ACH-10%	6.38	6.85	(+,77%) 5.62	(-,23%) -3.37
0.09 ACH-10%	5.78		(+,68%) 4.26	(-,32%) -5.70
0.18 ACH-10%	8.40		(+,23%) 3.53	(-,77%) -6.87
0.05 ACH-30%	6.60	5.91	(+,82%) 6.18	(-,18%) -2.04
0.09 ACH-30%	5.56		(+,77%) 5.13	(-,23%) -3.92
0.18 ACH-30%	5.56		(+,50%) 3.68	(-,27%) -4.92
0.05 ACH-60%	6.46	5.82	(+,77%) 6.55	(-,23%) -1.20
0.09 ACH-60%	5.81		(+,73%) 5.99	(-,50%) -2.12
0.18 ACH-60%	5.18		(+,64%) 4.72	(-,36%) -3.95

In summary, ceiling air leakage rate has negligible influence on the RMSD values of attic air temperature but considerable influence on the RMSD value of attic air RH under assumed constant un-intentional air infiltration (1ACH, 5ACH or 10ACH). The difference in RH between simulation and field measurements increases with the increase of ceiling air leakage rates and the increase of un-intentional air infiltration rates. As shown in Table 5.28, the best case is 30% ceiling air leakage rate with 0.09ACH un-intentional air infiltration rate.

5.4 Hygrothermal Model Validation

This section presents simulation results of House I and House III comparing with field measurements for model validation. RH/T of attic air and MC/T of plywood sheathing in attic space are two indicators used. According to parametric study presented in section 5.2, the best simulation scenario that match the experimental result is presented for model validation of House I and House III. The aim of model validation is to verify the reliability of established model. Validated models are then be applied to investigate the effect of different parameters on hygrothermal performance of attic. The detailed parametric study results on specific parameters can be used for improving attic design in extremely cold climate. On the other hand, validated model can also be applied to other climates to provide design recommendations for attic design.

5.4.1 Model Validation of House I: KMHB House

This section presents WUFI Plus model results compared with field measurements in hourly data, daily data and monthly data of House I (KMHB House). The best case is 10% ceiling air leakage rate with 1ACH attic ventilation rate which is used to present model validation results.

5.4.1.1 Hourly Data

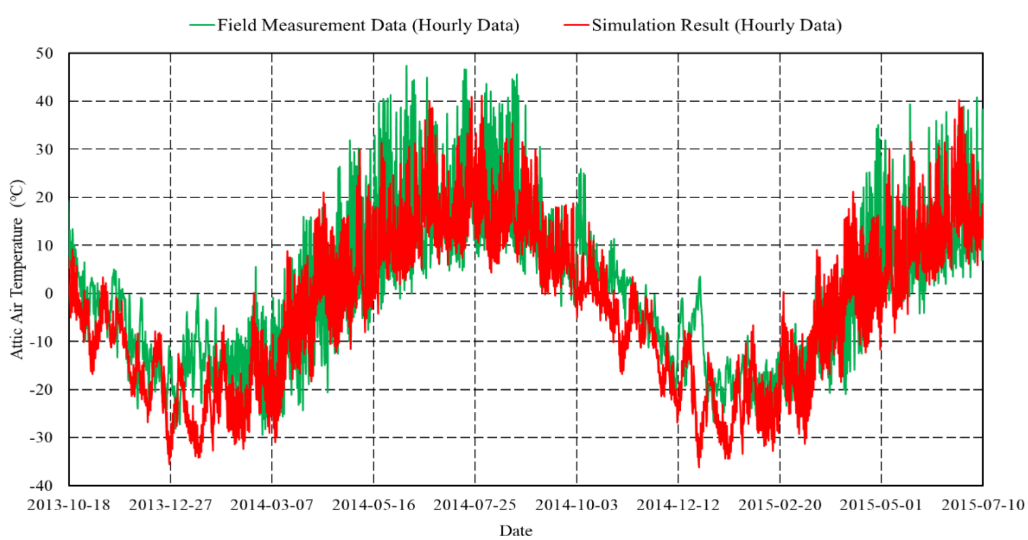


Figure 5-26. Hourly field measured temperature of attic air compared to simulation result in House I (KMHB House).

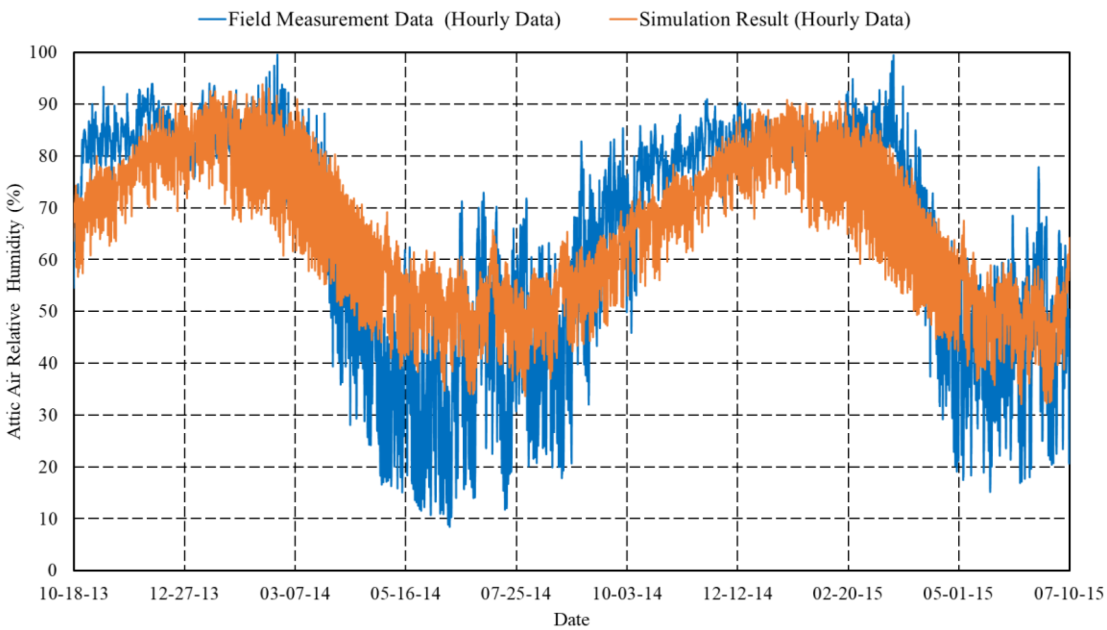
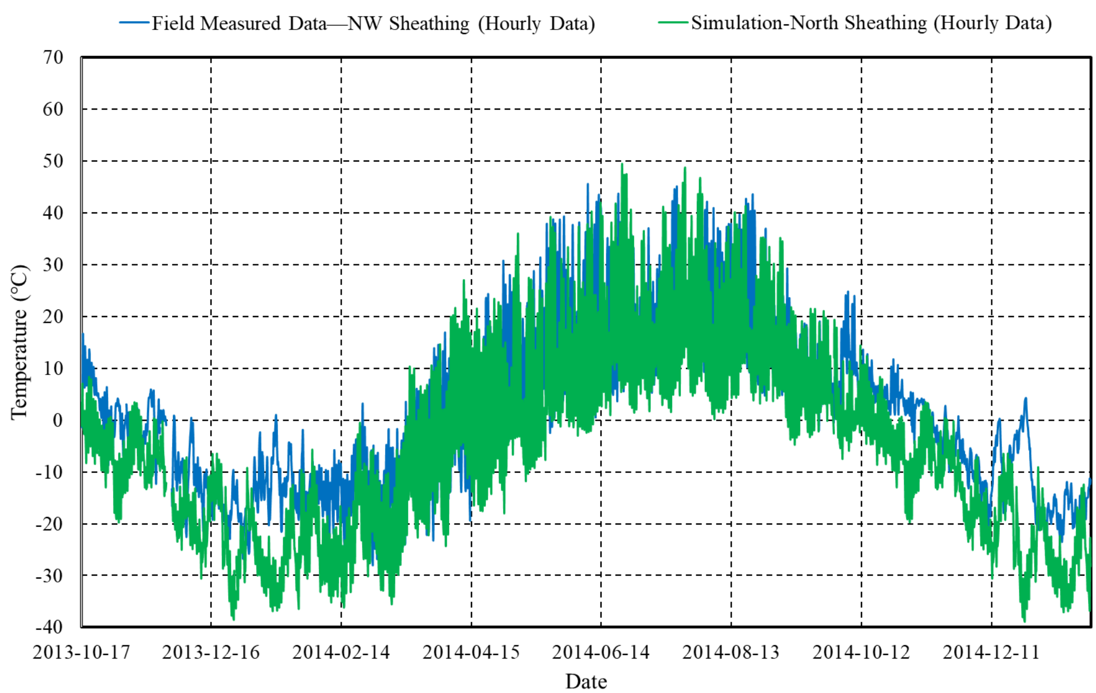


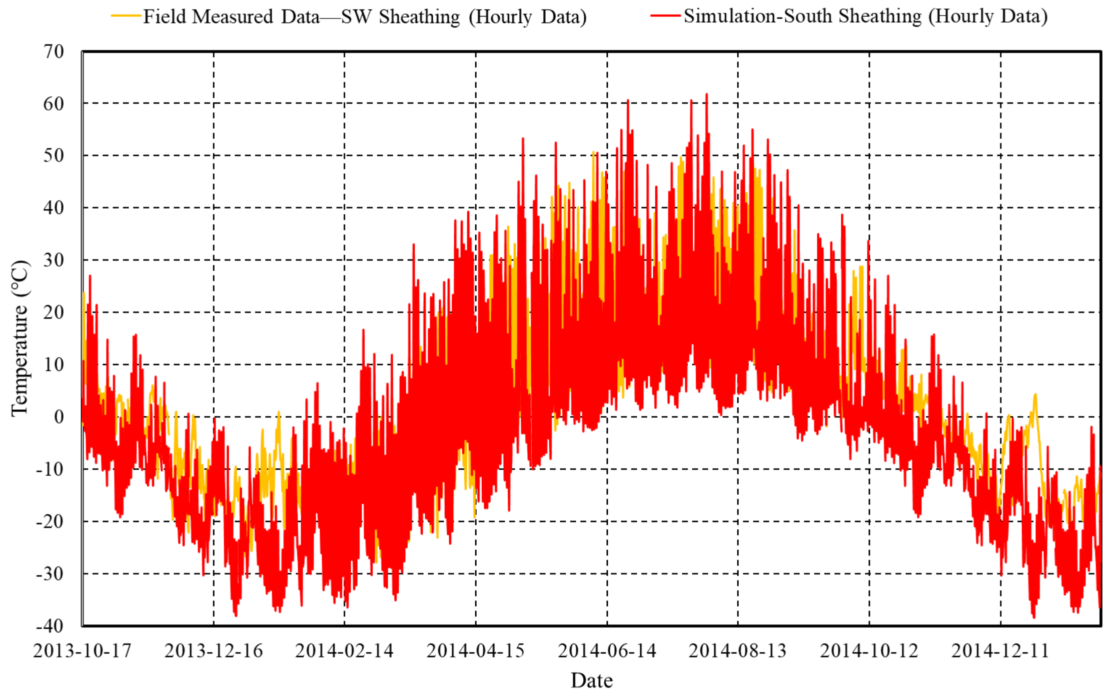
Figure 5-27. Hourly field measured RH of attic air compared to simulation result in House I (KMHB House).

Figure 5-26 and Figure 5-27 show the comparison in hourly temperature and RH of the ventilated attic between simulations and field measurements for House I during the period from mid-Oct. 2013 to July 2015. Both simulated temperature and RH profiles follow the trends of field measurements with obvious fluctuations. The field measured temperatures vary between -29.40℃ and 47.39℃ with an average value of -0.11℃, while the simulations vary from -36.19℃ to 41.17℃. The peaks of field measured temperature are higher than those of simulation results during the spring and summer months, while the differences in the fall and winter time are smaller. The hourly temperature RMSD value between field measurements and simulations is 10.27℃. And measured data is used as baseline. The field measured RH in attic space varies between 8.42% and 99.51% with an average value of 65.08%, while the simulated RH in attic space varies from 32.10% to 93.86% with an average value of 66.69%, while the simulated RH during the summer months are lower than measurements, which may be attributed to lower simulated temperatures during this period as shown in Figure 5-26. The difference in RH between simulation results and field measurements are smaller during the winter months, the hourly RH RMSD value between measurements and simulations is 13.77%.

Maximum value, minimum value and average value of temperature and RH difference between simulation results and field measurements data are 31.71℃ & -38.72℃ & -3.30℃ and 46.40% & -38.33% & 1.61%, respectively. The RMSD values of temperature and RH of attic air in House I are 10.27℃ and 13.77%.



a) Temperature of NW sheathing (field measurements) V.S. North sheathing (simulation results).



b) Temperature of SW sheathing (field measurements) V.S. South sheathing (simulation results).

Figure 5-28. Hourly field measured temperature of plywood sheathing compared to simulation result in House I (KMHB House).

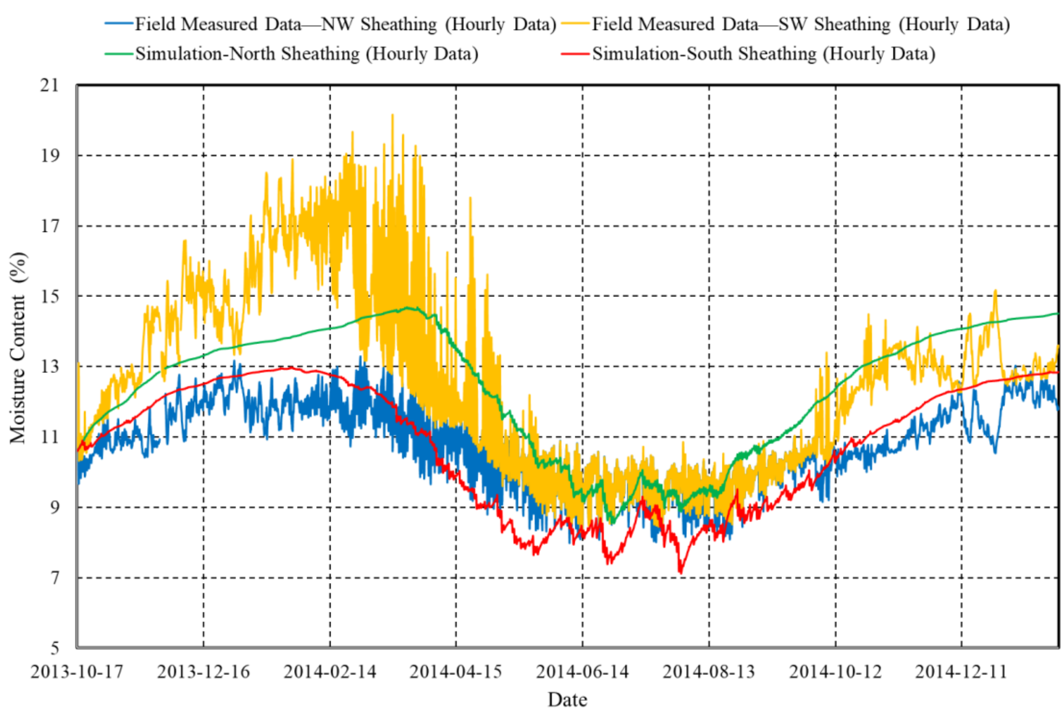


Figure 5-29. Hourly field measured MC level of plywood sheathing compared to simulation result in House I (KMHB House).

Figure 5-28 and Figure 5-29 show the comparison in hourly temperature and MC of plywood sheathing (north sheathing and south sheathing) compared with field measurements (NW sheathing and SW sheathing) in House I during the period from mid-Oct. 2013 to July 2015. Both simulated temperature and MC profiles follow the trend of field measurements with obvious fluctuations. The field measured temperature of SW sheathing varies between -27.85℃ and 50.72℃, while simulated temperature of south sheathing varies from -38.47℃ to 61.81℃. The field measured temperature of NW sheathing varies between -28.00℃ and 45.60℃, while the simulated temperature of north sheathing varies from -38.8℃ to 47.6℃. The temperature RMSD values of south and north sheathing are 14.05℃ and 12.57℃, respectively. The field measured MC of SW sheathing varies between 8.30% and 20.16%, while the simulated MC of south sheathing varies from 7.12% to 12.99%, with the RMSD is 2.21%. There are appearances of big differences during the winter months and a much smaller difference during the summer months. The field measured MC of NW sheathing varies between 7.99% and 13.29%, while the simulated MC of north sheathing varies from 8.55% to 14.69%, with the RMSD is 1.89%. The agreement between field measurements and simulations are better for north orientation. The simulated MC of plywood on south orientation is in general lower than that in north-oriented plywood, which makes sense because of the higher solar availability on the south. However, the field measured MC on the SW sheathing is much higher than that measured on the NW sheathing. This may be due to local effect of air leakage, therefore, a localized high MC level. Nevertheless, simulated MC profiles follow the trend of field measurements and the maximum difference in MC of south and north sheathing are 0.52% and 4.75%, respectively.

Maximum, minimum and average values of temperature difference between simulation results and field measurements of south sheathing are -41.71℃, 45.17℃ and -5.18%, and those of north sheathing are 32.12℃, -42.25℃ and -6.17℃, respectively. Maximum, minimum and average values of MC difference between simulation results and field measurements of south sheathing are 0.52%, -8.31% and -1.78%, and those of north sheathing are 4.75%, -1.63% and 1.53%, respectively. RMSD values of temperature and MC level of south and north sheathing are 14.05℃ & 12.57℃ and 2.21% & 1.89%.

5.4.1.2 Daily Data

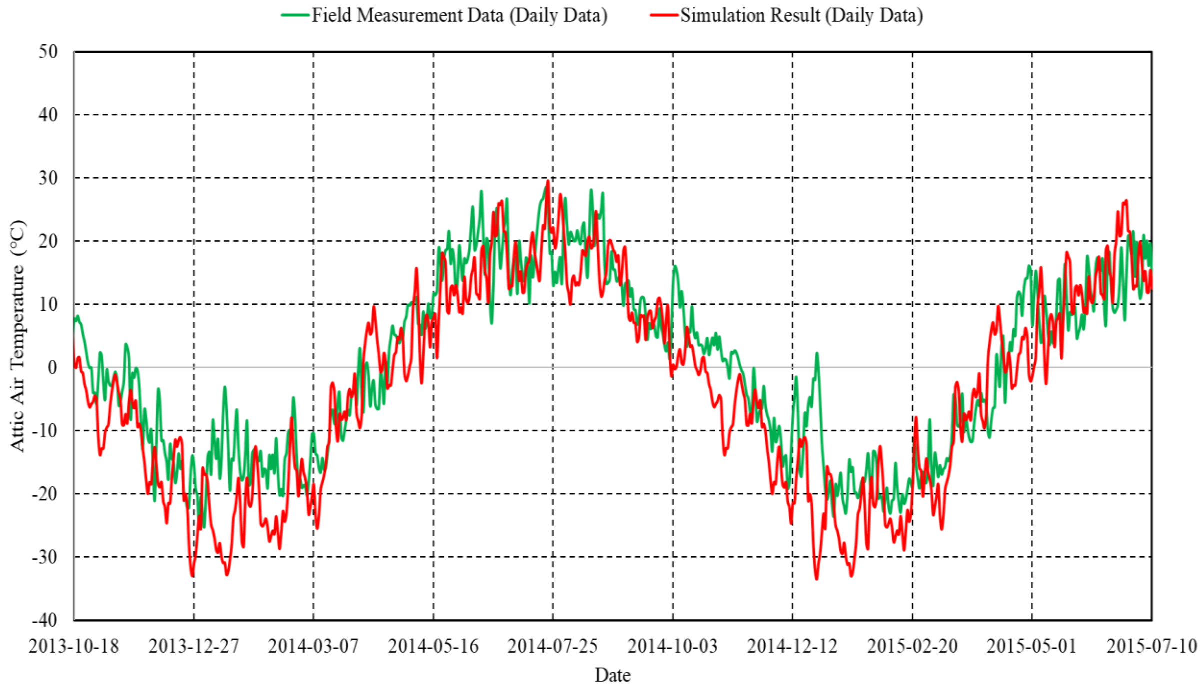


Figure 5-30. Daily field measured temperature of attic air compared to simulation result in House I (KMHB House).

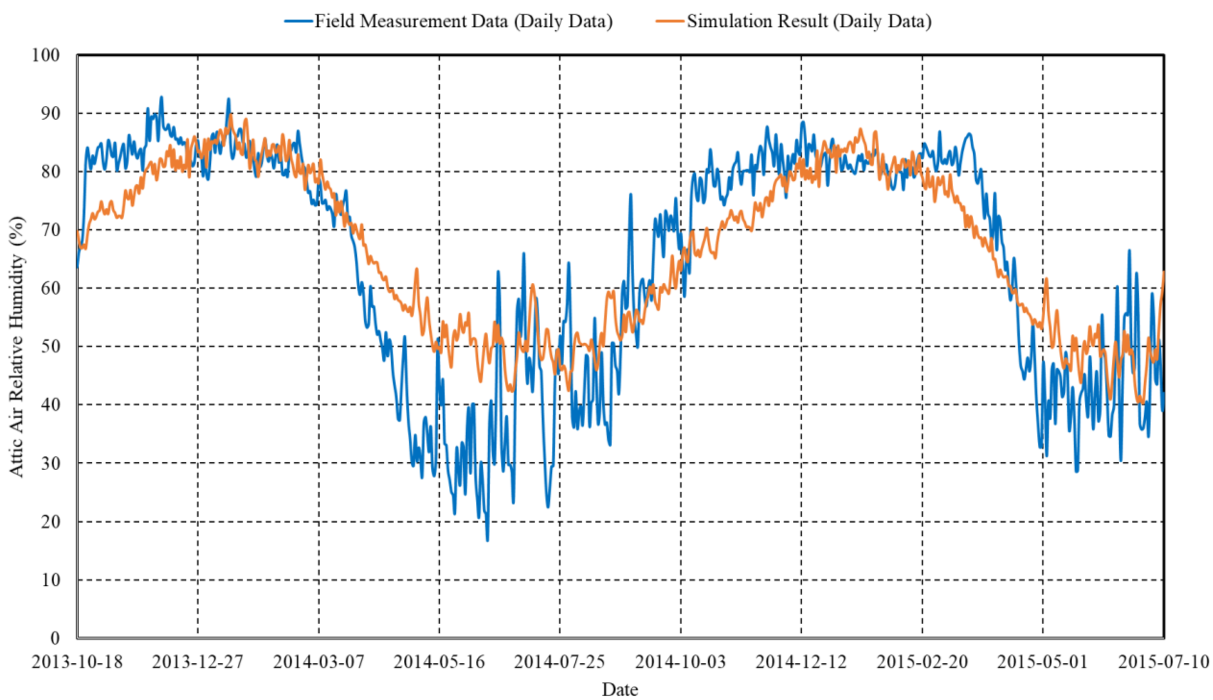


Figure 5-31. Daily field measured RH of attic air compared to simulation result in House I (KMHB House).

Figure 5-30 and Figure 5-31 show the comparison in daily averaged temperature and RH of ventilated attic between simulations and field measurements for House I during the period from mid-Oct. 2013 to July 2015. The daily averaged field measured temperatures vary between -25.51℃ and 28.51℃ with an average value of -0.10℃, while simulation results vary from -33.46℃ to 29.38℃. The daily temperature RMSD value between measurements and simulations is 7.83℃. The daily RH RMSD value between field measurements and simulations is 10.31%.

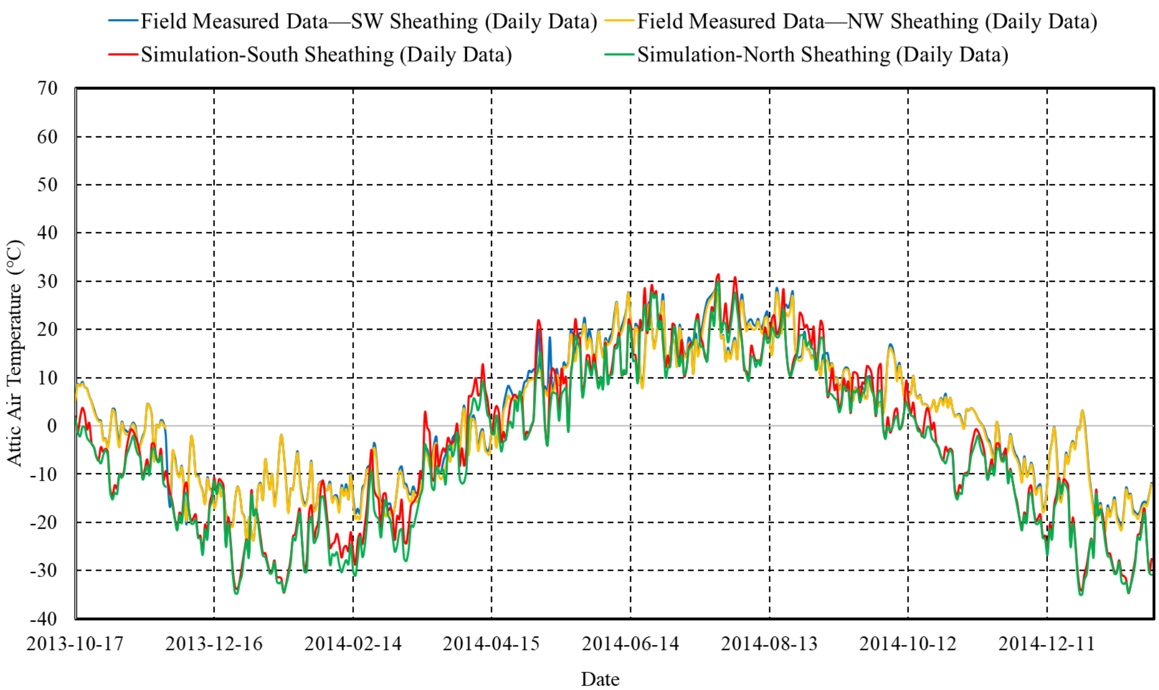


Figure 5-32. Daily field measured temperature of plywood sheathing compared to simulation result in House I (KMHB House).

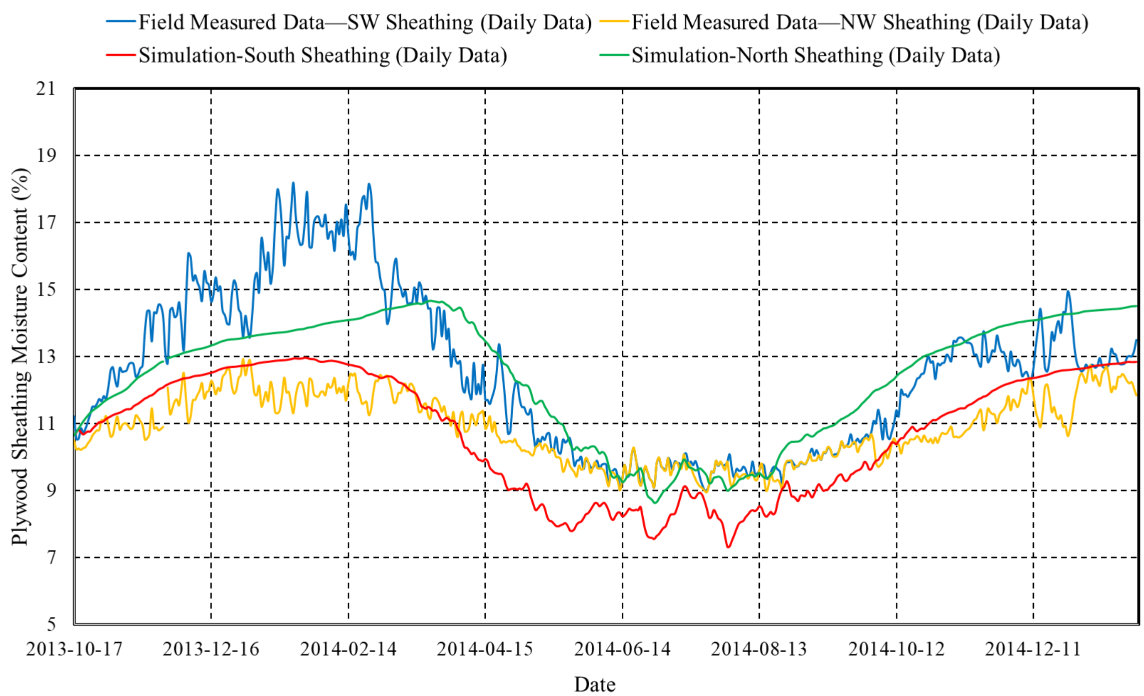


Figure 5-33. Daily field measured RH of plywood sheathing compared to simulation result in House I (KMHB House).

Figure 5-32 and Figure 5-33 show the comparison in daily temperature and MC of plywood sheathing (north sheathing and south sheathing) compared with field measurements (NW sheathing and SW sheathing) in House I during the period from mid-Oct. 2013 to July 2015. The daily averaged field measured temperature of SW sheathing varies between -23.90℃ and 28.57℃, while simulated temperature of south sheathing varies from -34.66℃ to 31.40℃. The daily averaged field measured temperature of NW sheathing varies between -24.13℃ and 28.37℃, while the simulated temperature of north sheathing varies from -35.03℃ to 29.90℃. The daily averaged temperature RMSD values of south and north sheathing are 9.34℃ and 9.65℃, respectively. The field measured MC of SW sheathing varies between 9.02% and 18.20%, while the simulated MC of south sheathing varies from 7.31% to 12.96%, and the RMSD value is 2.11%. The daily averaged field measured MC of NW sheathing varies between 8.95% and 12.92%, while the simulated MC of north sheathing varies from 8.63% to 14.66%, and the RMSD is 1.85%. And maximum difference in MC levels of south and north sheathing are 0.27% and 3.84%, respectively.

Maximum, minimum and average values of daily averaged temperature difference between simulations and field measurements of south sheathing are 14.41℃, -37.28℃ and -5.15℃, and those of north sheathing are 12.48℃, -38.22℃ and -6.19℃, respectively. Maximum, minimum and average values of MC difference between simulations and field measurements of south sheathing are 0.27%, -5.68% and -1.77%, and those of north sheathing are 3.84%, -1.24% and 1.52%, respectively.

5.4.1.3 Monthly Data

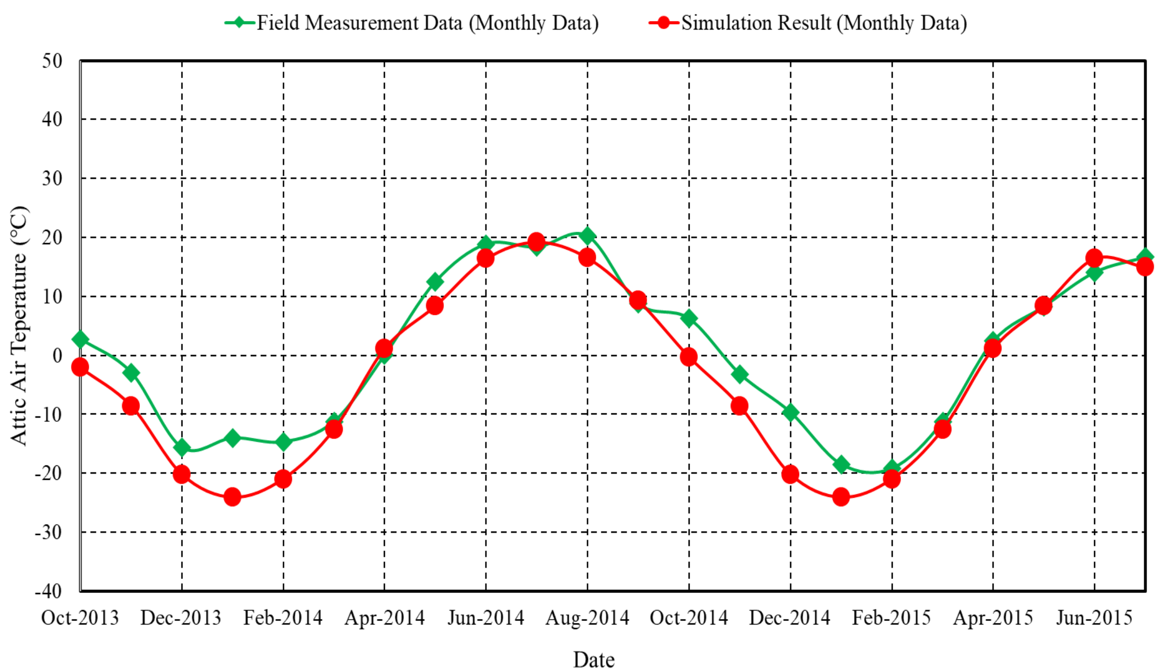


Figure 5-34. Monthly field measured temperature of attic air compared to simulation result in House I (KMHB House).

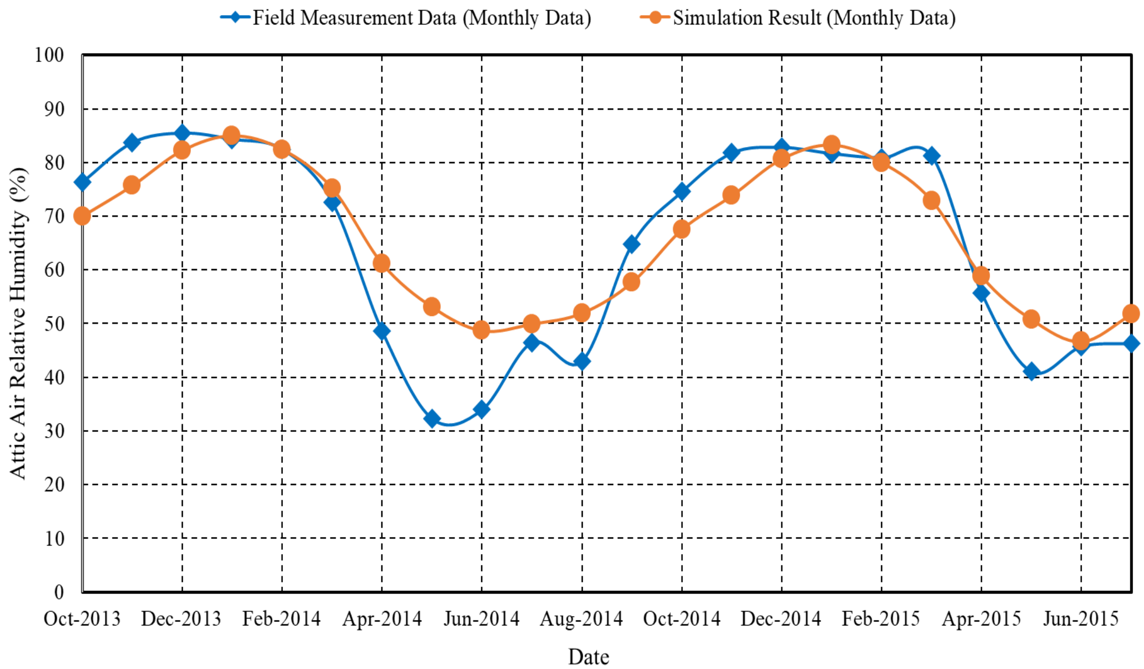


Figure 5-35. Monthly field measured RH of attic air compared to simulation result in House I (KMHB House).

Figure 5-34 and Figure 5-35 show the comparison in monthly temperature and RH of the ventilated attic between simulations and measurements for House I during the period from mid-Oct. 2013 to July 2015. The monthly averaged field measured temperatures vary between -19.21℃ and 20.21℃ with an average value of 0.40℃, while the simulations vary from -24.11℃ to 19.23℃. The monthly temperature RMSD between field measurements and simulations is 4.70℃. The monthly averaged field measured RH in attic space varies between 32.33% and 85.51% with an average value of 64.83%, while simulated RH in attic space varies from 46.69% to 85.02% with an average value of 66.36%. RH difference between simulations and field measurements are smaller during the winter months, the monthly RH RMSD between field measurements and simulations is 7.96%.

Maximum, minimum and average values of temperature and RH difference between simulations and field measurements are -10.52℃ & 2.36℃ & -3.27℃ and 20.79% & -8.27% & 1.53%, respectively. The RMSD values of temperature and RH of attic air in House I are 4.70℃ and 7.96%, respectively.

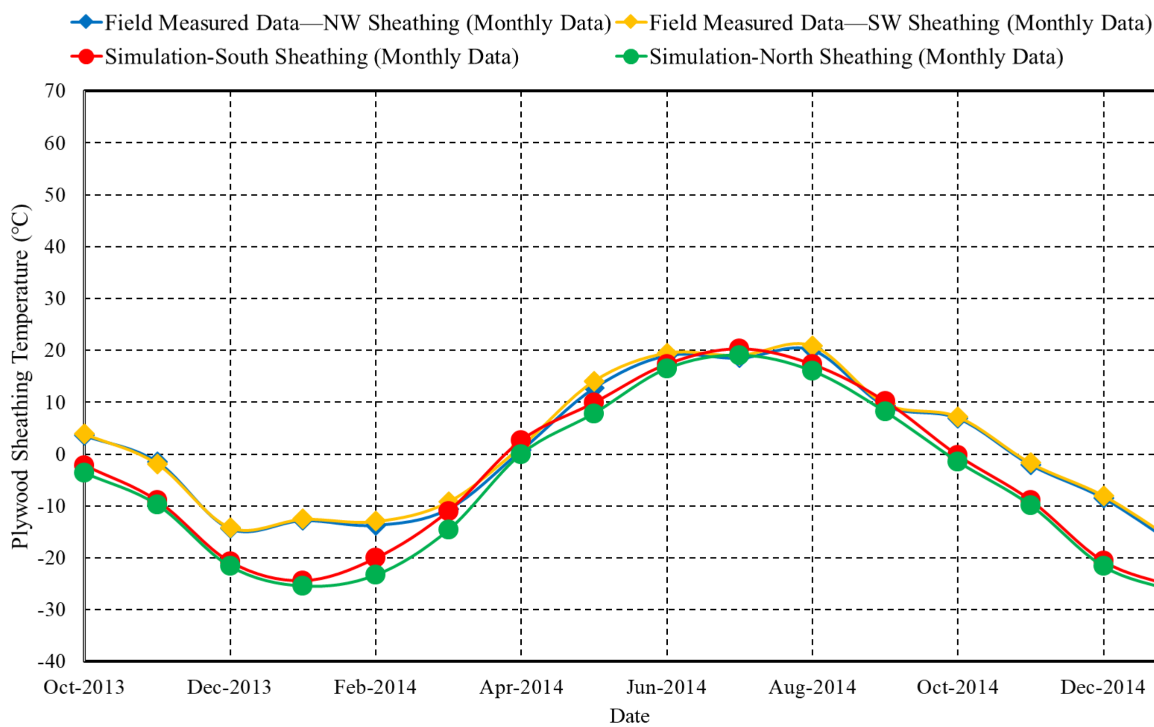


Figure 5-36. Monthly field measured temperature of plywood sheathing compared to simulation result in House I (KMHB House).

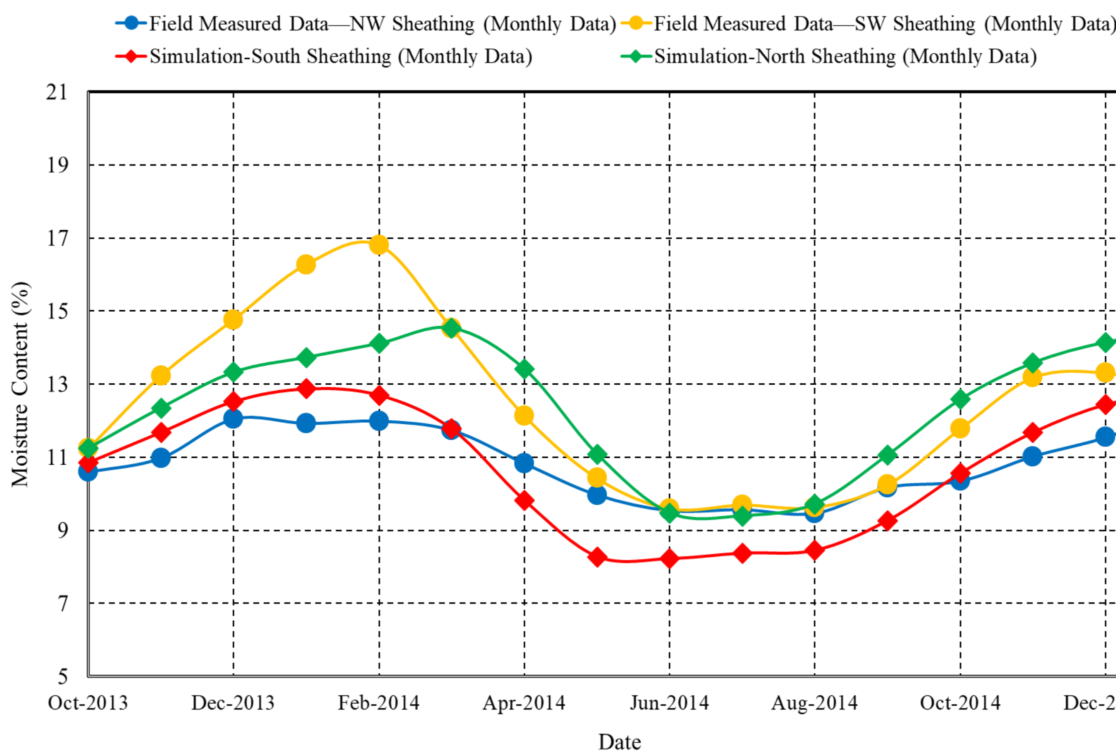


Figure 5-37. Monthly field measured MC level of plywood sheathing compared to simulation result in House I (KMHB House).

Figure 5-36 and Figure 5-37 show the comparison in monthly temperature and MC of plywood sheathing (north sheathing and south sheathing) compared with field measurements (NW sheathing and SW sheathing) in House I during the period from mid-Oct. 2013 to July 2015. The monthly averaged field measured temperature of SW sheathing varies between -16.80℃ and 20.92℃ with an average value of 1.18℃, while simulated temperature of south sheathing varies from -25.69℃ to 20.33℃ with an average value of -4.04℃. The monthly averaged field measured temperature of NW sheathing varies between -17.56℃ and 20.13℃ with an average value of 0.64℃, while simulated temperature of north sheathing varies from -26.49℃ to 19.03℃ with an average value of -5.62℃. Temperature RMSD values of south and north sheathing are 6.34℃ and 7.80℃, respectively. The field measured MC of SW sheathing varies between 9.60% and 16.80% with an average value of 12.48%, while the simulated MC of south sheathing varies from 8.22% to 12.87% with an average value of 10.77%, and the RMSD is 0.89%. The field measured MC of NW sheathing varies between 9.47% and 12.32% with an average value of 10.88%, while the simulated MC of north sheathing varies from 9.39% to 14.54% with an average value of 12.39%, and the RMSD is 1.21%. The maximum difference in MC between south and north sheathing are 0.95% and 1.55%, respectively.

Maximum, minimum and average values of monthly averaged temperature difference between simulations and field measurements of south sheathing are 1.95℃, -12.18℃ and -4.68℃, and those of north sheathing are -0.02℃, -13.61℃ and -6.81℃, respectively. Maximum, minimum and average values of MC difference between simulations and field measurements of south sheathing are 0.95%, -1.70% and -0.11%, and those of north sheathing are 1.55%, -2.69% and -0.10%, respectively.

5.4.2 Model Validation of House III: SIP House

Based on model setting described in Section 5.2.2, validated model results of House III are indicated in following sub-sections. Meanwhile, RH/T of attic space are selected as indicator. This sub-section presents validated WUFI Plus model results compared with field measured data in hourly data, daily data and monthly data. The best case is 30% ceiling air leakage rate with 0.09ACH un-intentional air infiltration rate which is used to present model validation result.

5.4.2.1 Hourly Data

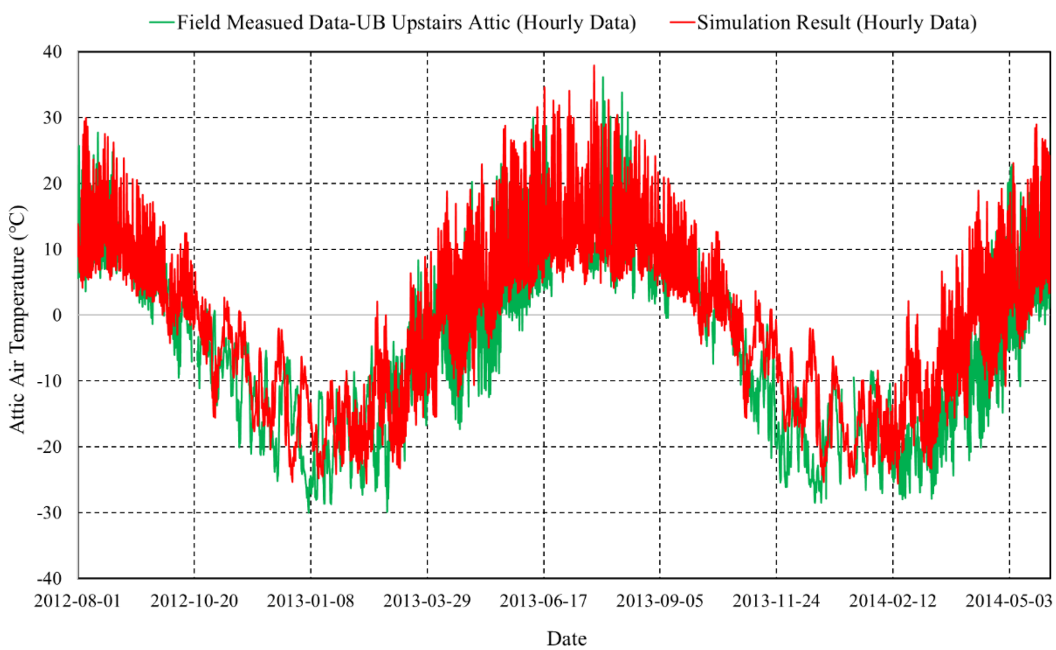


Figure 5-38. Hourly field measured temperature of attic air compared to simulation results in House III (SIP House).

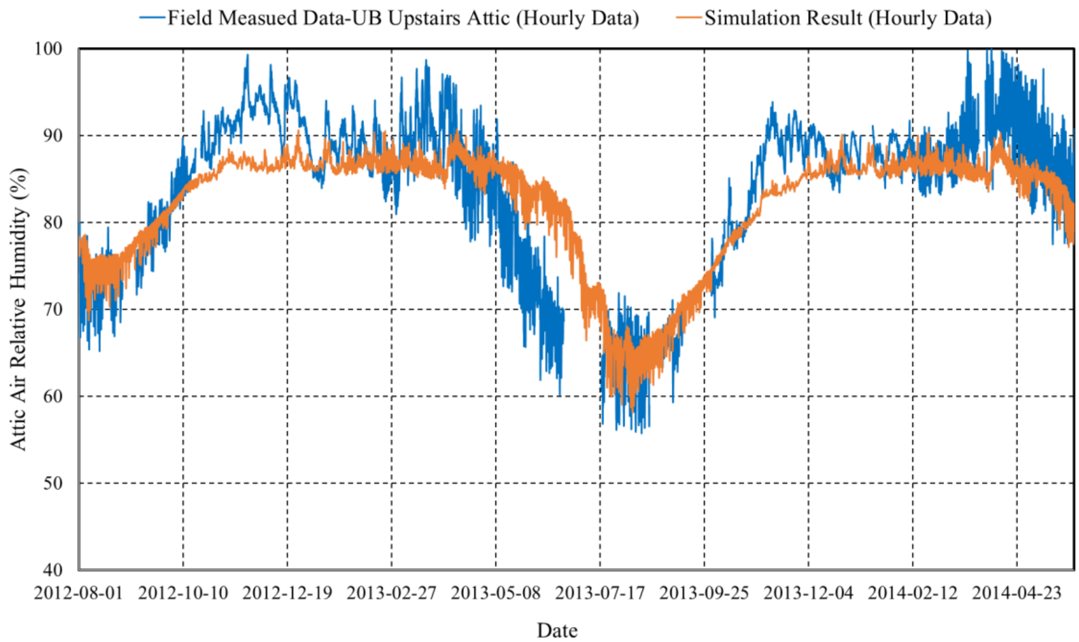


Figure 5-39. Hourly field measured RH of attic air compared to simulation results in House III (SIP House).

Figure 5-38 and Figure 5-39 show the comparison in hourly temperature and RH of the un-ventilated attic between simulations and measurements for House III during the period from mid-Oct. 2013 to July 2015. Both simulated temperature and RH profiles follow the trend of field measurements with obvious fluctuations. The field measured temperatures vary between -30.02℃ and 36.15℃, while the simulations vary from -25.59℃ to 37.92℃. The peaks of field measured temperature are higher than those of simulation results during the spring and summer months, while the differences in the fall and winter months are smaller. The hourly temperature RMSD value between field measurements and simulations are 7.32℃. And measured data is used as baseline. The field measured RH in attic space varies between 55.73% and 99.95% with an average value of 84.22%, while the simulated RH in attic space varies from 58.09% to 90.70% with an average value of 82.20%. The hourly RMSD values of RH between field measurements and simulations are 3.75%.

Maximum, minimum and average values of temperature and RH difference between simulation results and field measurements are 20.16℃ & -14.94℃ & 1.98℃ and 10.36% & -7.42% & 1.38%, respectively. The hourly RMSD values of temperature and RH of attic air in House III are 7.32℃ and 3.75%, respectively.

5.4.2.2 Daily Data

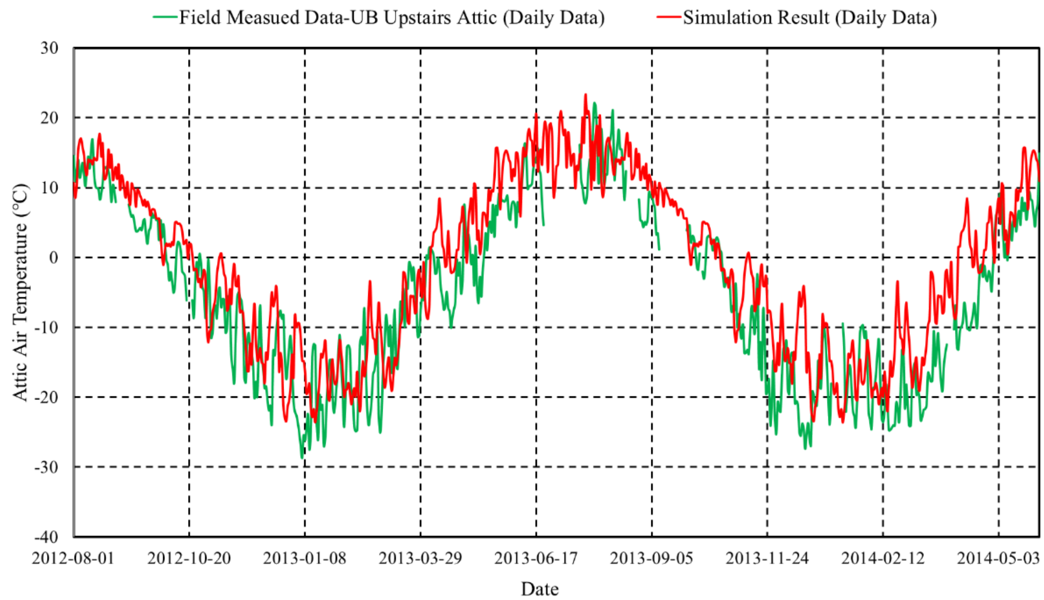


Figure 5-40. Daily field measured temperature of attic air compared to simulation results in House III (SIP House).

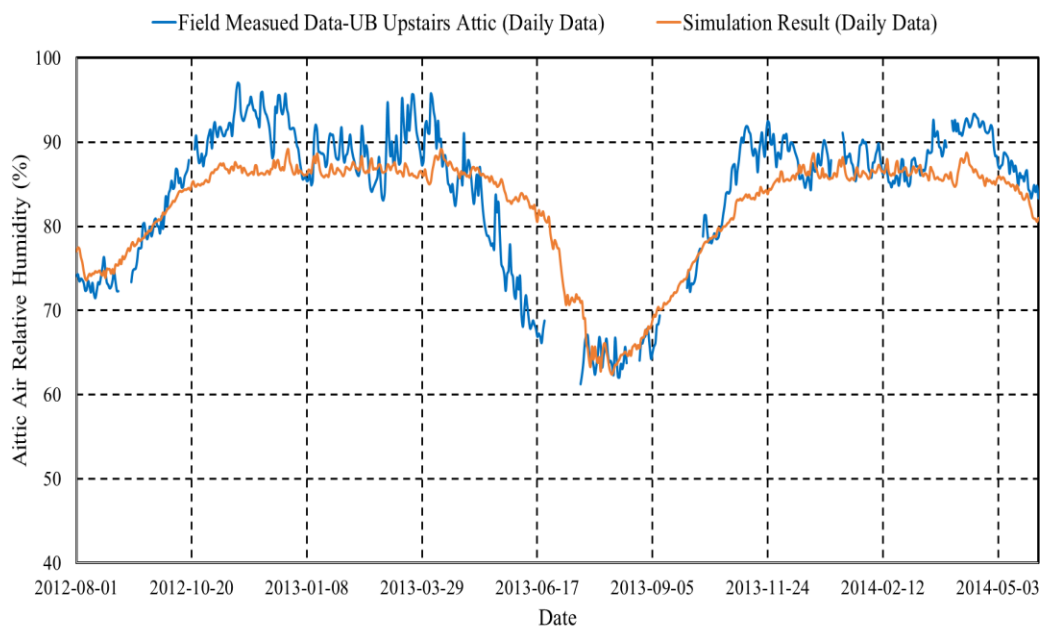


Figure 5-41. Daily field measured RH of attic air compared to simulation results in House III (SIP House).

Figure 5-40 and Figure 5-41 show the comparison in daily averaged temperature and RH of the un-ventilated attic between simulations and field measurements for House III during the period from mid-Oct. 2013 to July 2015. The daily averaged field measured temperatures vary between

-28.66℃ and 22.03℃, while the simulations vary from -23.64℃ to 23.27℃. The daily RMSD values of temperature between measurements and simulations are 6.94℃. The daily averaged field measured RH in attic space varies between 61.29% and 97.04% with an average value of 84.13%, while the simulated RH in attic space varies from 62.41% to 89.20% with an average value of 82.20%. The daily RMSD values of RH between measurements and simulations are 5.10%.

Maximum, minimum and average values of temperature and RH difference between simulations and field measurements are 20.47℃ & -14.21℃ & 3.57℃ and 15.64% & -10.39% & -1.10%, respectively. The daily RMSD values of temperature and RH of attic air in House III are 6.94℃ and 5.10%, respectively.

5.4.2.3 Monthly Data

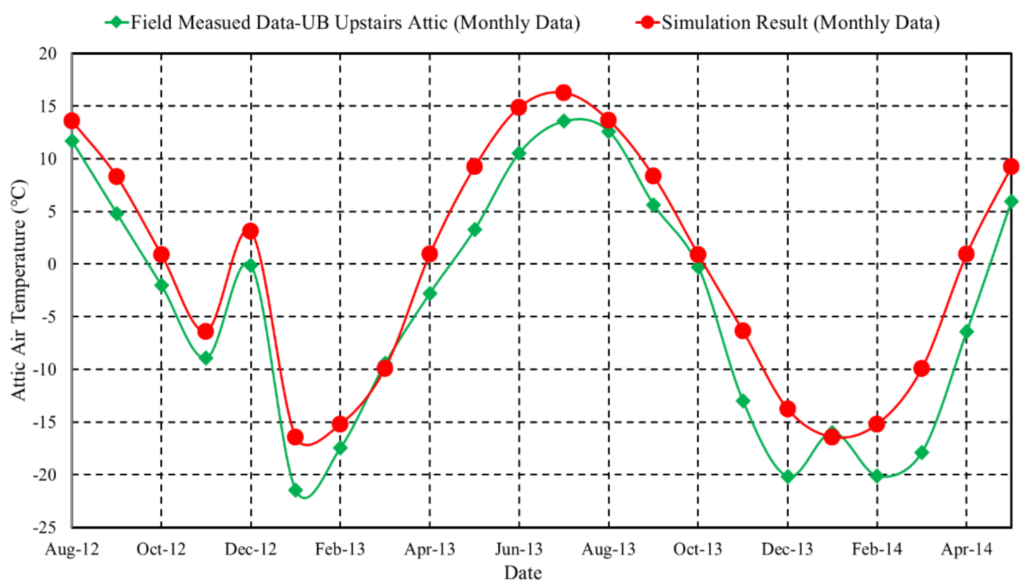


Figure 5-42. Monthly field measured temperature of attic air compared to simulation results in House III (SIP House).

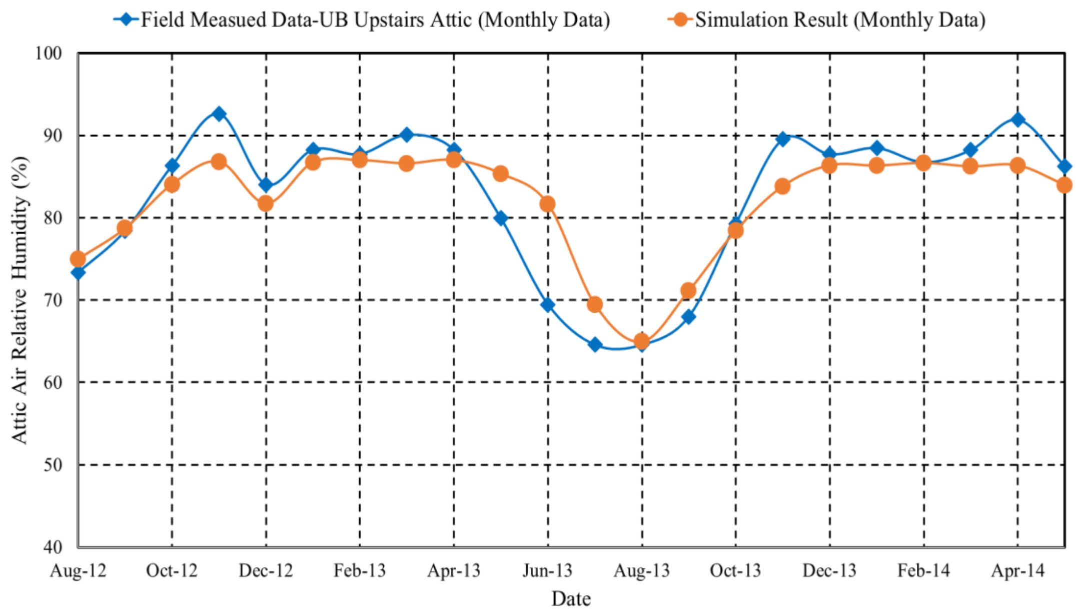


Figure 5-43. Monthly field measured RH of attic air compared to simulation results in House III (SIP House).

Figure 5-42 and Figure 5-43 show the comparison in monthly temperature and RH of the ventilated attic between simulations and field measurements for House III during the period from mid-Oct. 2013 to July 2015. The monthly averaged field measured temperatures vary between -21.44℃ and 13.56℃, while the simulations vary from -16.43℃ to 16.28℃. The monthly temperature RMSD between field measurements and simulations are 4.33℃. The monthly averaged field measured RH in attic space varies between 64.56% and 92.60% with an average value of 82.44%, while the simulated RH in attic space varies from 64.95% to 87.00% with an average value of 82.01%.

Maximum, minimum and average values of temperature and RH difference between simulations and field measurements data are 7.96℃ & -0.46℃ & 3.57℃ and 12.18% & -5.82% & -0.43%, respectively. The values of temperature and RH of attic air in House III are 4.33℃ and 4.11%.

5.4.3 Comparison of House I in Kuujjuaq and Iqaluit under Same Conditions

To further verify the universality of WUFI Plus model of ventilated and un-ventilated attic, validated House I and House III models are set in same conditions for comparison of simulation results in both Kuujjuaq and Iqaluit. Simulated results' comparison based on validated hygrothermal model is intended to provide more solid evidence on model validation. The purpose of performing the same model in different locations is to further investigate reliability of WUFI Plus model. Validated models are excepted to be applied in other locations to discuss hygrothermal performance of ventilated and un-ventilated attics, and then design recommendations can be summarized for key technical points. The unique variable of further validated model is location and other parameters are set in the same circumstances.

For ventilated attic in House I, the best scenario case (1ACH ventilation rate + 10% ceiling air leakage rate) after model validation is selected as benchmark model. To ensure the same simulation environment, also as far as possible in line with the general actual situation, indoor conditions choose "EN 15026-Normal Moisture Load" from WUFI Plus database to instead and initial relative humidity of plywood sheathing changes to 80%. Other detail settings in WUFI Plus model remain unchanged and the same model of House I is performed in both Kuujjuaq and Iqaluit for comparison of simulation results.

Comparison of simulation results of House I in Kuujjuaq and Iqaluit is presented in following sub-sections:

5.4.3.1 Hourly Data

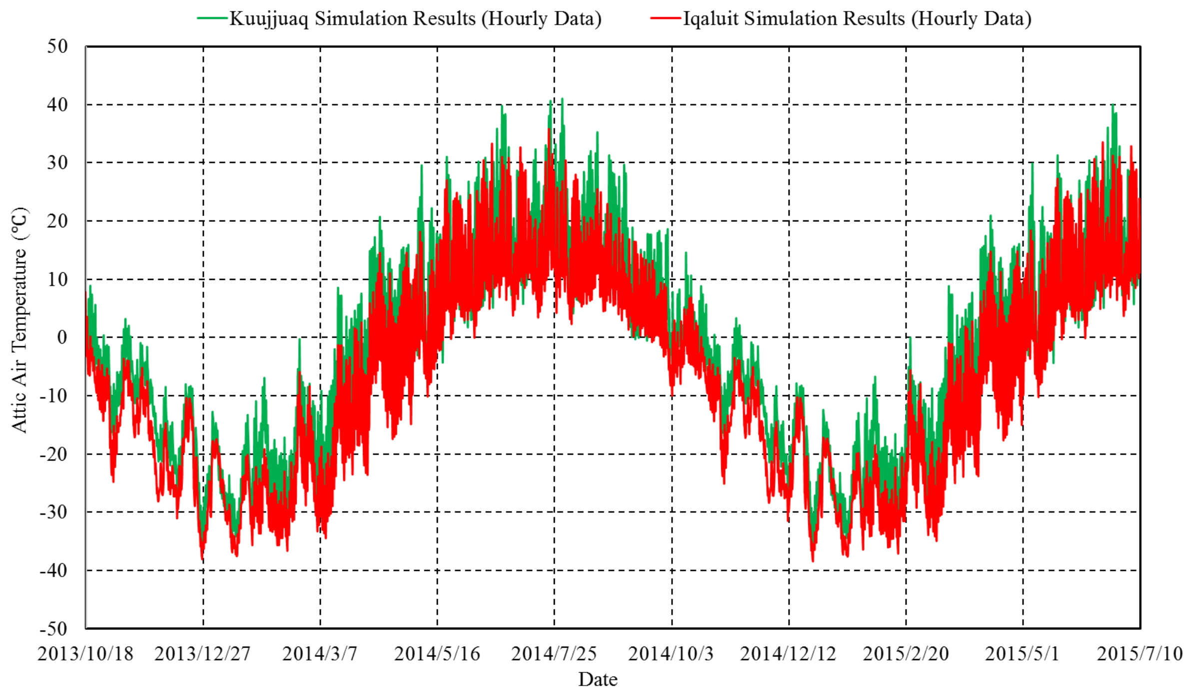


Figure 5-44. Hourly simulation results (attic air temperature) of comparison between Kuujjuaq and Iqaluit in House I (KMHB House).

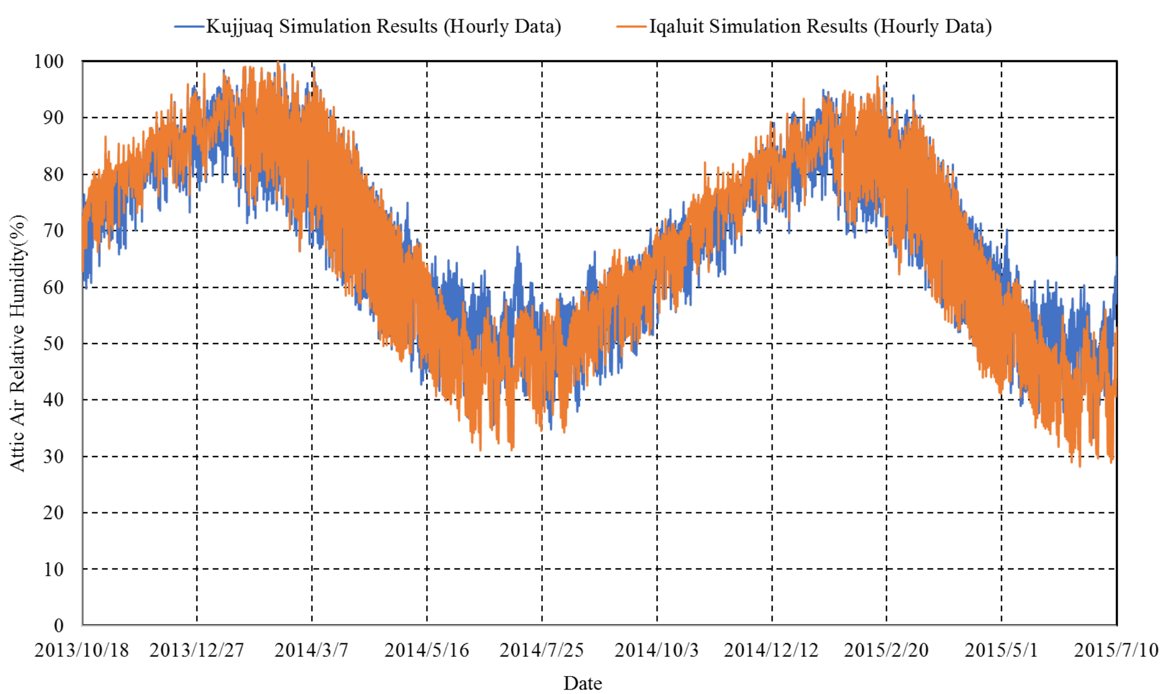
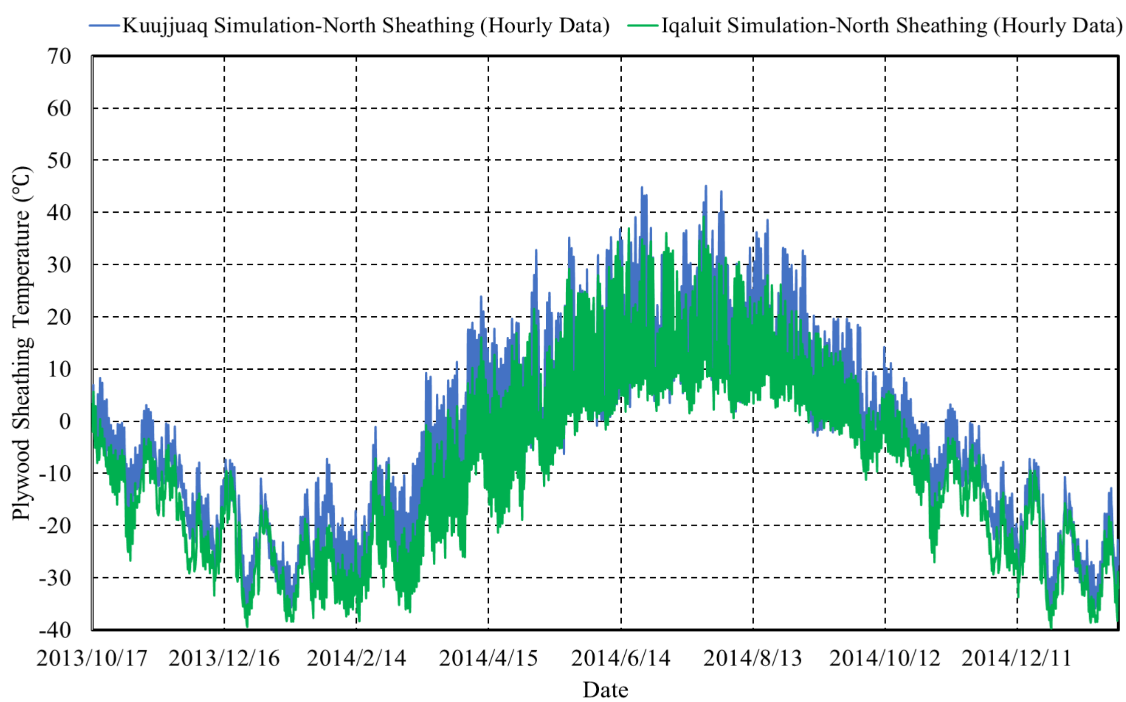


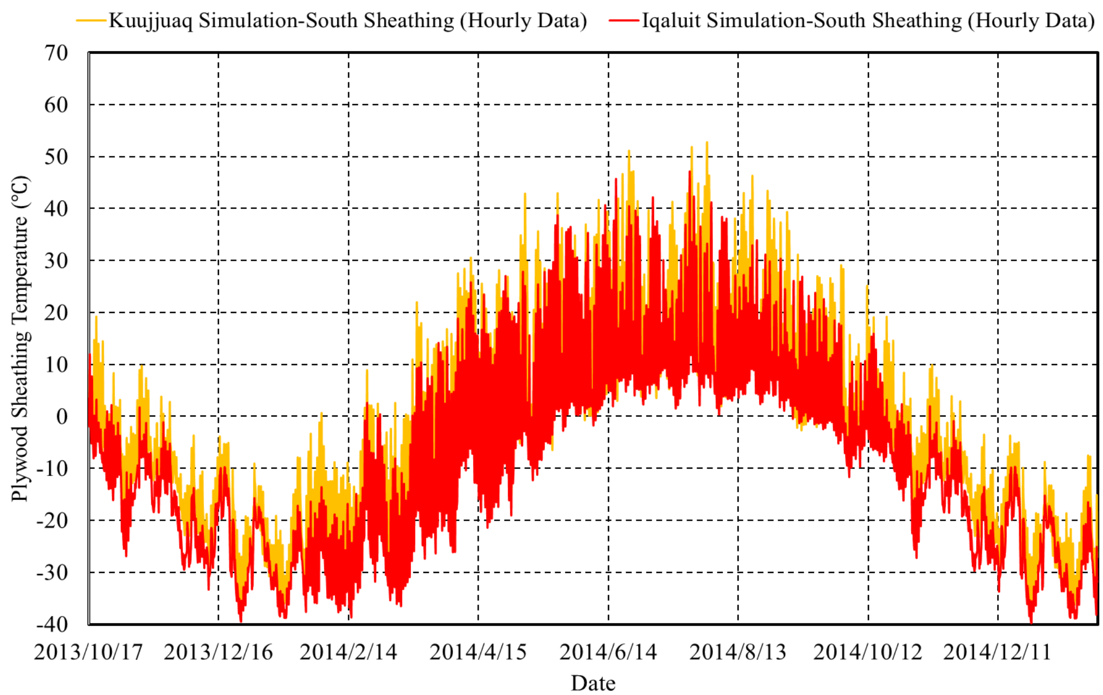
Figure 5-45. Hourly simulation results (attic air temperature) of comparison between Kuujjuaq and Iqaluit in House I (KMHB House).

Figure 5-44 and Figure 5-45 show comparison of hourly simulation results (attic air temperature and RH) of ventilated attic between different locations (Kuujjuaq and Iqaluit) for House I during the period from mid-Oct. 2013 to July 2015. Both simulated temperature and RH profiles in different locations almost coincide with obvious hourly fluctuations. Simulation results of attic air temperature and RH in Kuujjuaq range from -36.24℃ to 41.02℃ with an average value of -3.55℃ and from 33.25% to 100% with an average value of 69.72%, respectively. Simulation results of attic air temperature and RH in Iqaluit range from -38.46℃ to 35.83℃ with an average value of -7.62℃ and from 28.17% to 100% with an average value of 68.66%, respectively. There are no significant differences of simulation results of attic air in House I between Kuujjuaq and Iqaluit. However, in general, simulation results of attic air (temperature and RH) in Kuujjuaq are slightly higher than those in Iqaluit.

Maximum, minimum and average values of temperature and RH difference of simulation results between Kuujjuaq and Iqaluit are 23.54℃ & -22.05℃ & -4.06℃ and 24.28% & -14.96% & 1.07%, respectively. Hourly RMSD values of temperature and RH between Kuujjuaq and Iqaluit are 5.67℃ and 4.64%.



a) Temperature of simulation results of North sheathing between Kuujjuaq and Iqaluit.



b) Relative Humidity of simulation results of North sheathing between Kuujjuaq and Iqaluit.

Figure 5-46. Hourly simulation results (plywood sheathing temperature) of comparison between Kuujjuaq and Iqaluit in House I (KMHB House).

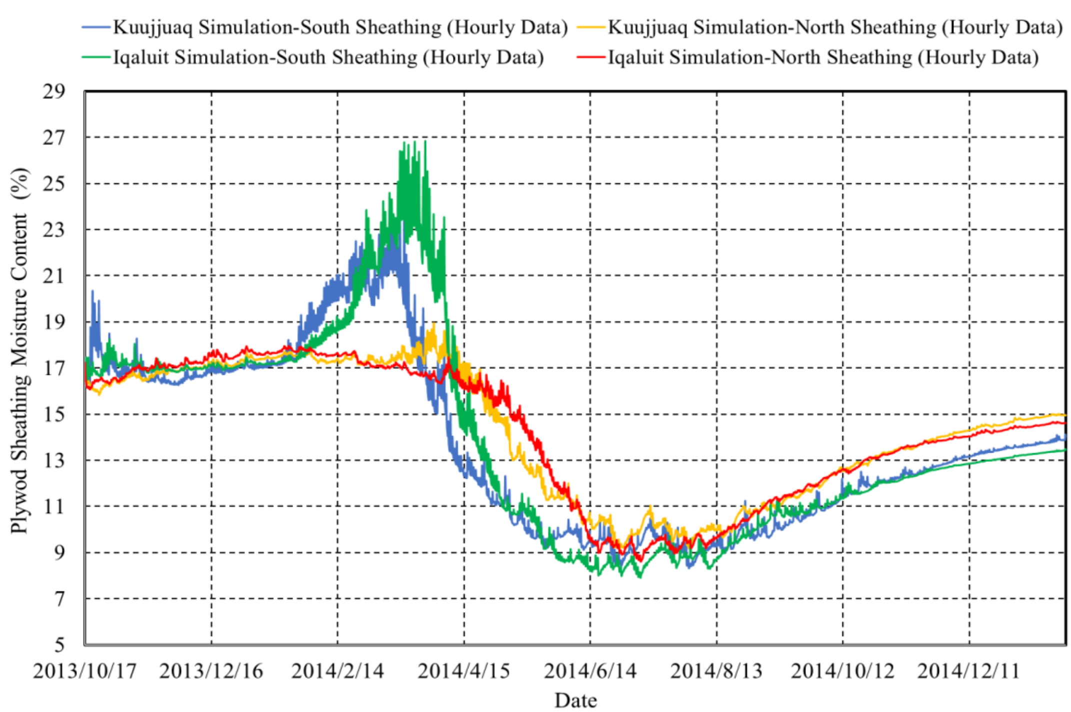


Figure 5-47. Hourly simulation results (plywood sheathing MC level) of comparison between Kuujjuaq and Iqaluit in House I (KMHB House).

Figure 5-46 and Figure 5-47 show hourly compared simulation results of plywood sheathing (north and south sheathing) in House I located between Kuujjuaq and Iqaluit during the period from mid-Oct. 2013 to July 2015. Both simulated temperature and MC profiles in Kuujjuaq follow the trend of those in Iqaluit with obvious fluctuations. Simulated temperatures of South and North sheathing in Kuujjuaq are in the range of -37.49℃~52.76℃ with an average value of -4.10℃ and -37.79℃~45.11℃ with an average value of -5.02℃, respectively. Simulated temperatures of South and North sheathing in Iqaluit are in the range of -39.81℃~47.13℃ with the average of -8.35℃ and -39.73℃~39.22℃ with the average of -9.09℃, respectively. The temperature RMSD values of south and north sheathing between Kuujjuaq and Iqaluit are 6.61℃ and 5.73℃. It's obvious that temperature profiles almost coincide for both North and South sheathing in Kuujjuaq and Iqaluit, while a better agreement can be found in North sheathing. Meanwhile, simulated temperatures in Kuujjuaq are generally higher than those in Iqaluit.

Simulated MC levels of South and North sheathing in Kuujjuaq are in the range of 8.32%~24.84% with an average value of 13.66% and 9.18%~18.96% with an average value of 14.25%, respectively. Simulated moisture levels of South and North sheathing in Iqaluit are in the range of 7.90℃~26.84℃ with an average value of 13.86% and 8.60%~17.96% with an average value of 14.22%, respectively. The MC RMSD values of south and north sheathing between Kuujjuaq and Iqaluit are 1.41% and 0.54%. The agreement of simulated MC levels of plywood sheathing between Kuujjuaq and Iqaluit are better for North sheathing. In general, simulated MC value of north sheathing is higher than which of south sheathing in both Kuujjuaq and Iqaluit. This phenomenon is caused by distribution of solar radiation, the amount of solar radiation in south is higher than which in north. The annual average amount of direct solar radiation in Iqaluit is round 162.27 W/m^2 which is significantly higher than that in Kuujjuaq (around 60W/m^2). Therefore, simulated MC values in Kuujjuaq are higher than those in Iqaluit for both north and south sheathing.

Maximum, minimum and average values of temperature difference between Kuujjuaq and Iqaluit of South sheathing are 33.65℃, -34.98℃ and -4.25℃, and those of North sheathing are 25.19℃, -27.69℃ and -4.07℃, respectively. Maximum, minimum and average values of MC difference between Kuujjuaq and Iqaluit of south sheathing are 9.09%, -3.22% and 0.21%, and those of north sheathing are 2.00%, -2.14% and -0.03%, respectively. The RMSD values of temperature and MC level of south and north sheathing between Kuujjuaq and Iqaluit are 6.61℃ & 5.73℃ and 1.41% & 0.54%.

5.4.3.2 Daily Data

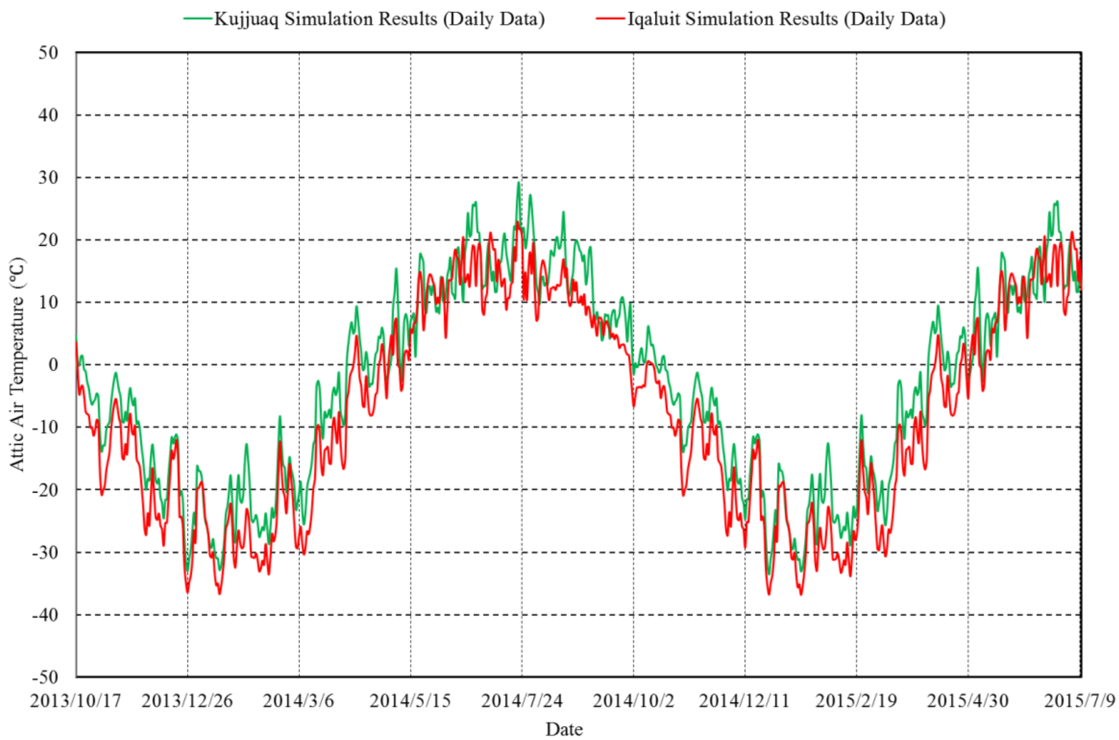


Figure 5-48. Daily simulation results (attic air temperature) of comparison between Kuujjuaq and Iqaluit in House I (KMHB House).

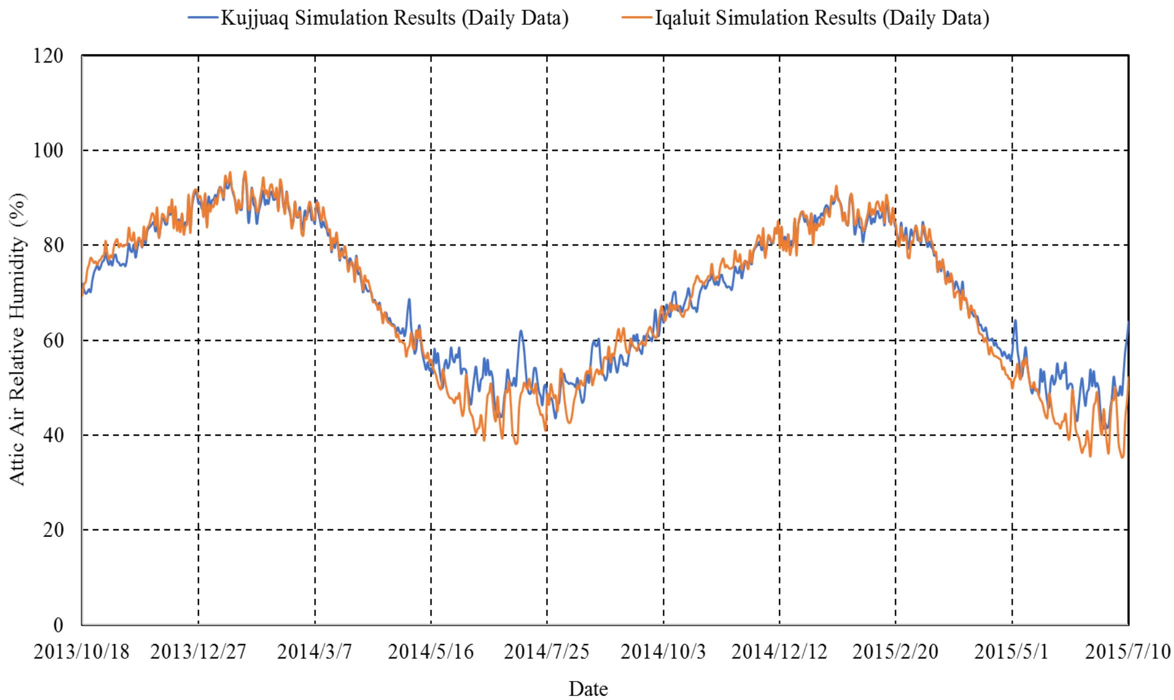


Figure 5-49. Daily simulation results (attic air RH) of comparison between Kuujjuaq and Iqaluit in House I (KMHB House).

Figure 5-48 and Figure 5-49 show the comparison in daily averaged simulated temperature and RH of the ventilated attic between Kuujjuaq and Iqaluit for House I during the period from mid-Oct. 2013 to July 2015. The daily averaged simulated temperatures in Kuujjuaq vary between -33.53℃ and 29.16℃ with an average value of -3.53℃, while those in Iqaluit vary from -36.84℃ to 22.86℃ with an average value of -7.59℃. The daily averaged simulated RH values in Kuujjuaq vary between 41.43% and 94.90% with an average value of 69.71%, while those in Iqaluit vary from 35.28% to 95.50% with an average value of 68.64%. The daily RMSD value of simulated temperature between Kuujjuaq and Iqaluit is 1.07℃. The daily RMSD value of simulated RH between Kuujjuaq and Iqaluit is 0.84%.

Maximum, minimum and average values of temperature and RH difference of simulation results between Kuujjuaq and Iqaluit are 10.41℃ & -13.56℃ & -4.06℃ and 7.70% & -18.33% & -1.07%, respectively. Daily RMSD values of temperature and RH between Kuujjuaq and Iqaluit are 1.07℃ and 0.84%.

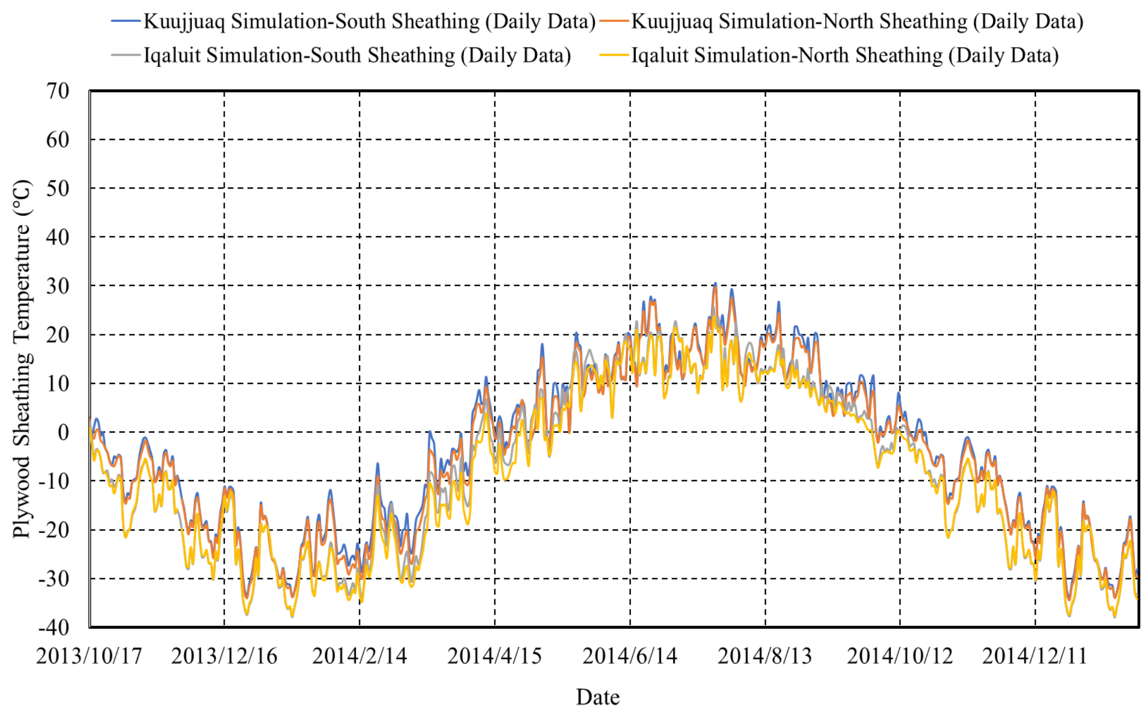


Figure 5-50. Daily simulation results (plywood sheathing temperature) of comparison between Kuujjuaq and Iqaluit in House I (KMHB House).

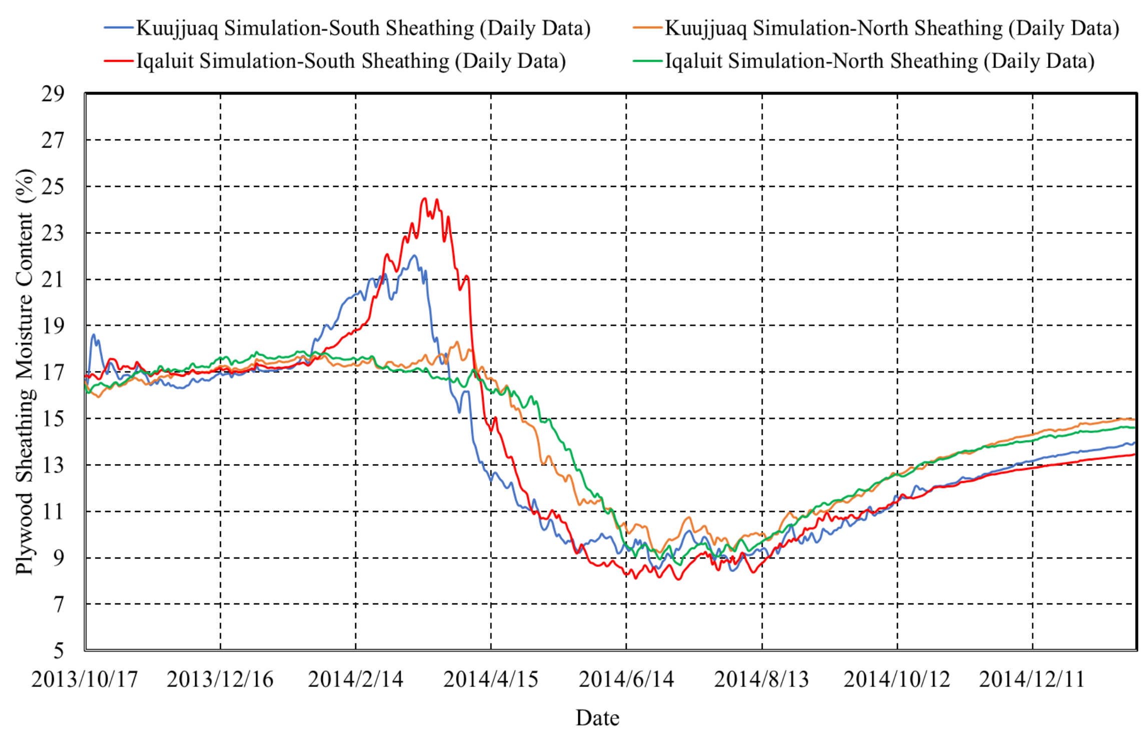


Figure 5-51. Daily simulation results (plywood sheathing MC level) of comparison between Kuujjuaq and Iqaluit in House I (KMHB House).

Figure 5-50 and Figure 5-51 show the comparison in daily temperature and MC of plywood sheathing (South sheathing and North sheathing) between Kuujjuaq and Iqaluit in House I during the period from mid-Oct. 2013 to July 2015. The daily averaged simulated temperature of South and North sheathing in Kuujjuaq varies from -34.00℃ to 30.37℃ with an average value of -4.11℃ and from -34.44℃ to 29.49℃ with an average value of -5.02℃. The daily averaged simulated temperatures of South and North sheathing in Iqaluit vary from -37.98℃ to 25.49℃ with an average value of -8.36℃ and from -37.71℃ to 23.64℃ with an average value of -9.09℃. It's easy to see that all temperature curves almost coincide with obvious daily fluctuations. Meanwhile, simulated temperatures in Kuujjuaq are slightly higher than those in Iqaluit. However, there are few temperature differences between South and North sheathing in both Kuujjuaq and Iqaluit, the maximum values of temperature difference are 12.99℃ and 11.58℃, respectively. Temperature RMSD values between South and North sheathing in Kuujjuaq and Iqaluit are 5.61℃ and 5.14℃, respectively.

The daily averaged simulated MC levels of South and North sheathing in Kuujjuaq vary from 8.45% to 22.02% with an average value of 13.66% and from 9.24% to 18.31% with an average value of 14.25%. The daily averaged simulated MC levels of South and North sheathing in Iqaluit vary from vary from 8.05% to 24.47% with an average value of 13.86% and from 8.70% to 17.89% with an average value of 14.22%. In general, MC levels of south sheathing are lower than those of north sheathing, except for the period from mid-Feb. 2014 to mid-April 2014. This phenomenon is due to solar radiation distribution, which is explained in sub-section 5.4.3.1.

Maximum, minimum and average values of daily averaged temperature difference between simulations and field measurements of south sheathing are 12.99℃, -15.44℃ and -4.25℃, and those of north sheathing are 11.58℃, -14.91℃ and -4.07℃, respectively. Maximum, minimum and average values of MC difference between simulations and field measurements of south sheathing are 6.69%, -1.74% and 0.21%, and those of north sheathing are 1.82%, -1.56% and -0.03%, respectively.

5.4.3.3 Monthly Data

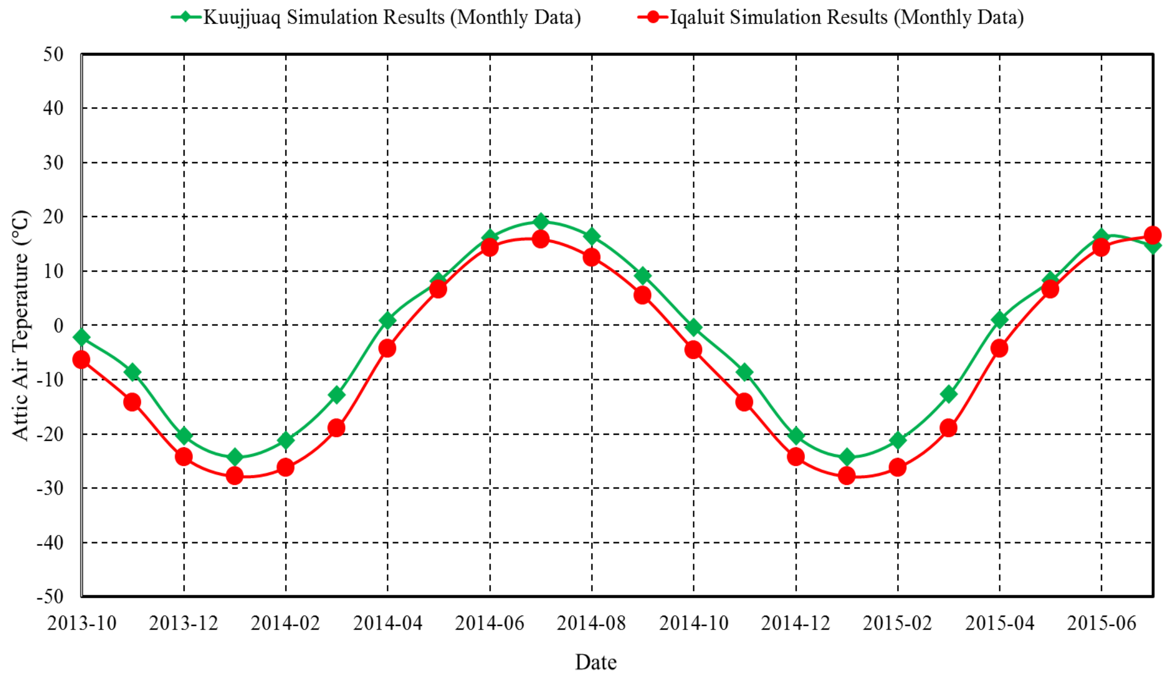


Figure 5-52. Monthly simulation results (attic air temperature) of comparison between Kuujjuaq and Iqaluit in House I (KMHB House).

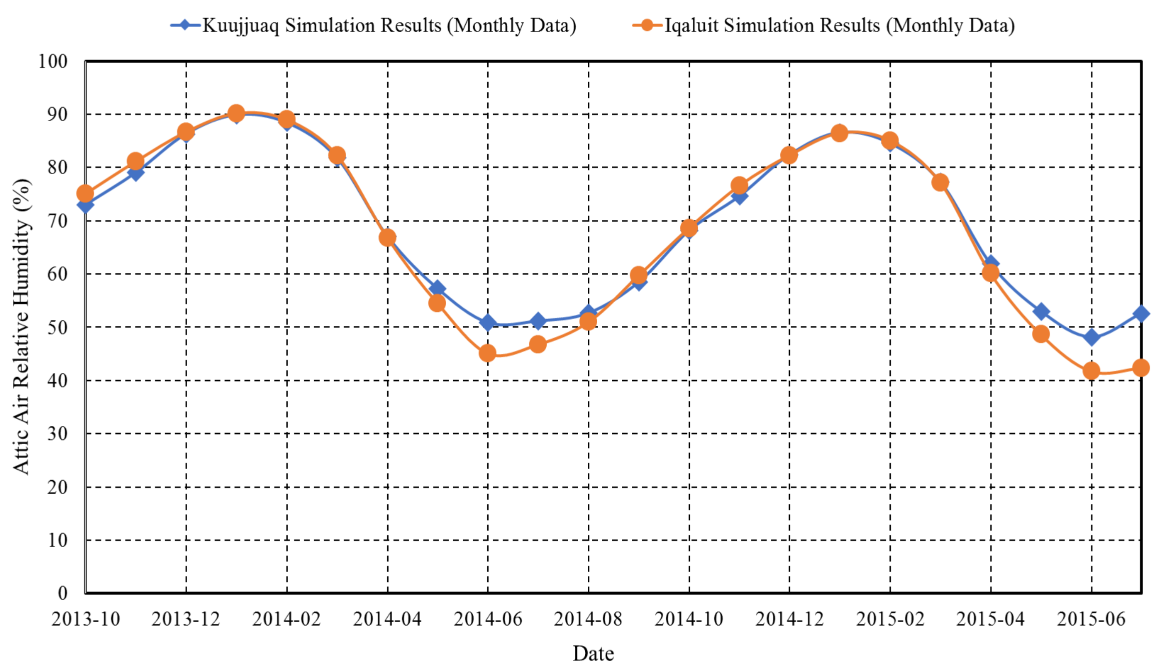


Figure 5-53. Monthly simulation results (attic air RH) of comparison between Kuujjuaq and Iqaluit in House I (KMHB House).

Figure 5-52 and Figure 5-53 show the comparison in monthly averaged simulated temperature and RH of the ventilated attic between Kuujjuaq and Iqaluit for House I during the period from mid-Oct. 2013 to July 2015. The monthly averaged simulated temperatures in Kuujjuaq vary between -24.20℃ and 19.04℃ with an average value of -3.02℃, while those in Iqaluit vary from -27.79℃ to 16.52℃ with an average value of -6.82℃. The monthly averaged simulated RH values in Kuujjuaq vary between 48.17% and 89.90% with an average value of 69.33%, while those in Iqaluit vary from 41.75% to 90.15% with an average value of 68.06%.

Maximum, minimum and average values of temperature and RH difference of simulation results between Kuujjuaq and Iqaluit are 16.42℃ & -27.86℃ & -6.91℃ and 2.10% & -10.24% & -1.27%, respectively. Monthly RMSD values of temperature and RH between Kuujjuaq and Iqaluit are 4.22℃ and 3.35%. The monthly RMSD value of simulated temperature between Kuujjuaq and Iqaluit is 4.22℃. The monthly RMSD value of simulated RH between Kuujjuaq and Iqaluit is 3.35%.

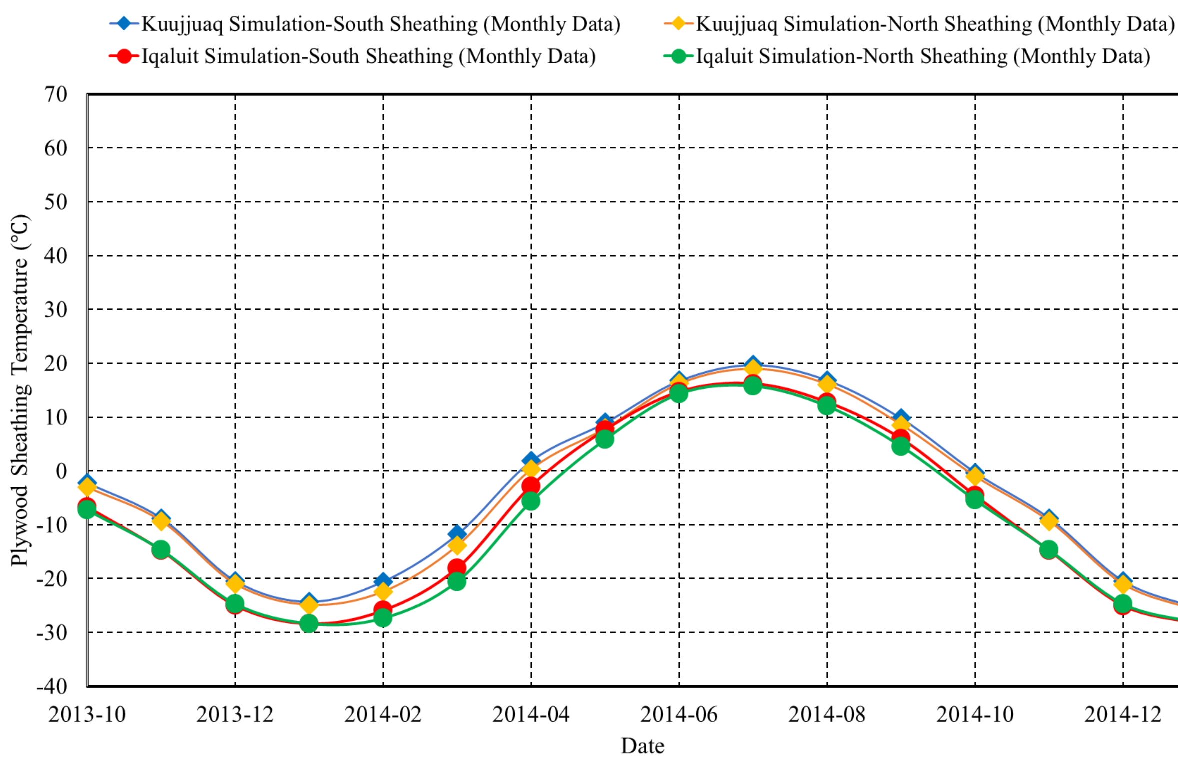


Figure 5-54. Monthly simulation results (plywood sheathing temperature) of comparison between Kuujjuaq and Iqaluit in House I (KMHB House).

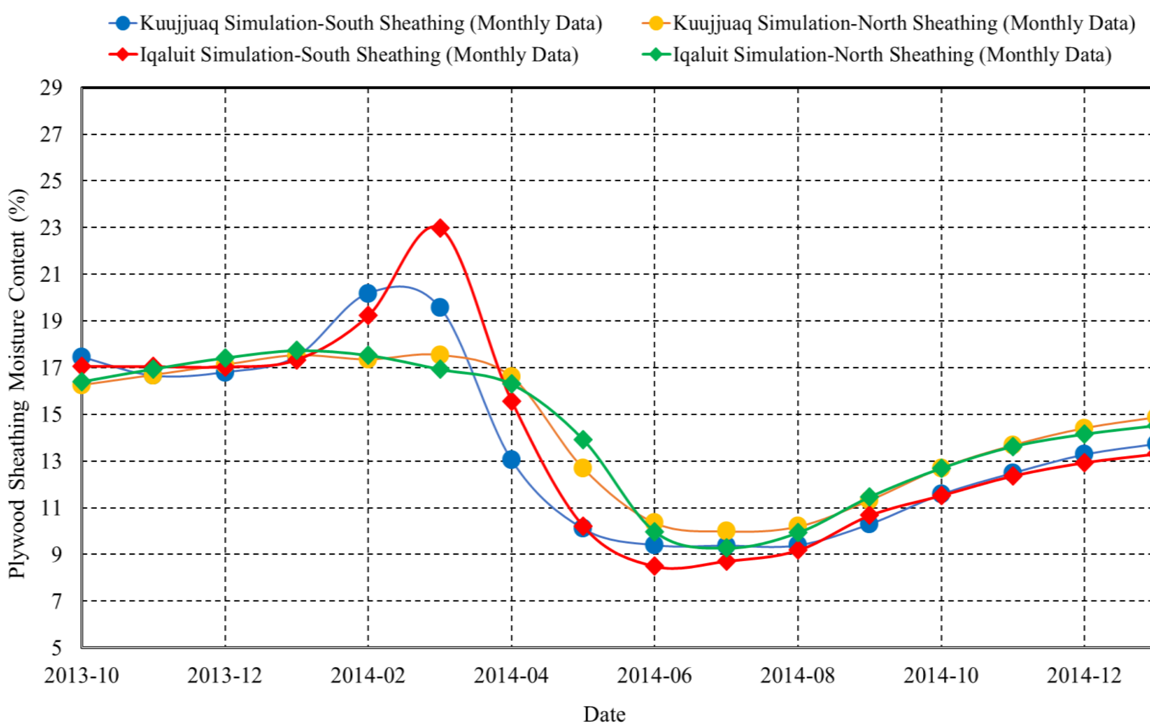


Figure 5-55. Monthly simulation results (plywood sheathing MC level) of comparison between Kuujjuaq and Iqaluit in House I (KMHB House).

Figure 5-54 and Figure 5-55 show the comparison in monthly temperature and MC of plywood sheathing (South sheathing and North sheathing) between Kuujjuaq and Iqaluit in House I during the period from mid-Oct. 2013 to July 2015. The monthly averaged simulated temperature of South and North sheathing in Kuujjuaq varies from -25.58℃ to 19.70℃ with an average value of -4.35℃ and from -26.01℃ to 18.95℃ with an average value of -5.26℃. The monthly averaged simulated temperatures of South and North sheathing in Iqaluit vary from -28.42℃ to 16.17℃ with an average value of -8.60℃ and from -28.37℃ to 15.78℃ with an average value of -9.33℃. It's easy to see that all temperature curves almost coincide with obvious daily fluctuations. Meanwhile, simulated temperatures in Kuujjuaq are slightly higher than those in Iqaluit. However, there are few temperature differences between South and North sheathing in both Kuujjuaq and Iqaluit, the maximum values of temperature difference are -1.35℃ and -1.90℃, respectively. Temperature RMSD values between South and North sheathing in Kuujjuaq and Iqaluit are 4.45℃ and 4.28℃, respectively.

The monthly averaged simulated MC levels of South and North sheathing in Kuujjuaq vary from 9.39% to 20.18% with an average value of 13.81% and from 10.00% to 17.54% with an average value of 14.33%. The monthly averaged simulated MC levels of South and North sheathing in Iqaluit vary from vary from 8.50% to 22.97% with an average value of 13.98% and from 9.28% to 17.74% with an average value of 14.31%. In general, MC levels of south sheathing are lower than those of north sheathing, except for the period from mid-Feb. 2014 to mid-April 2014. This phenomenon is due to solar radiation distribution, which will be explained in sub-section 5.4.3.1.

Maximum, minimum and average values of monthly averaged temperature difference between simulations and field measurements of south sheathing are -1.35℃, -6.30℃ and -4.25℃, and which of north sheathing are -1.90℃, -6.69℃ and -4.07℃, respectively. Maximum, minimum and average values of MC difference between simulations and field measurements of south sheathing are 3.38%, -0.95% and 0.13%, and those of north sheathing are 1.22%, -0.72% and -0.03%, respectively.

5.4.4 Comparison of House III in Kuujjuaq and Iqaluit under Same Conditions

The aim of comparison of simulation results of House III is to further validate the hygrothermal model of un-ventilated attic. Detail meaning of further model validation of House III is as same as that of House I presented in Section 5.4.3.

For un-ventilated attic in House III, the case (0.05ACH un-intentional air infiltration + 10% ceiling air leakage rate) is selected as benchmark model. Similar to House I, “EN 15026-Normal Moisture Load” from WUFI Plus database is set as indoor conditions to instead and 80% is set as initial relative humidity of plywood sheathing. Other detail settings in WUFI Plus model remain unchanged and the same model of House III is performed in both Kuujjuaq and Iqaluit for comparison of simulation results.

Comparison of simulation results of House III in Kuujjuaq and Iqaluit is presented in the following sub-sections:

5.4.4.1 Hourly Data

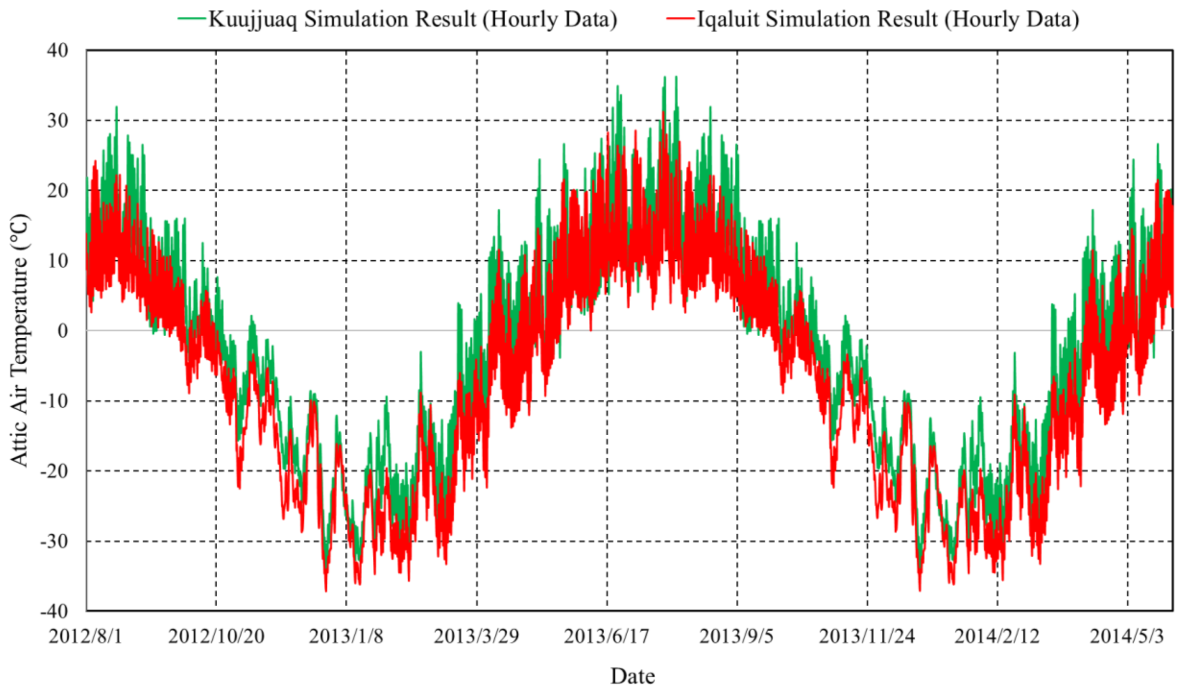


Figure 5-56. Hourly simulation results (attic air temperature) of comparison between Kuujjuaq and Iqaluit in House III (SIP House).

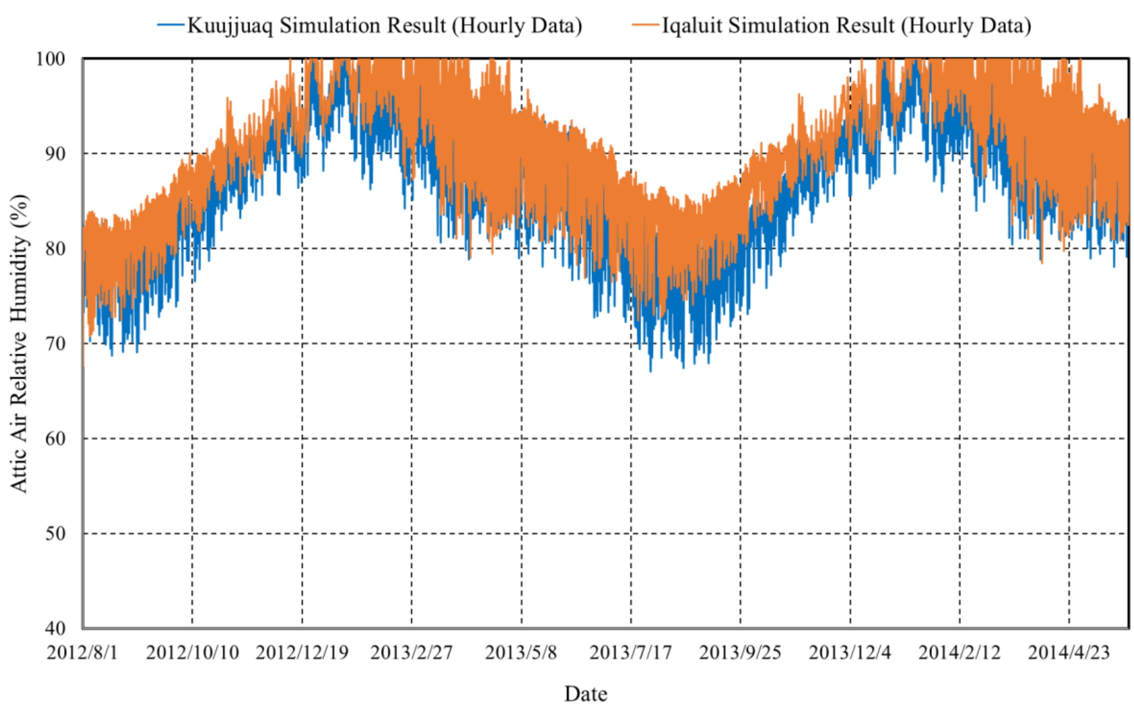


Figure 5-57. Hourly simulation results (attic air RH) of comparison between Kuujjuaq and Iqaluit in House III (SIP House).

Figure 5-56 and Figure 5-57 show comparison of hourly simulation results (attic air temperature and RH) of un-ventilated attic between different locations (Kuujjuaq and Iqaluit) for House III during the period from Aug. 2012 to June 2014. Both simulated temperature and RH profiles in different locations almost coincide with obvious hourly fluctuations. Simulation results of attic air temperature and RH in Kuujjuaq range from -34.81℃ to 36.23℃ with an average value of -3.13℃ and from 67.04% to 100% with an average value of 88.24%, respectively. Simulation results of attic air temperature and RH in Iqaluit range from -37.16℃ to 31.21℃ with an average value of -7.18℃ and from 67.6% to 100% with an average value of 90.76%, respectively. There are no significant differences of simulation results of attic air in House I between Kuujjuaq and Iqaluit. However, in general, simulated attic air temperatures in Kuujjuaq are slightly higher than those in Iqaluit, while simulated attic air RHs in Kuujjuaq are slightly lower than those in Iqaluit.

Maximum, minimum and average values of temperature and RH difference of simulation results between Kuujjuaq and Iqaluit are 17.28℃ & -20.89℃ & -4.05℃ and 14.16% & -9.80% & 2.52%, respectively. Hourly RMSD values of temperature and RH between Kuujjuaq and Iqaluit are 5.57℃ and 2.83%, respectively.

5.4.4.2 Daily Data

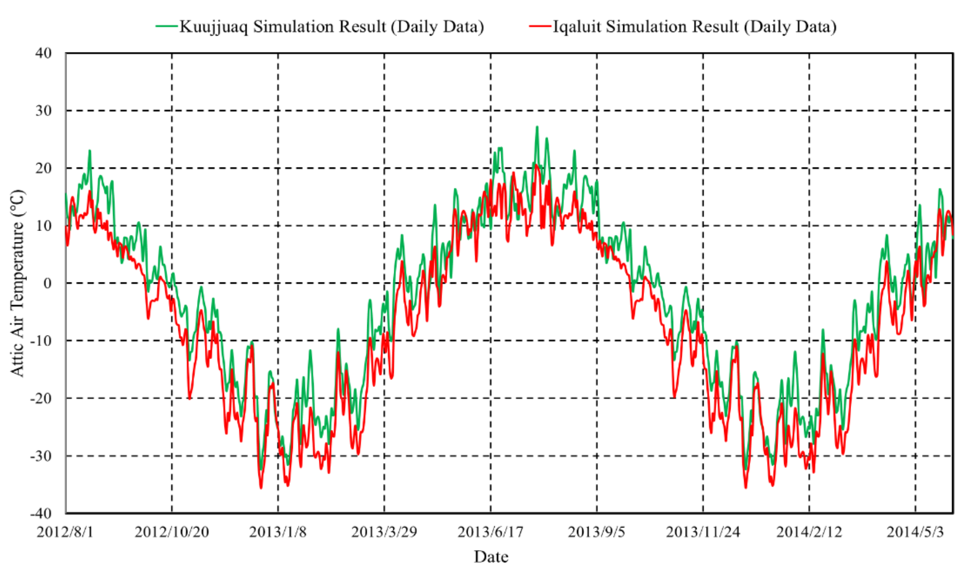


Figure 5-58. Daily simulation results (attic air temperature) of comparison between Kuujjuaq and Iqaluit in House I (KMHB House).

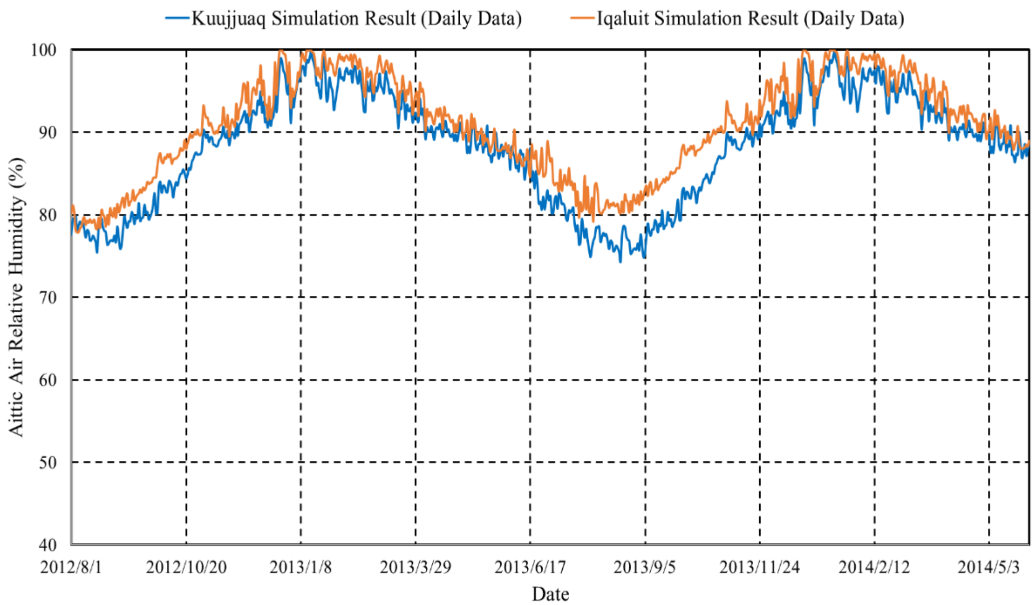


Figure 5-59. Daily simulation results (attic air temperature) of comparison between Kuujjuaq and Iqaluit in House I (KMHB House).

Figure 5-58 and Figure 5-59 show the comparison in daily averaged temperature and RH of the un-ventilated attic between simulations and measurements for House III during the period from Aug. 2012 to June 2014. The daily averaged simulated temperatures in Kuujjuaq vary between -32.35℃ and 27.07℃ with an average value of -3.13℃, while those in Iqaluit vary from -35.57℃ to 20.57℃ with an average value of -7.18℃. The daily averaged simulated RH values in Kuujjuaq vary between 74.33% and 99.75% with an average value of 88.24%, while those in Iqaluit vary from 77.92% to 100% with an average value of 90.76%.

Maximum, minimum and average values of temperature and RH difference of simulation results between Kuujjuaq and Iqaluit are 8.59℃ & -10.74℃ & -4.14℃ and 7.79% & -3.31% & -2.36%, respectively. The daily RMSD value of simulated temperature between Kuujjuaq and Iqaluit is 4.93℃. The daily RMSD value of simulated RH between Kuujjuaq and Iqaluit is 3.06%.

5.4.4.3 Monthly Data

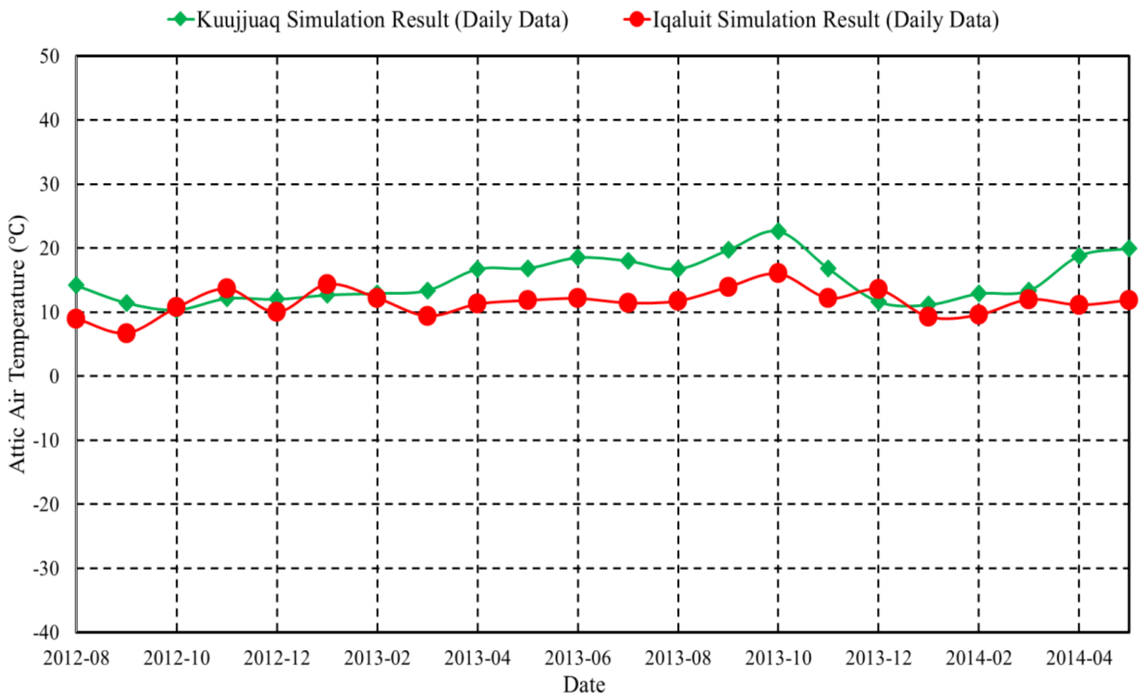


Figure 5-60. Monthly simulation results (attic air temperature) of comparison between Kuujjuaq and Iqaluit in House I (KMHB House).

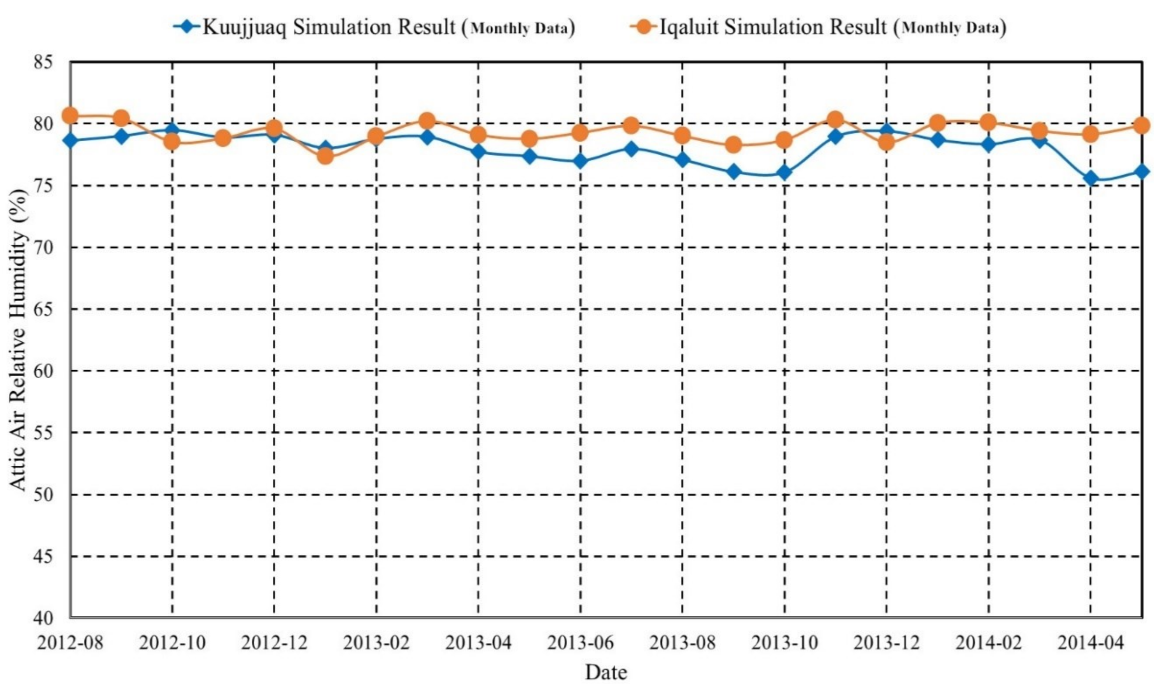


Figure 5-61. Monthly simulation results (attic air temperature) of comparison between Kuujjuaq and Iqaluit in House I (KMHB House).

Figure 5-60 and Figure 5-61 show the comparison in monthly temperature and RH of the un-ventilated attic between simulations and measurements for House III during the period from Aug. 2012 to June 2014. The monthly averaged simulated temperatures in Kuujjuaq vary between 10.41℃ and 22.66℃ with an average value of 15.17℃, while those in Iqaluit vary from 6.73℃ to 16.06℃ with an average value of 11.57℃. The monthly averaged simulated RH values in Kuujjuaq vary between 75.61% and 79.47% with an average value of 78.00%, while those in Iqaluit vary from 77.35% to 80.62% with an average value of 79.31%.

Maximum, minimum and average values of temperature and RH difference of simulation results between Kuujjuaq and Iqaluit are 1.88℃ & -8.09℃ & -3.60℃ and 3.73% & -0.95% & 1.31%, respectively. The monthly RMSD value of simulated temperature between Kuujjuaq and Iqaluit is 4.79℃. The monthly RMSD value of simulated RH between Kuujjuaq and Iqaluit is 1.84%.

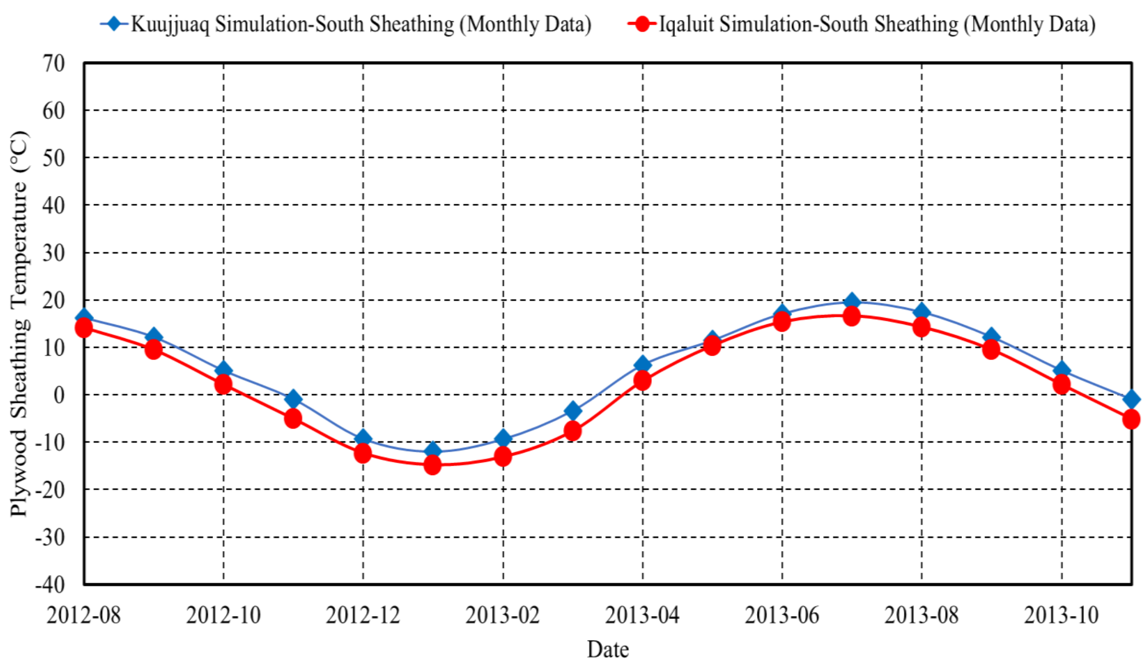


Figure 5-62. Monthly simulation results (plywood sheathing temperature) of south sheathing of comparison between Kuujjuaq and Iqaluit in House III (SIP House).

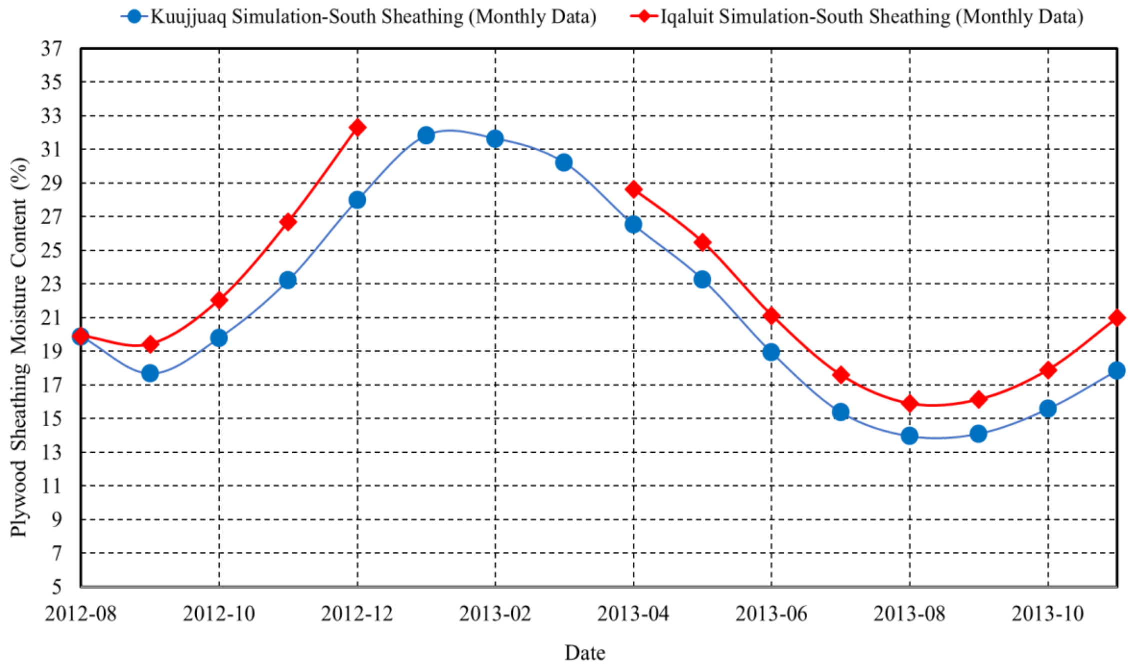


Figure 5-63. Monthly simulation results (plywood sheathing moisture content) of south sheathing of comparison between Kuujjuaq and Iqaluit in House III (SIP House).

Figure 5-62 and Figure 5-63 show the comparison in monthly temperature and MC of plywood sheathing (South sheathing) between Kuujjuaq and Iqaluit in House III during the period from mid-Aug. 2012 to May 2014. The monthly averaged simulated temperature of South sheathing in Kuujjuaq varies from -11.93℃ to 19.41℃ with an average value of 3.20℃. The monthly averaged simulated temperatures of South sheathing in Iqaluit vary from -14.81℃ to 16.60℃ with an average value of 0.17℃. It's easy to see that temperature curves almost coincide with obvious daily fluctuations. Meanwhile, simulated temperatures in Kuujjuaq are slightly higher than those in Iqaluit. Temperature RMSD values of South sheathing between Kuujjuaq and Iqaluit is 3.16℃.

The monthly averaged simulated MC levels of South sheathing in Kuujjuaq varies from 13.95% to 31.81% with an average value of 21.83%. The monthly averaged simulated MC levels of South sheathing in Iqaluit vary from vary from 15.87% to 32.28% with an average value of 23,12%. MC curves of Kuujjuaq and Iqaluit almost coincide, while MC levels in Iqaluit are obviously higher than those in Kuujjuaq.

Maximum, minimum and average values of monthly averaged temperature difference between simulations and field measurements of south sheathing are -1.07℃, -4.30℃ and -3.03℃, respectively. Maximum, minimum and average values of MC difference between simulations and field measurements of south sheathing are 5.01%, 0.04% and 2.77%, respectively.

Chapter 6 PARAMETRIC STUDY FOR ATTIC DESIGN RECOMMANDATIONS IN EXTREMELY COLD CLIMATE

This chapter presents the detailed parametric study and its result for attic design (both ventilated and un-ventilated attics) recommendations in extremely cold climate. The mold growth index M ≤ 3 is selected as criteria to determine the recommended range of key parameters for moisture safe attic design in extremely cold climate. WUFI Plus models of ventilated and un-ventilated attics created for parametric study are also excepted to apply to attic design under other climates or even future climates.

6.1 Mold Growth Index as A Criteria

As introduced in section 4.2, mold growth index is calculated by a mathematical model which is based on regression model for mold growth on spruce and pine through previous studies (Hukka & Viitanen, 1999). Specifically, mold growth index is divided into six levels according to visual appearance of wood surface which are listed in Table 6.1 as follows:

Table 6.1. Detail Explanation of Mold Growth Index (Hukka & Viitanen, 1999).

Mold Growth Index (M)	**Visual Appearance on the surface of Wooden Materials**
0	no growth
1	some growth detected only with microscopy
2	moderate growth detected with microscopy (coverage more than 10%)
3	some growth detected visually
4	visually detected coverage more than 10%
5	visually detected coverage more than 50%
6	visually detected coverage 100%

According to ASHRAE 160, mold growth index of three (M ≤ 3) is selected as criteria for hygrothermal performance evaluation. Parametric analysis is carried out and results are summarized to determine the range of key parameters that have a mold growth index of less than three. Design recommendations for safe attic design in extremely cold climate are provided based on the parametric study results.

6.2 Parametric Study

This section investigates the effect of variables on mold growth index of attic sheathing surface for both ventilated and un-ventilated attics. For ventilated attic, attic ventilation rate and ceiling air leakage rate are selected as variables. For un-ventilated attic, un-intentional air infiltration rate and ceiling air leakage rate are selected as variables.

6.2.1 Ventilated Attic

6.2.1.1 Hourly Attic Ventilation Rate

For ventilated attic, constant attic ventilation rates are input to WUFI Plus model for model validation. However, this parameter continuously changes with the variation of wind direction and wind speed.

Forest and Walker took field measurements of attic ventilation rates of two ventilated attics (attic 5 & attic 6) with different venting designs in University of Alberta. Figure 6-1 and Figure 6-2 show measured hourly ventilation rates under different wind speeds collecting from different wind directions and the effect of wind direction on normalised ventilation rates, respectively. Based on field measured results, in spite of their different venting arrangements, ventilation rate is mainly related to wind speed and wind direction. It's easy to observe that there is a linear relationship between wind speed and ventilation rate, and the linear slope depends on wind directions. In the meantime, wind direction is a cosine curve on normalised ventilation rate.

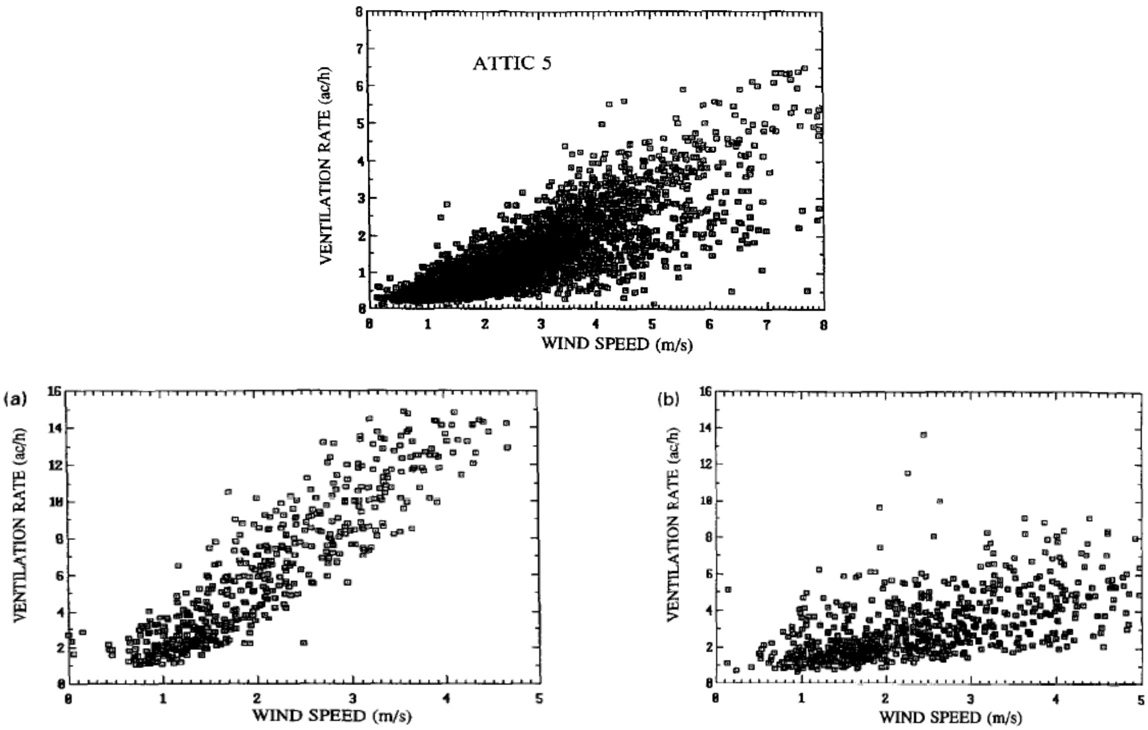


Figure 6-1. Measured hourly averaged ventilation rates in attic 5 for all wind speeds, wind directions, and outdoor temperatures (3758 data points) and in attic 6 for (a) unsheltered south direction 180” k 45” (497 data points) and (b) sheltered west direction 270” f 45” (697 data points) (Walker & Forest, 1995).

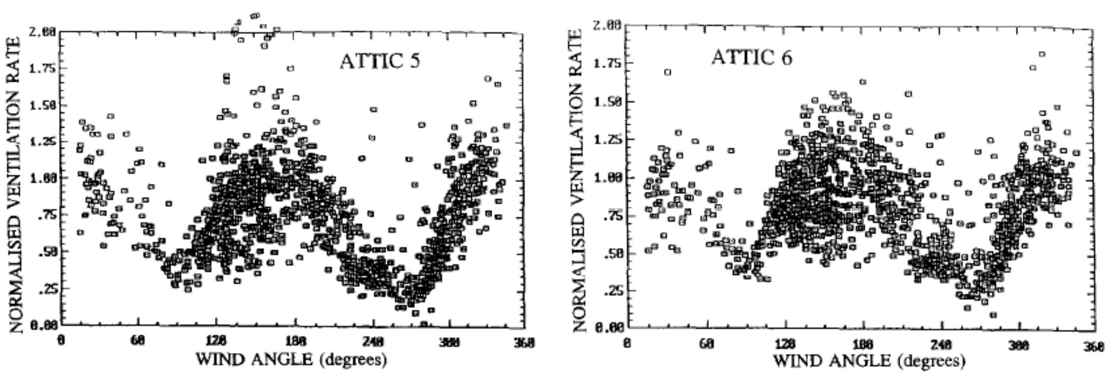


Figure 6-2. Effect of wind direction on normalised ventilation rates for attic 5 and attic 6 (1302 points). Direction of 0” corresponds to north. (Walker & Forest, 1995).

An empirical correlation shown in Equation 6.1 can be used to calculate attic ventilation rate as a function of wind speed and wind direction:

$$\mathrm{ACH} = \omega(0.25X\cos 2\theta + 0.75X) \quad (6.1)$$

where:

ACH — Air change rate per hour (1/h)

ω — Wind speed (m/s)

X — Constant value

θ — Wind direction (°)

Hourly attic ventilation rates assigned in WUFI Plus model are calculated by wind speed and wind direction data from TMY2 file using Equation 6.1. Calculation result indicates hourly attic ventilation rates varies between 0.007 ACH and 7.93 ACH.

6.2.1.2 Model Setup

For ventilated attic, validated WUFI Plus model of House I is used as base model to investigate the safety range of ceiling air leakage rate and attic ventilation rate under controlled indoor conditions. The detailed model setup of ventilated attic is as same as House I which is presented in Section 5.1.2.

Moisture balance within ventilated attic space is a dynamic process which depends on the balance of moisture sources. As introduced in Section 5.1.2 and Chapter 2 (literature review), ceiling air leakage rate and attic ventilation rate are selected as investigated parameters. Mold growth index calculated by simulation results of temperature and RH on sheathing surface is chosen as indicator to provide recommended design range of key parameters.

Simulation period is set from October 17^{th}, 2013 to July 18^{th}, 2015.

Table 6.2 summarizes variables and constant parameters setup for parametric study in WUFI Plus model of House I.

Table 6.2. Investigated key parameters of WUFI Plus Model of ventilated attic.

Parametric Items	**Specific Parameter**	**Detailed Setting**
Determined Parameter	Indoor Conditions	Hourly field measured data of House I (collected by on-site sensors)
	Outdoor Conditions	TMY2 Weather File—Kuujjuaq
	Un-intentional air infiltration	0.05 ACH
Variable Parameter	Ceiling Air Leakage Rate	1) Low Rate — 10% penetration

		2) Medium Rate — 30% penetration
		3) High Rate — 60% penetration
	Ventilation Rate	1) 1 ACH
		2) 5 ACH
		3) 10 ACH
		4) Hourly Data (0.007 ACH ~ 7.93 ACH)

6.2.1.2.1 Parametric Study Results

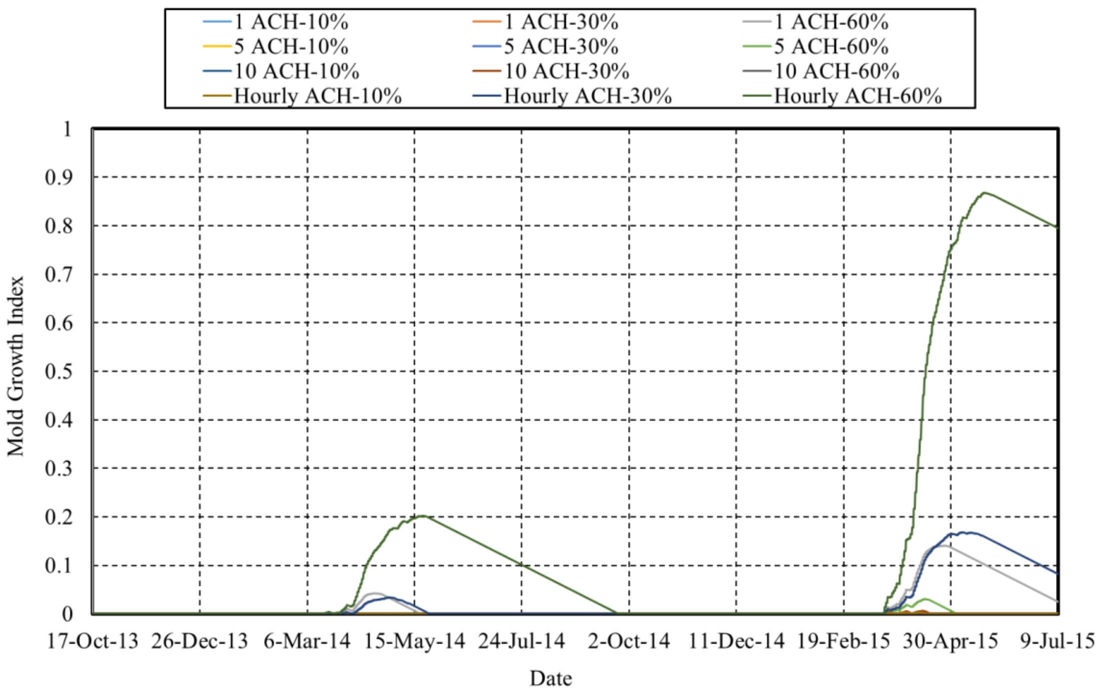


Figure 6-3. Mold growth index of plywood sheathing (north sheathing) of ventilated attic model during the whole simulation period (Oct. 17th, 2013 to July 18th, 2015).

Figure 6-3 shows mold growth index of plywood sheathing (north sheathing) of ventilated attic and mold growth index value of plywood sheathing is zero during the whole simulation period (Oct. 17th, 2013 to July 18th, 2015). For both south and north sheathing, mold growth index values are near zero during the whole simulation period. For south sheathing, mold growth index calculated by simulation results maintains zero during the whole simulation period. For north sheathing, mold growth index values are near zero and the maximum value of mold growth of all simulation scenarios is 0.87 when ceiling air leakage rate is set for 60% and attic ventilation rate is set for hourly changed values. And it's obvious that there is an obvious seasonal change of mold growth index curves, mold growth index values are more than zero during spring and summer months. Mold growth index value of worst scenario is still less than one, which means there is no visible mold growth occurring on the surface of plywood sheathing based on WUFI Plus simulation model.

Table 6.3 lists average mold growth index values of plywood sheathing (South sheathing and North sheathing) of ventilated attic during the whole simulation period. Mold growth index values of all scenarios of south sheathing maintain zero during the whole period. While mold growth index values of north sheathing are greater than zero when ceiling air leakage rate is set as 60%. When attic ventilation rates are under constant values, mold growth index will decrease with the increase of attic ventilation rates and with the decrease of ceiling air leakage rates. This phenomenon is mainly affected by solar radiation, solar radiation in the south is higher than that in the north. In general, there is no mold problem will occur (M≤3) based on mold growth index calculation of WUFI Plus simulation results.

Table 6.3. Average mold growth index of plywood sheathing of ventilated attic during the whole simulation period.

South Sheathing			
Ceiling Air Leakage Rate / Attic Ventilation Rate	Low Rate (10% penetration)	Medium Rate (30% penetration)	High Rate (60% penetration)
1 ACH	0	0	0
5 ACH	0	0	0
10 ACH	0	0	0
Hourly Attic Ventilation Rate	0	0	0
North Sheathing			
Ceiling Air Leakage Rate / Attic Ventilation Rate	Low Rate (10% penetration)	Medium Rate (30% penetration)	High Rate (60% penetration)
1 ACH	0	0	0.016
5 ACH	0	0	0.001
10 ACH	0	0	0
Hourly Attic Ventilation Rate	0	0.02	0.149

For ventilated attic, mold growth index values calculated by different simulation scenarios changes in accordance with mass balance principle within ventilated attic. Although attic ventilation will introduce excessive moisture, it also has positive effect on moisture removal from attic space. When un-intentional air infiltration rate of attic construction is assumed, the process of moisture took out by attic ventilation and introduced by penetrating through ceiling plane from indoor space forms a dynamic moisture balance. But based on this simulation model, all mold growth index results are near zero and the maximum value is less than 0.9. Therefore, as long as the ceiling air tightness remains in a reasonable range, there is no mold growth risk in ventilated attic.

6.2.2 Un-Ventilated Attic

6.2.2.1 Model Setup

For un-ventilated attic, validated WUFI Plus model of House III is used as the base model to investigate the safety range of ceiling air leakage rate and un-intentional air infiltration rate under controlled indoor conditions. The detailed model setup of ventilated attic is as same as House I which is presented in Section 5.1.2.

Moisture accumulation is an important issue for un-ventilated attic because its structure has no openings to remove excessive moisture. As introduced in Section 5.1.3 and Chapter 2 (literature review), ceiling air leakage rate and un-intentional air infiltration rate are selected as investigated parameters. Mold growth index calculated by simulation results of temperature and RH on sheathing surface is chosen as indicator to provide recommended design range of key parameters.

Simulation period of first parametric study presented in sub-section 6.2.2.2.1 (field measured initial MC/T) is set from Aug. 1st, 2012 to May 31st, 2014 when field measured initial MC/T of attic plywood sheathing is assigned.

Simulation period of second parametric study presented in sub-section 6.2.2.2.2 (default initial MC/T) is set from Jan. 1st, 2012 to Dec. 31st, 2017 when default initial MC/T of attic plywood sheathing is assigned.

Table 6.4 summarizes the variables and their values assigned in the parametric study in WUFI Plus model of House III.

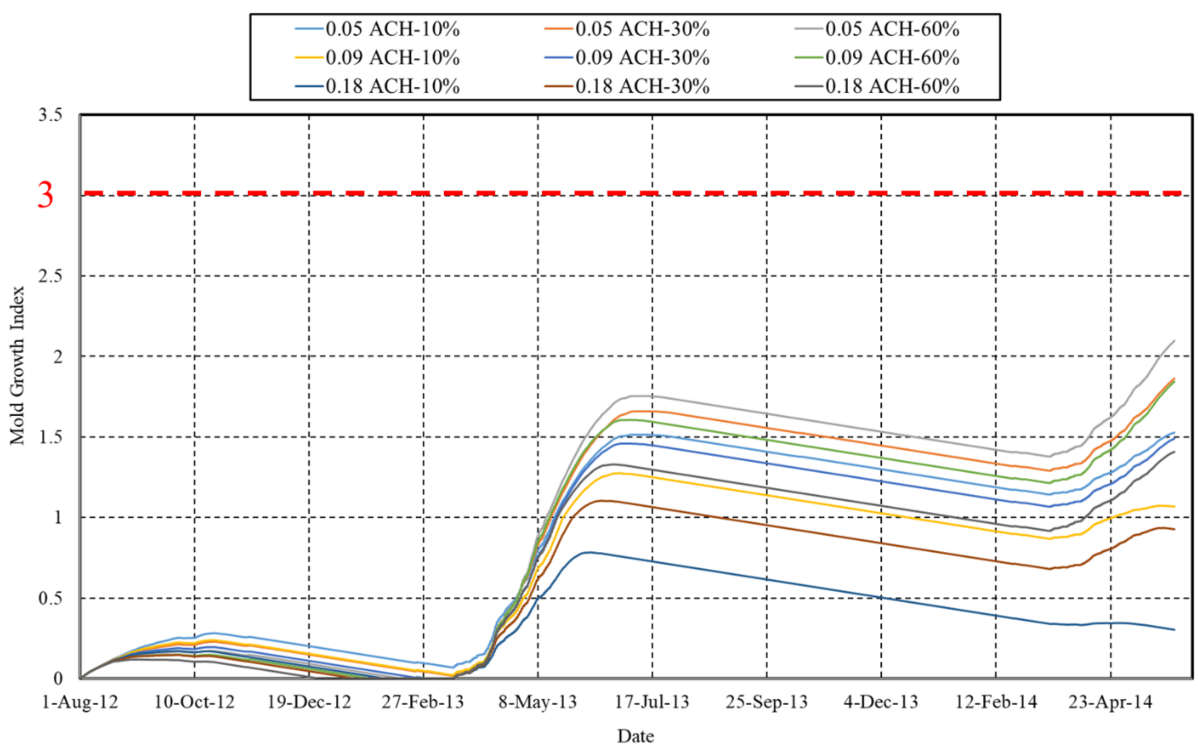
Table 6.4 Investigated key parameters of WUFI Plus model of un-ventilated attic.

Parametric Items	Specific Parameter	Detail Setting
Determined Parameter	Indoor Conditions	Standard EN 15026 (normal moisture load)
	Outdoor Conditions	TMY2 Weather File - Iqaluit
Variable Parameter	Ceiling Air Leakage Rate	1) Low Rate — 10% penetration (Upstairs—5.22 m^3/h; Upstairs—3.65 m^3/h)
		2) Medium Rate — 30% penetration (Upstairs—15.66 m^3/h; Upstairs—10.94 m^3/h)
		3) High Rate — 60% penetration (Upstairs—31.32 m^3/h; Upstairs—21.88 m^3/h)
	Un-intentional air infiltration	1) 0.05 ACH
		2) 0.09 ACH
		3) 0.18 ACH

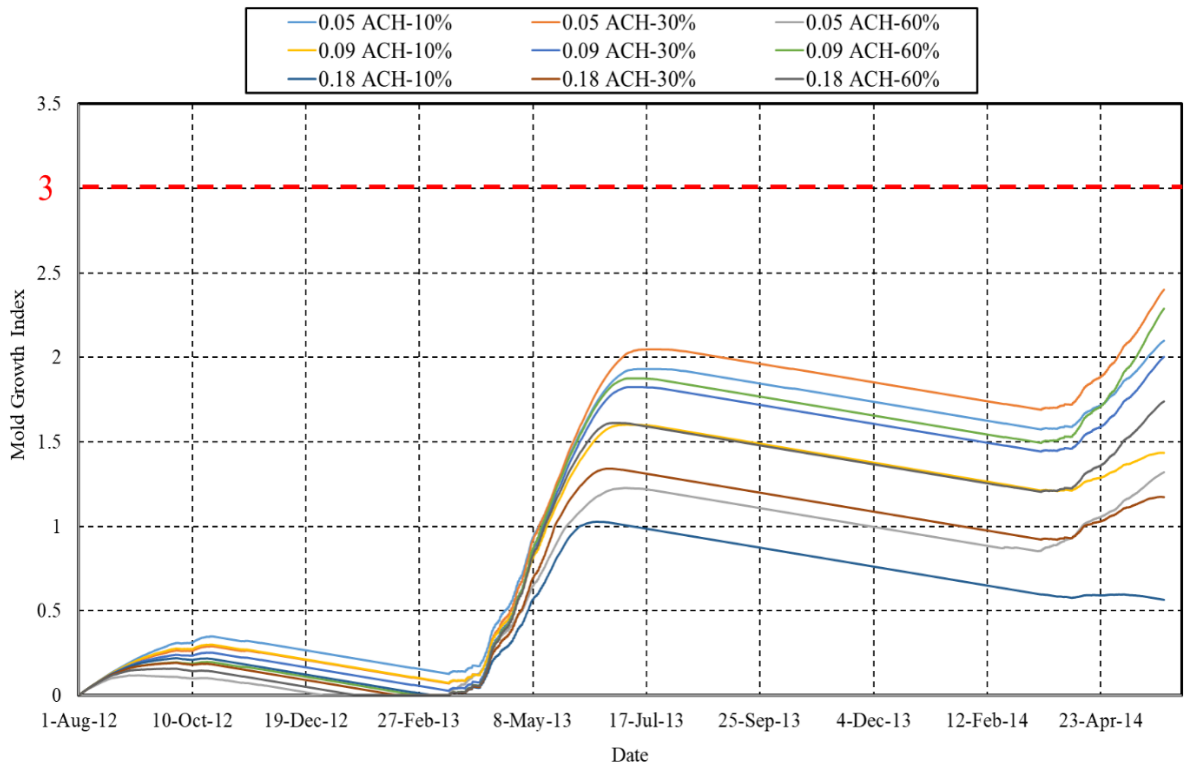
6.2.2.2 Parametric Study Results

This section presents parametric study results based on WUFI Plus model under the different setting of initial conditions of plywood sheathing. Sub-section 6.2.2.2.1 presents the results when initial MC/T values are set according to field measured data of House III and the simulation period is from Oct. 17th, 2013 to July 18th, 2015. Sub-section 6.2.2.2.2 presents the results when initial MC/T values are set according to default values of material database in WUFI Plus and the simulation period is from Jan. 1st, 2012 to Dec. 31st, 2017. Design recommendations of key parameters (ceiling air leakage rate & un-intentional air infiltration) of un-ventilated attic are provided based on parametric study results.

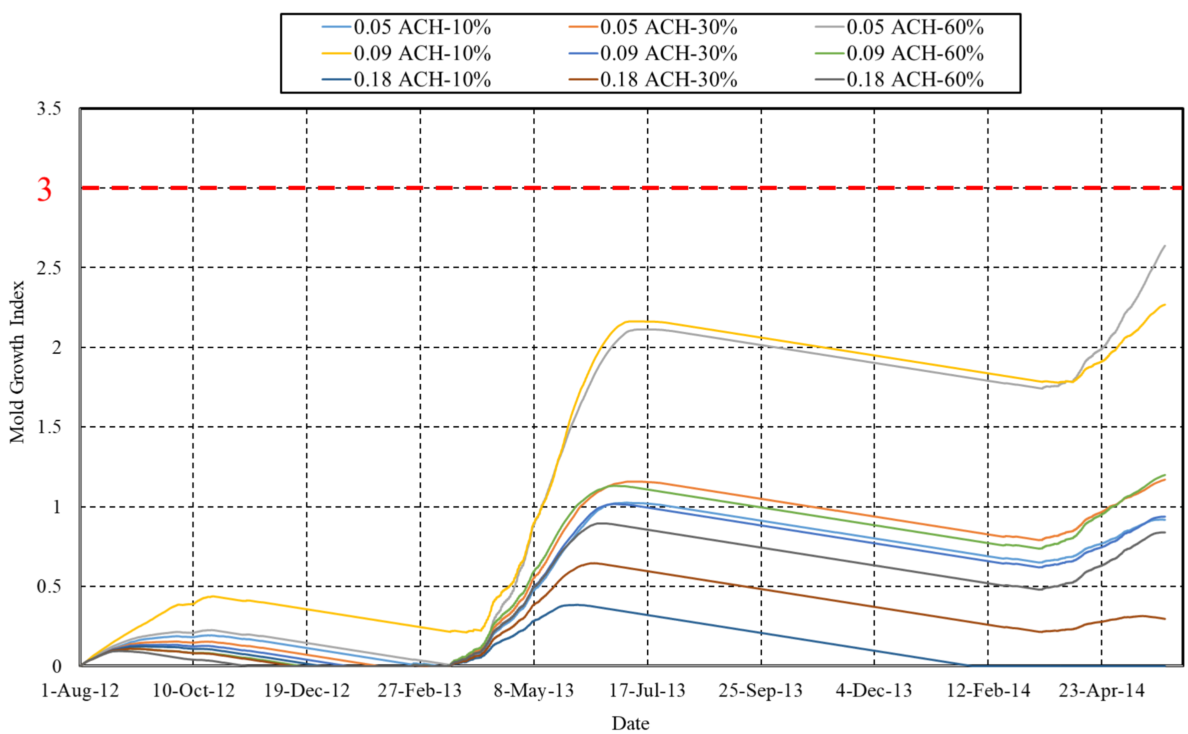
6.2.2.2.1 Field Measured Initial Conditions of Plywood Sheathing



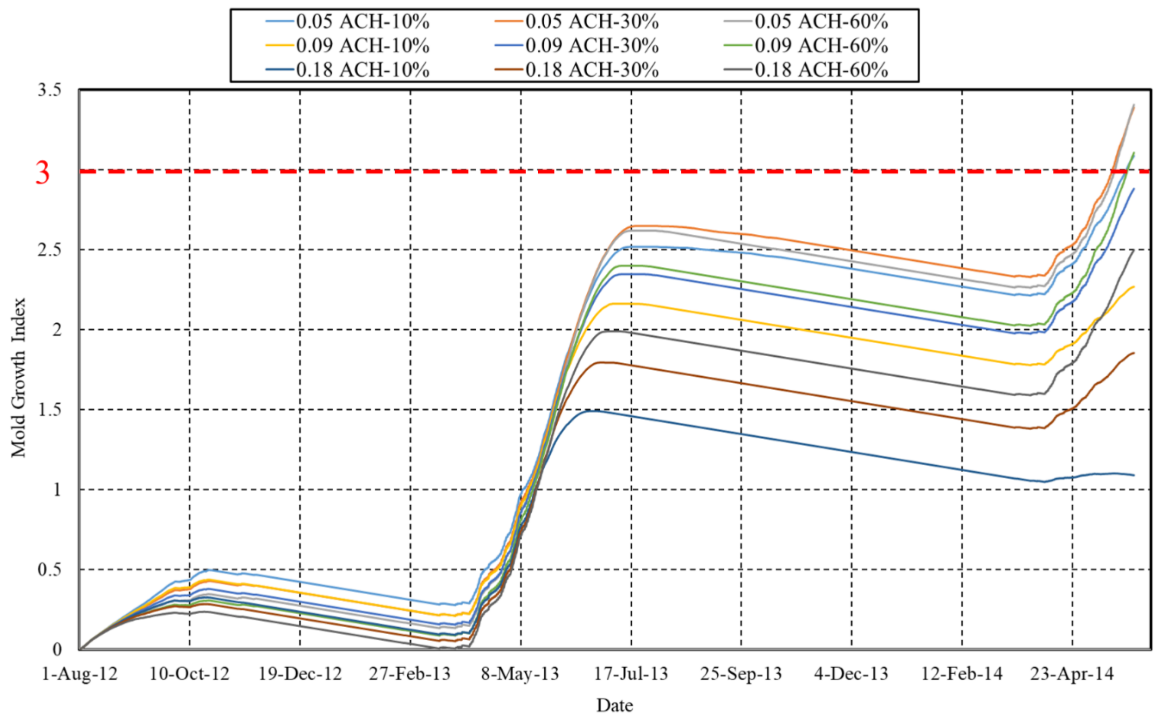
a) West sheathing.



b) East sheathing



c) South sheathing.



d) North Sheathing.

Figure 6-4. Mold growth index of plywood sheathing (west, east, south and north sheathing) under different combinations of ceiling air leakage rates and un-intentional air infiltration rates of un-ventilated attic model during the whole simulation period (Aug. 1st, 2012 to May 31st, 2014).

Figure 6-4 shows mold growth index of plywood sheathing (north sheathing) under different combinations of ceiling air leakage rates and un-intentional air infiltration rates of un-ventilated attic model during the whole simulation period (Oct. 17th, 2013 to July 18th, 2015). It's obvious that the mold growth index increases significantly over the spring period and decreases gradually from summer to winter, and peaks again in the next spring for all scenarios during the whole simulation period. Mold growth index values are less than three of sheathing under west, east and south orientations during the whole simulation period, and the maximum values are 2.10, 2.40 and 2.64 of west, east and south sheathing, respectively. Mold growth index values of north sheathing exceed three after May 2014. Generally, mold growth index values of sheathing under different orientations from high to low is: north sheathing, east sheathing, west sheathing and south sheathing. This phenomenon is caused by differences in the absorption of solar radiation by attic materials under different orientations. The results presented in Figure 6-4 show mold growth index increase with the increase of ceiling air leakage rates with the decrease of un-intentional air infiltration rates among all sheathing under different orientations. These results are consistent with mass balance principle within un-ventilated attic space, the main moisture source of un-ventilated attic is from indoors and there is no intentional opening for moisture removal from un-ventilated attic. It means moisture risk increases with the ceiling air leakage rate which is one of the main moisture sources and decrease with un-intentional air infiltration rate which depends on attic construction itself and it's the main path for moisture removal.

Table 6.5 lists highest mold growth index values of plywood sheathing (west sheathing, east sheathing, south sheathing and north sheathing) under different combinations of ceiling air leakage rates (10%, 30%, 60%) and un-intentional air infiltration rates (0.05 ACH, 0.09 ACH, 0.18 ACH) of un-ventilated attic. The ranges of mold growth index are 0.35~0.92, 0.50~1.11, 0.12~0.61 and 0.80~1.47 of west, east, south and north sheathing, respectively. It's obvious that average mold growth index values have significant differences among sheathing under different orientations, the order of mold growth index values from large to small is north>east>west>south. Different orientations of attic assembly receive different amounts of solar radiation. The value of global solar radiation sum of south orientation in Iqaluit is the highest. The maximum value of mold growth index can be found in the scenario of "0.05 ACH un-intentional air infiltration & 60% ceiling air leakage rate" of all different sheathing. Note that the mold growth index listed in Table 6.5 is the highest value at the end of the simulation period. Given the increasing trend, over a longer simulation period, mold growth index will exceed three, the threshold for mold growth risk.

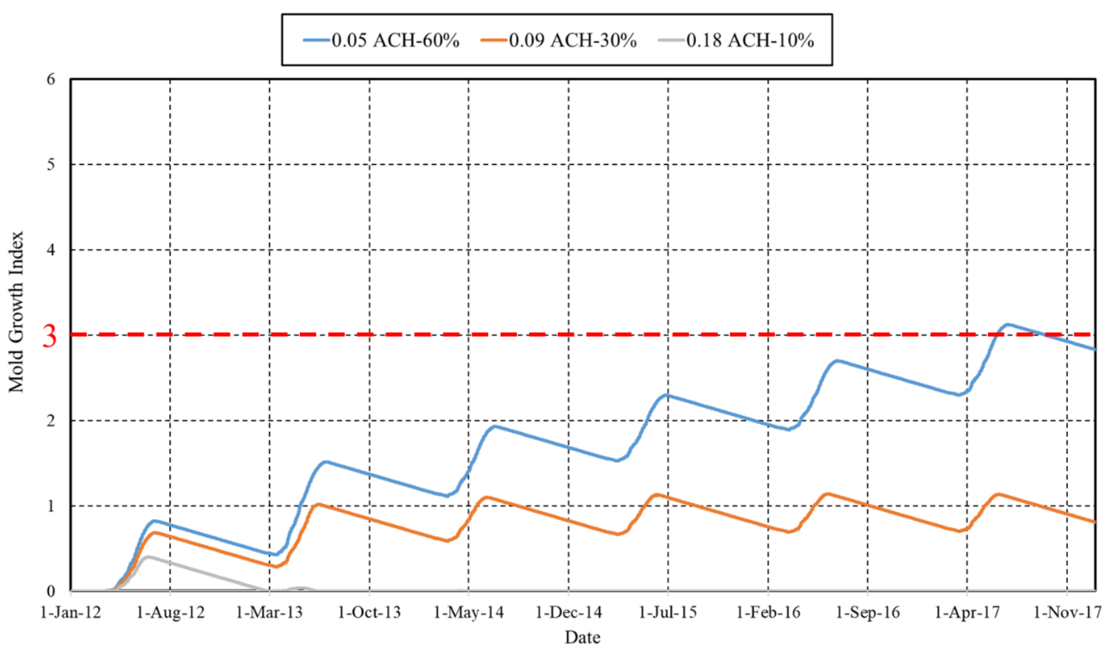
Table 6.5. Highest mold growth index of plywood sheathing of un-ventilated attic (field measured initial conditions of plywood sheathing) during the whole simulation period.

West Sheathing			
Ceiling Air Leakage Rate / Un-intentional air infiltration	Low Rate (10% penetration)	Medium Rate (30% penetration)	High Rate (60% penetration)
0.05 ACH	1.51	1.86	2.10
0.09 ACH	1.27	1.49	1.84
0.18 ACH	0.78	1.10	1.41
East Sheathing			
Ceiling Air Leakage Rate / Un-intentional air infiltration	Low Rate (10% penetration)	Medium Rate (30% penetration)	High Rate (60% penetration)
0.05 ACH	1.93	1.17	2.64
0.09 ACH	1.60	2.00	2.29
0.18 ACH	1.03	1.34	1.74

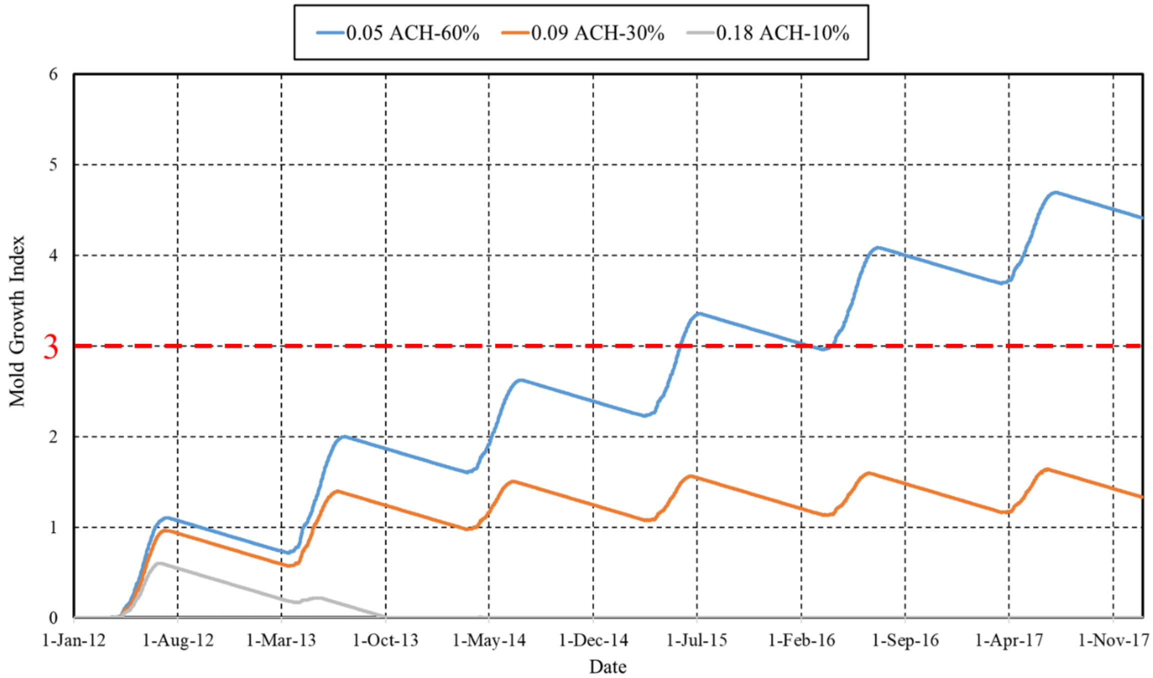
South Sheathing			
Ceiling Air Leakage Rate / Un-intentional air infiltration	Low Rate (10% penetration)	Medium Rate (30% penetration)	High Rate (60% penetration)
0.05 ACH	1.03	1.17	1.32
0.09 ACH	0.80	1.02	1.20
0.18 ACH	0.39	0.65	0.90
North Sheathing			
Ceiling Air Leakage Rate / Un-intentional air infiltration	Low Rate (10% penetration)	Medium Rate (30% penetration)	High Rate (60% penetration)
0.05 ACH	1.51	3.39	3.41
0.09 ACH	2.27	2.88	3.11
0.18 ACH	1.49	1.85	2.50

6.2.2.2.2 Default Initial Conditions of Plywood Sheathing

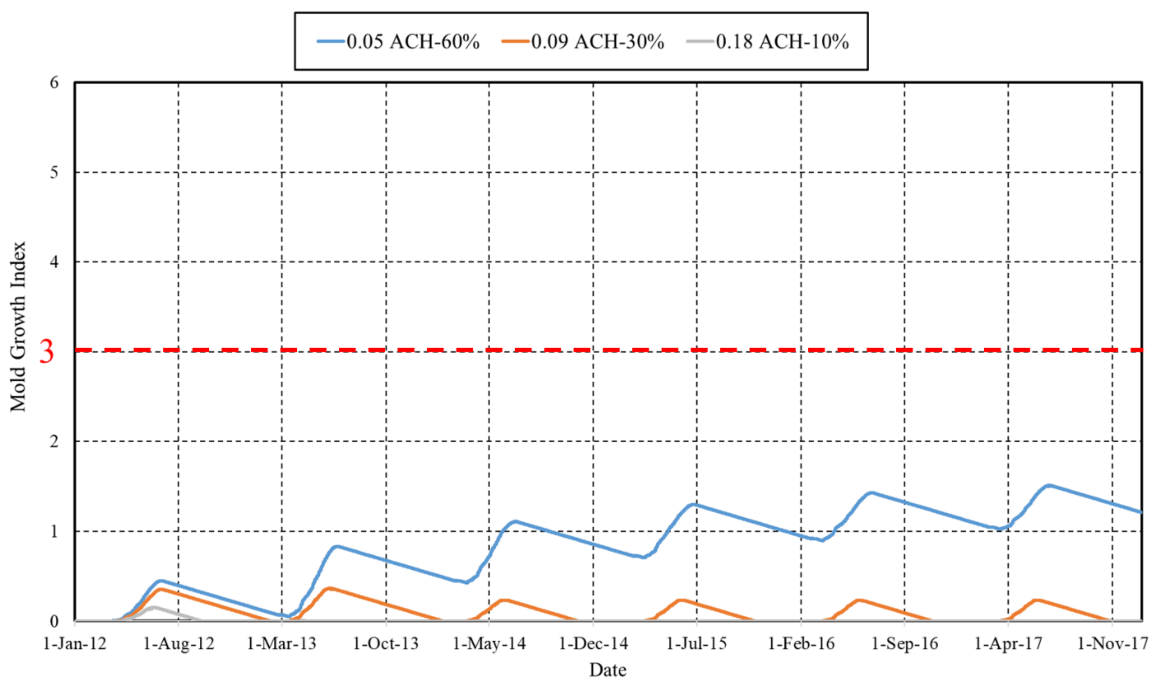
Based on parametric study results presented in previous sub-section, it's easy to find that "0.05ACH+60%", "0.09ACH+30%" and "0.18ACH+10%" are the worst, medium and best scenarios of mold growth index during the one and half year simulation period which matches field measurement period. To verify the reliability of these results, simulations are performed under these three scenarios exposed in a longer period from Jan. 1st, 2012 to May 1st, 2015. The default MC level and temperature values are 13℃ and 15.67%.



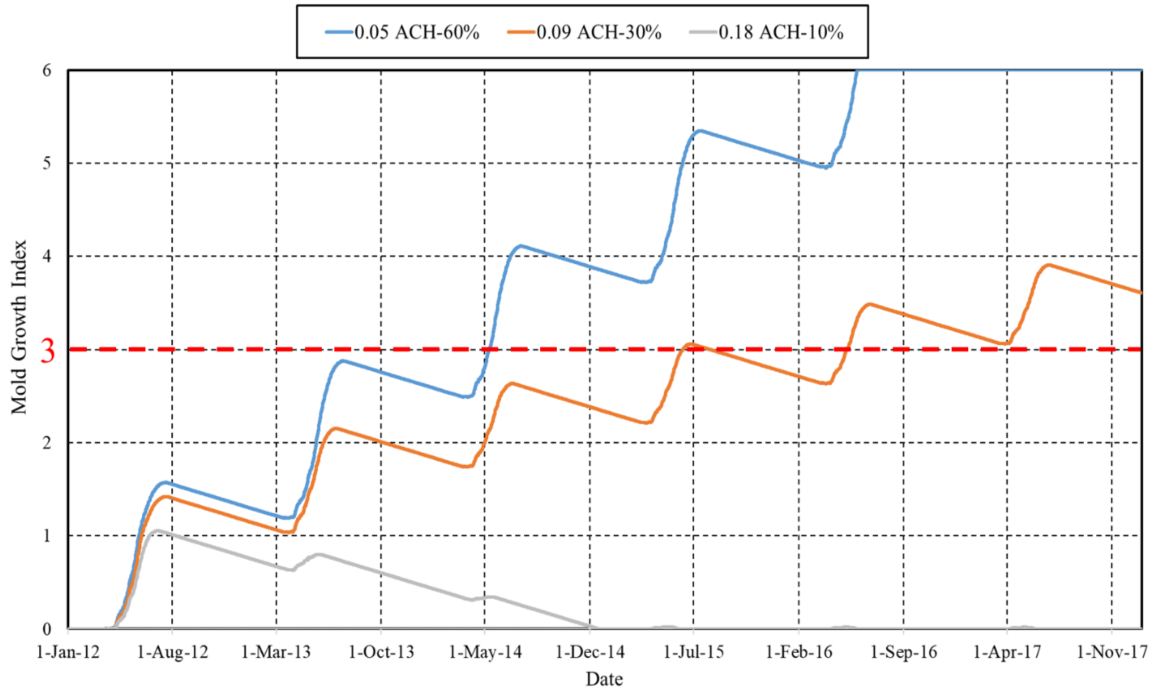
a) West Sheathing.



b) East Sheathing.



c) South Sheathing.



d) North Sheathing.

Figure 6-5. Mold growth index of plywood sheathing (west, east, south and north sheathing) under three typical scenarios of un-ventilated attic model during the whole simulation period (Jan. 1st, 2012 to Dec. 31st, 2017).

Figure 6-5 shows mold growth index of plywood sheathing (west, east, south and north sheathing) under three typical scenarios of un-ventilated attic model during the whole simulation period (Jan. 1st, 2012 to Dec. 31st, 2017). It can be seen that mold growth index values of sheathing under different orientations from high to low is: north>east>west>south. And mold growth index value of "0.05 ACH+60%" is the highest followed by the case of "0.09 ACH+30%" and the case of "0.18 ACH+10%". Mold growth index calculated within five-year period have obviously seasonal variation. The values of mold growth index are near zero of all sheathing when un-intentional air infiltration rate maintains 0.18 ACH. Mold growth index is always under three of west, east and south sheathing when un-intentional air infiltration rate maintains 0.09 ACH during the whole simulation time, except for north sheathing. Mold growth index values of north sheathing exceed three starting from 2015 and the peak value is close to four in mid-2017. Mold growth index values are basically greater than three in west, east and north sheathing when un-intentional air infiltration rate maintains 0.05 ACH, except for south sheathing, mold growth index values of which are lower than two during the whole simulation period. The mold growth index values are the highest under the case of "0.05 ACH + 60%" in north sheathing and the lowest under the case of "0.18 ACH + 10%" in west sheathing. Again, with higher ceiling air leakage rate and lower un-intentional air infiltration rate, the mold growth index is higher.

Table 6.6 lists highest mold growth index values of plywood sheathing (west sheathing, east sheathing, south sheathing and north sheathing) under three typical scenarios of un-ventilated attic during the simulation period from Jan. 1st, 2012 to Dec. 31st, 2017. The maximum value of mold growth index is 3.81 which can be found when un-intentional air infiltration rate is 0.05ACH and ceiling air leakage rate is 60% in north sheathing. The minimum value of mold growth index is 0.03 which can be found when un-intentional air infiltration is 0.18ACH and ceiling air leakage rate is 10% in west sheathing. The best case of these three scenarios is "0.18ACH un-intentional air infiltration & 10% ceiling air leakage rate" which has minimum mold growth index values among all sheathing under different orientations. Therefore, to have a moisture safe un-ventilated attic, it is critical to control ceiling air leakage rate to the minimum and un-intentional air infiltration from attic can provide some levels of ventilation for moisture removal. Note that the simulation results shown in this section is over five-year only. Given the increase trend, over a longer period, i.e. 10 years or 20 years, the mold growth index may exceed three, the threshold value.

Table 6.6. Highest mold growth index of plywood sheathing of un-ventilated attic (default initial conditions of plywood sheathing) during the whole simulation period.

	Highest Mold Growth Index of West Sheathing	**Highest Mold Growth Index of East Sheathing**	**Highest Mold Growth Index of South Sheathing**	**Highest Mold Growth Index of North Sheathing**
0.05 ACH + 60%	3.12	4.69	1.51	6
0.09 ACH + 30%	1.14	1.64	0.37	3.91
0.18 ACH + 10%	0.40	0.60	0.15	1.05

6.2.2.3 Further Parametric Study under Longer Simulation Period

Based on simulation results and calculated mold growth index of parametric study in previous sub-sections, this sub-section presents parametric study results of typical scenarios with more variables (un-intentional air infiltration, indoor conditions, initial conditions of plywood sheathing, ceiling air leakage rate) during five-year simulation period (from Aug. 1st, 2012 to July 31st, 2017).

Parametric study under longer simulation period further investigates the combination effects of indoor conditions (normal and high moisture load), initial RH of plywood sheathing (60%, 80%, 90%), un-intentional infiltration (0.05ACH, 0.18ACH) and ceiling air leakage rate (0%, 10%, 20%, 30%, 60%) through 25 selected typical scenarios. Simulation period is extended to five years to get more reliable results to predict moisture risk in un-ventilated attic and provide design recommendations.

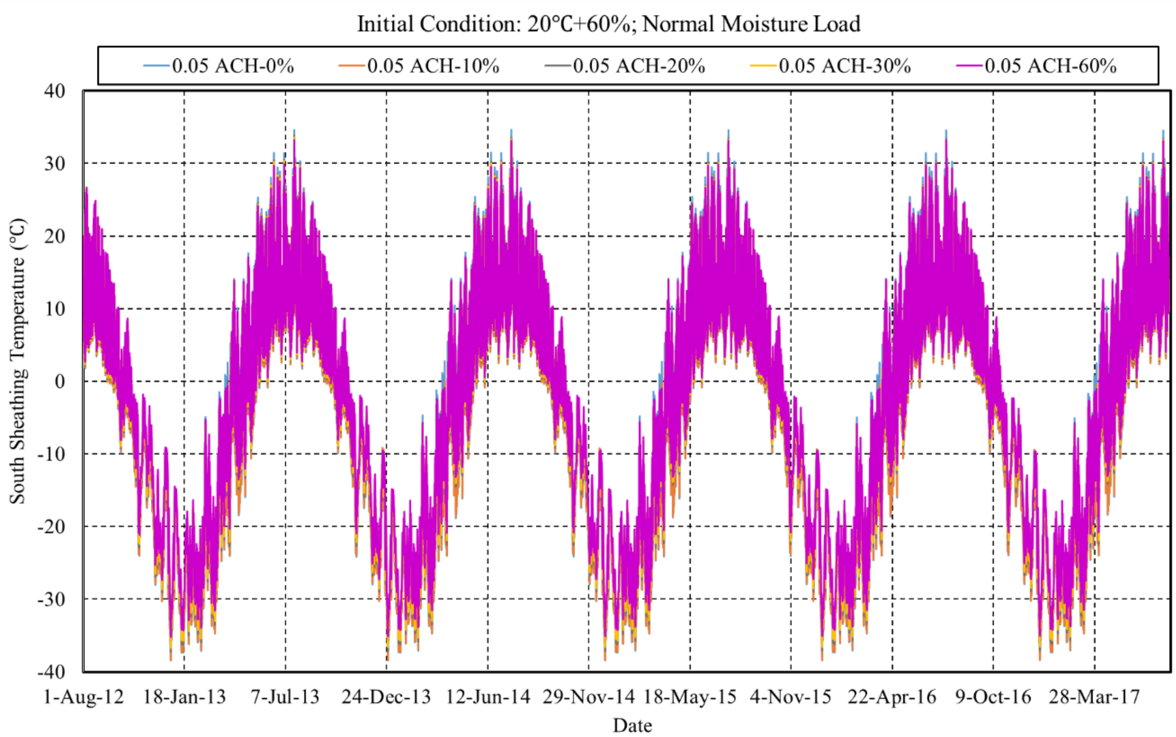
Twenty-five typical scenarios divided into five groups performed in this parametric study part, key parameters of each hygrothermal model are listed in following Table 6.7. Other settings of WUFI Plus model are the same as the details introduced in sub-section 6.2.2.2.

Table 6.7. Key parameters of 25 typical scenarios of parametric study under longer simulation period.

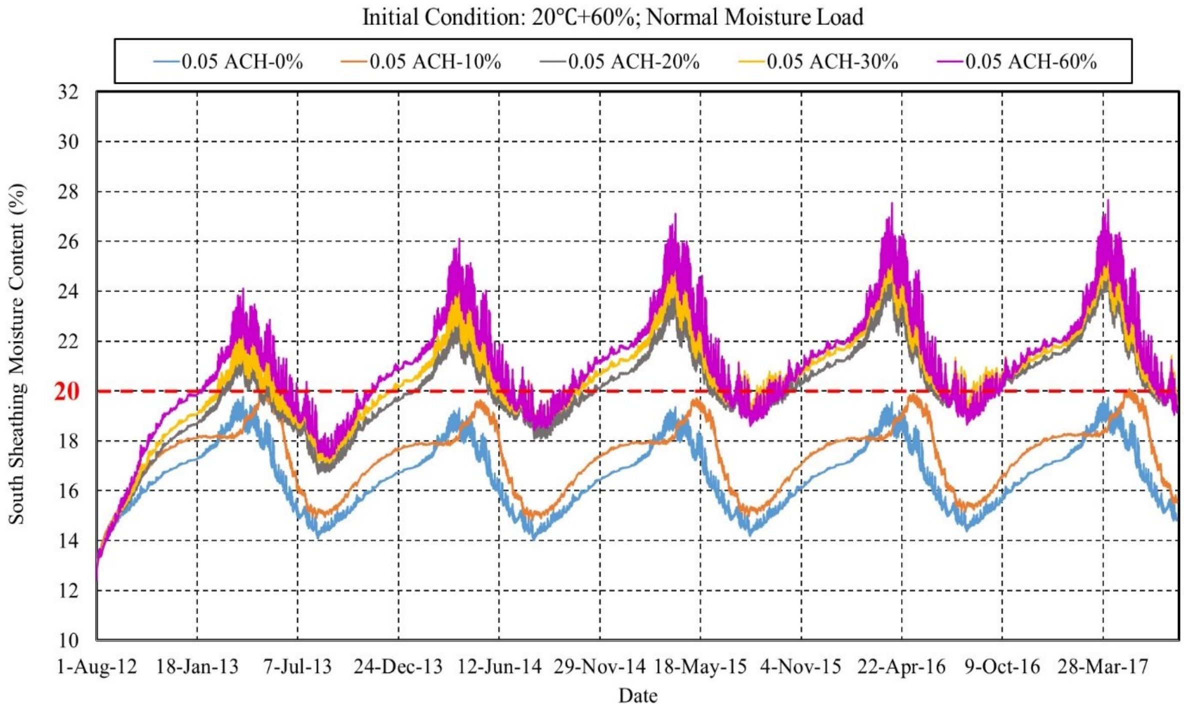
Group 1	Case 1~Case 5	➢ **Un-intentional Infiltration:** 0.05 ACH ➢ **Indoor Conditions:** EN15026 Normal Moisture Load ➢ **Initial Conditions of Plywood Sheathing:** 20 ℃+60% ➢ **Ceiling Air Leakage Rate:** 0%, 10%, 20%, 30%, 60%
Group 2	Case 6~Case 10	➢ **Un-intentional Infiltration:** 0.05 ACH ➢ **Indoor Conditions:** EN15026 Normal Moisture Load ➢ **Initial Conditions of Plywood Sheathing:** 20 ℃+80% ➢ **Ceiling Air Leakage Rate:** 0%, 10%, 20%, 30%, 60%
Group 3	Case 11~Case 15	➢ **Un-intentional Infiltration:** 0.05 ACH ➢ **Indoor Conditions:** EN15026 High Moisture Load ➢ **Initial Conditions of Plywood Sheathing:** 20 ℃+80% ➢ **Ceiling Air Leakage Rate:** 0%, 10%, 20%, 30%, 60%

Group 4	Case 16~Case 20	➢ **Un-intentional Infiltration:** 0.05 ACH ➢ **Indoor Conditions:** EN15026 Normal Moisture Load ➢ **Initial Conditions of Plywood Sheathing:** 20 ℃+90% ➢ **Ceiling Air Leakage Rate:** 0%, 10%, 20%, 30%, 60%
Group 5	Case 21~Case 25	➢ **Un-intentional Infiltration:** 0.18 ACH ➢ **Indoor Conditions:** EN15026 Normal Moisture Load ➢ **Initial Conditions of Plywood Sheathing:** 20 ℃+80% ➢ **Ceiling Air Leakage Rate:** 0%, 10%, 20%, 30%, 60%

Parametric study results under five-year simulation period are presented in this sub-section. Temperature/MC level and mold growth index (MGI) of South and North sheathing of un-ventilated attic under different scenarios are chose as main indicators to present parametric study results, and then provide solid support for design recommendations. The reason to choose South and North sheathing is that the moisture content of plywood sheathing in these two orientations is more sensitive to solar radiation compared with west and east orientations.



a) South sheathing temperature (Case 1~5).

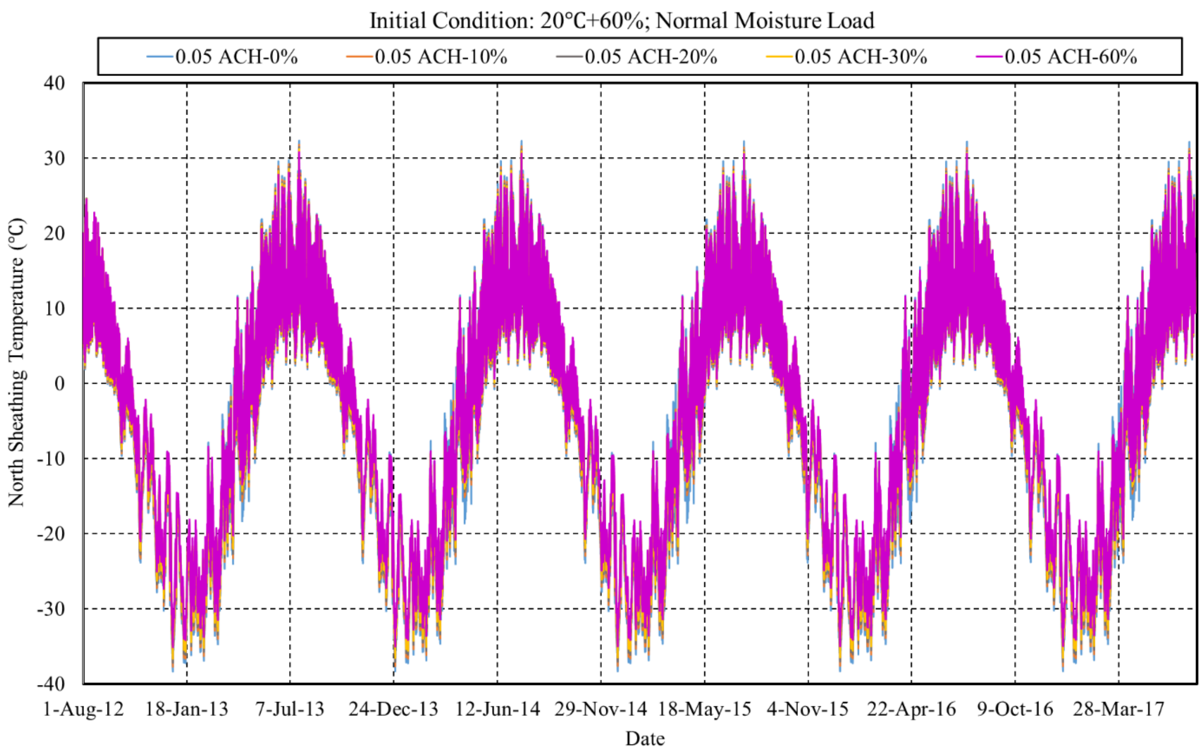


b) South sheathing MC (Case 1~5).

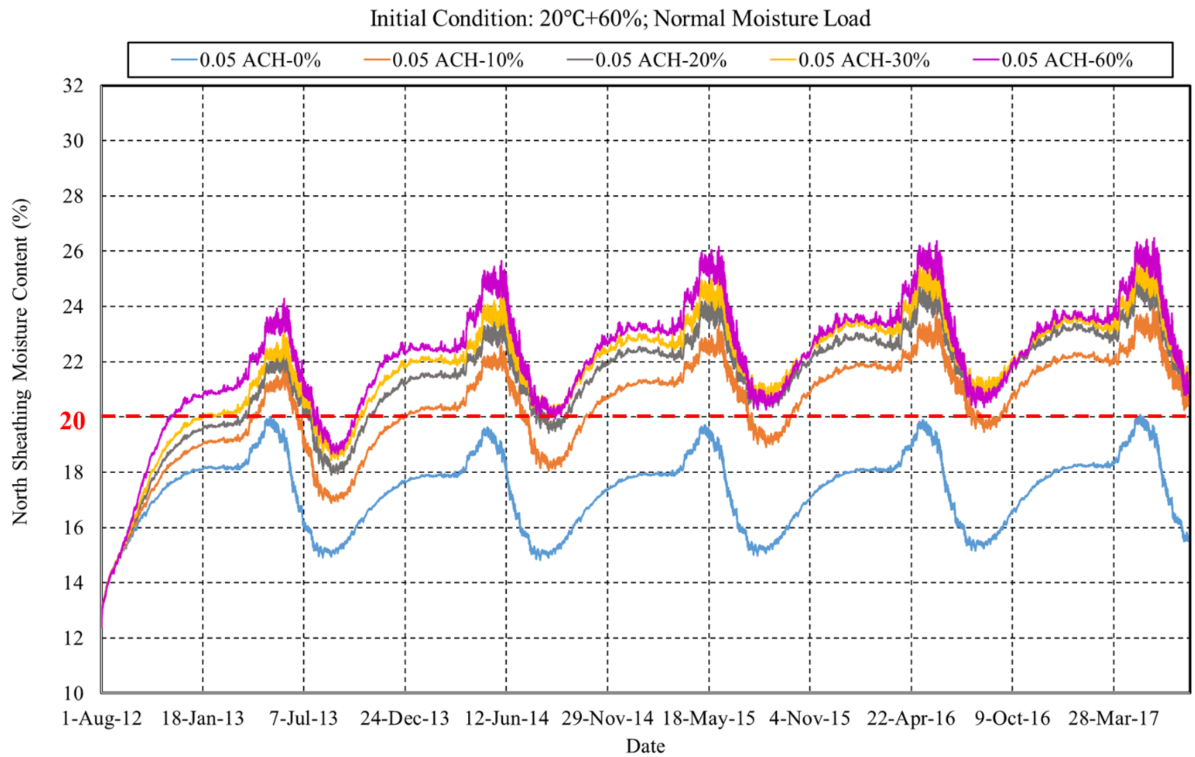
Figure 6-6. Temperature and MC level of South plywood sheathing under different ceiling air leakage rates (initial condition is 20℃/60%, normal moisture load, un-intentional ventilation rate is 0.05ACH) of un-ventilated attic model during the five-year simulation period (Case 1~5).

Figure 6-6-a) & b) show temperature and moisture content of South plywood sheathing under different ceiling air leakage rates (initial condition is 20℃/60%, normal moisture load, un-intentional ventilation rate is 0.05ACH) of un-ventilated attic model during five-year simulation period (from Aug. 1st, 2012 to July 31st, 2017). It's easy to see that temperature profiles of South sheathing in five scenarios almost coincide. The average temperature values of five scenarios are -5.69℃, -6.04℃, -5.17℃, -4.95℃ and -4.29℃. The range of temperatures of South sheathing in five scenarios are -38.44℃~34.63℃, -38.38℃~32.31℃, -37.25℃~33.84℃, -36.72℃~33.59℃ and -35.19℃~33.24℃, respectively.

MC levels of South sheathing in five scenarios increase with the increase of ceiling air leakage rates, and MC profiles periodically and slightly increase year by year except for when ceiling air leakage rate is 0%. When ceiling air leakage rates are 0% and 10%, MC levels generally under 20% which is the safety line for mold growth and moisture damage, and the general trend is stable or slightly increases year by year. The maximum MC level of five scenarios are 19.77%, 20.09%, 26.07%, 26.75% and 27.66% when ceiling air leakage rate are 0%, 10%, 20%, 30%, 60%, which means that there are higher risks of moisture related problems when the ceiling air leakage rate exceeds 10% under the initial condition of south sheathing at 20℃/60%, un-intentional infiltration rate is 0.05ACH and normal indoor moisture load.



a) North sheathing temperature (Case 1~5).



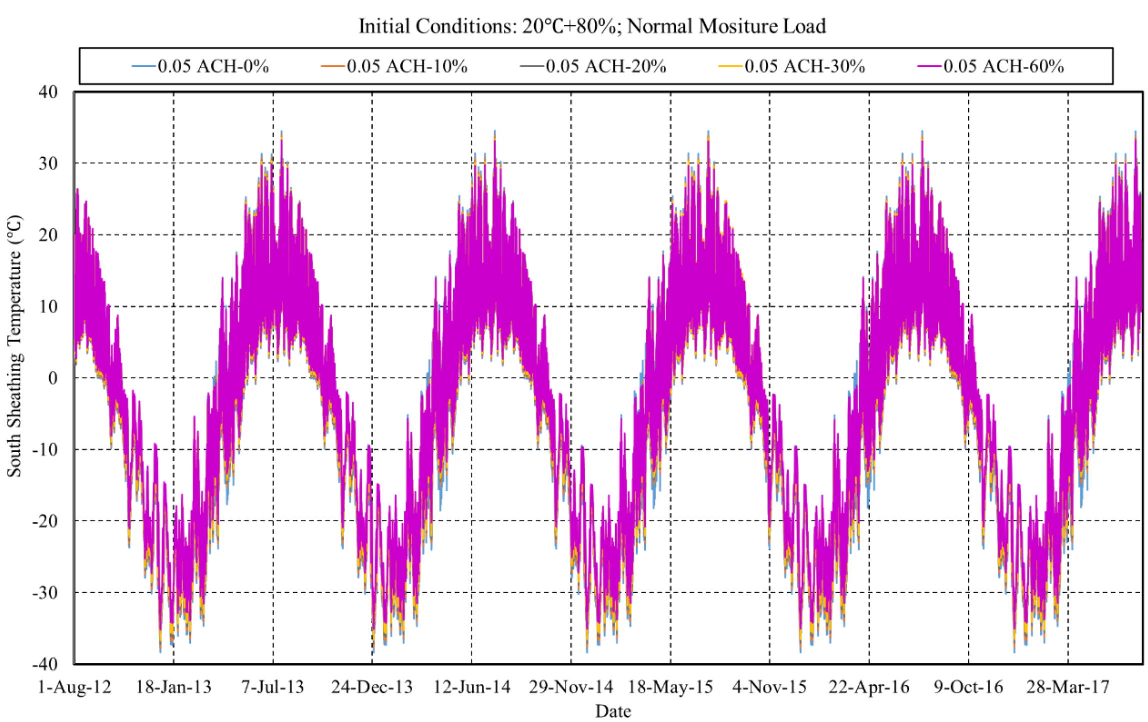
b) North sheathing MC (Case1~5).

Figure 6-7. Temperature and MC level of North plywood sheathing under different ceiling air leakage rates (initial condition is 20℃/60%, normal moisture load, un-intentional ventilation rate is 0.05ACH) of un-ventilated attic model during the five-year simulation period (Case1~5).

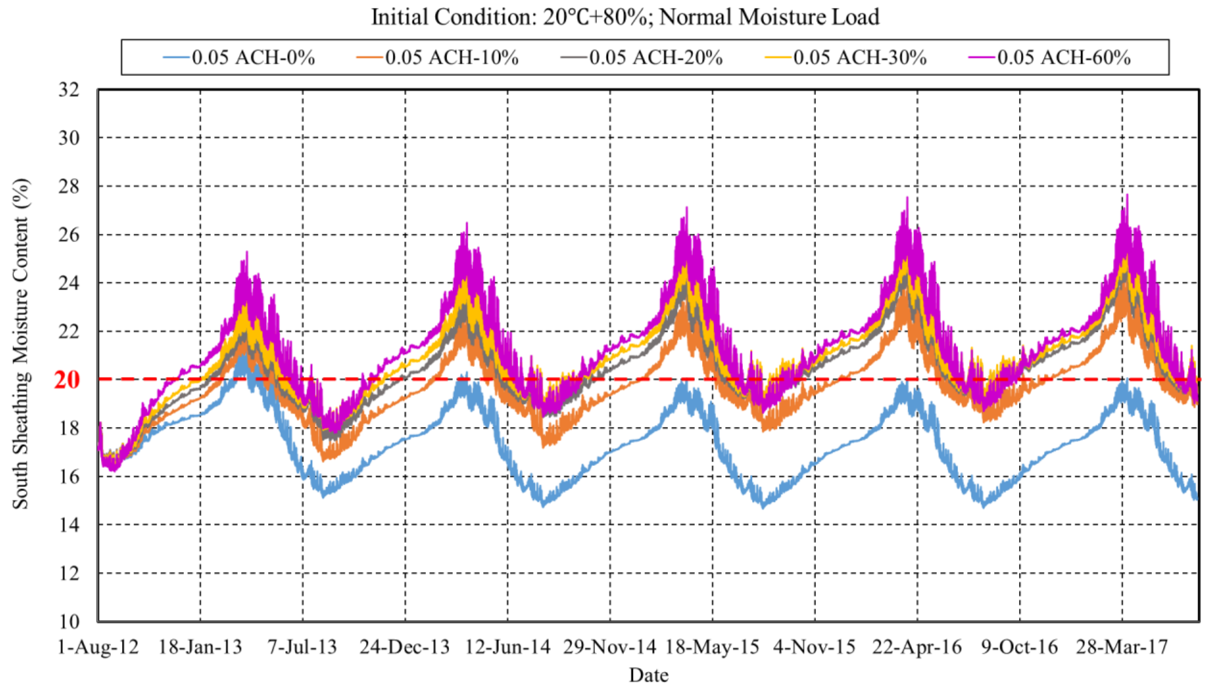
Figure 6-7-a) & b) show temperature and moisture content of North plywood sheathing under different ceiling air leakage rates (initial condition is 20℃/60%, normal moisture load, un-intentional ventilation rate is 0.05ACH) of un-ventilated attic model during five-year simulation period (from Aug. 1st, 2012 to July 31st, 2017). It's easy to see that temperature profiles of North sheathing in five scenarios almost coincide. The average temperature values of five scenarios are -6.05℃, -5.78℃, -5.55℃, -5.31℃ and -4.65℃. The range of temperatures of south sheathing in five scenarios are -38.38℃~32.31℃, -37.74℃~31.79℃, -37.19℃~31.48℃, -36.66℃~31.22℃ and -35.13℃~30.80℃, respectively.

MC levels of North sheathing in five scenarios increase with the increase of ceiling air leakage rates, and MC profiles periodically and slightly increase year by year except for when ceiling air leakage rate is 0%. When ceiling air leakage rate is 0%, MC level is generally under 20% which is the safety line for mold growth. Only MC level in the first year is slightly over 20% (the maximum MC level is 20.08%), and it decreases year by year. The maximum MC level of other four scenarios are 24.08%, 25.26%, 25.76% and 26.49% when ceiling air leakage rate are 10%, 20%, 30%, 60%, which means there is higher risk of moisture related problems as long as there is ceiling air penetration when initial condition of north sheathing is at 20℃/60% and indoor condition is under normal moisture load.

In general, temperatures of South sheathing are slightly higher than which of North sheathing in all scenarios, while MC levels of South sheathing are slightly lower than that of North sheathing in all scenarios. This difference is attributed to the difference in solar radiation, the amount of solar radiation available in south orientation is higher than that in north.



a) South sheathing temperature (Case 6~10).

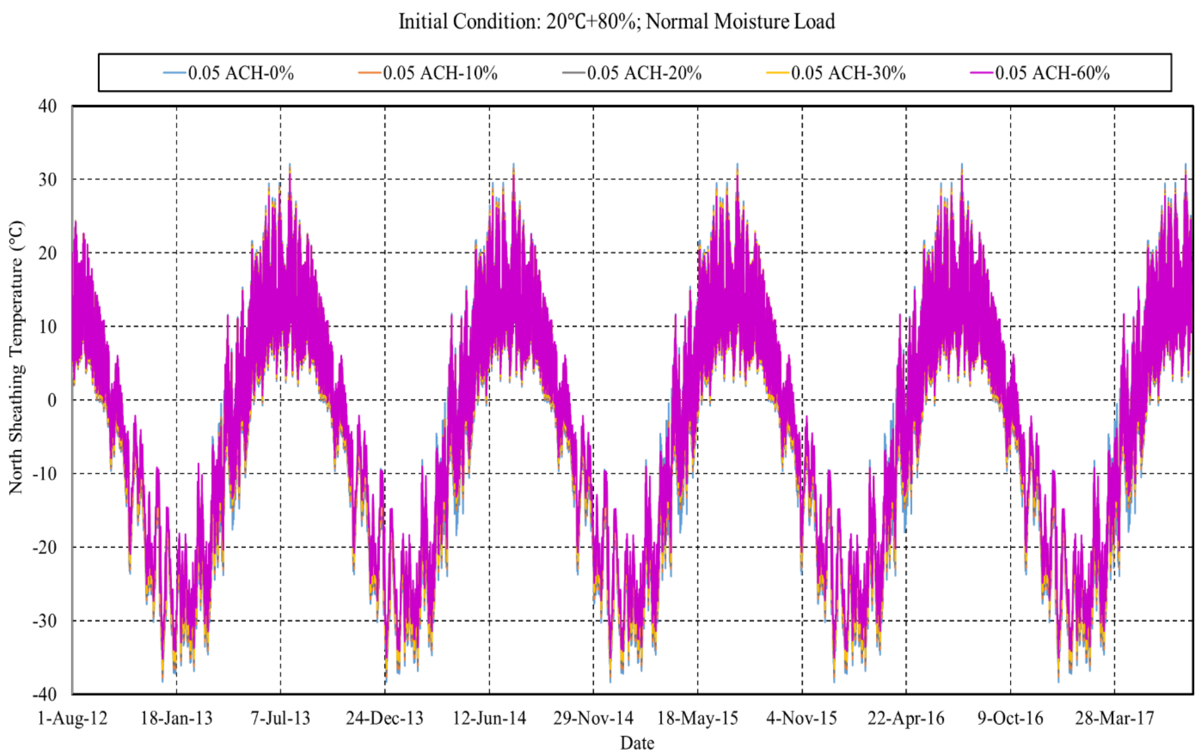


b) South sheathing MC (Case 6~10).

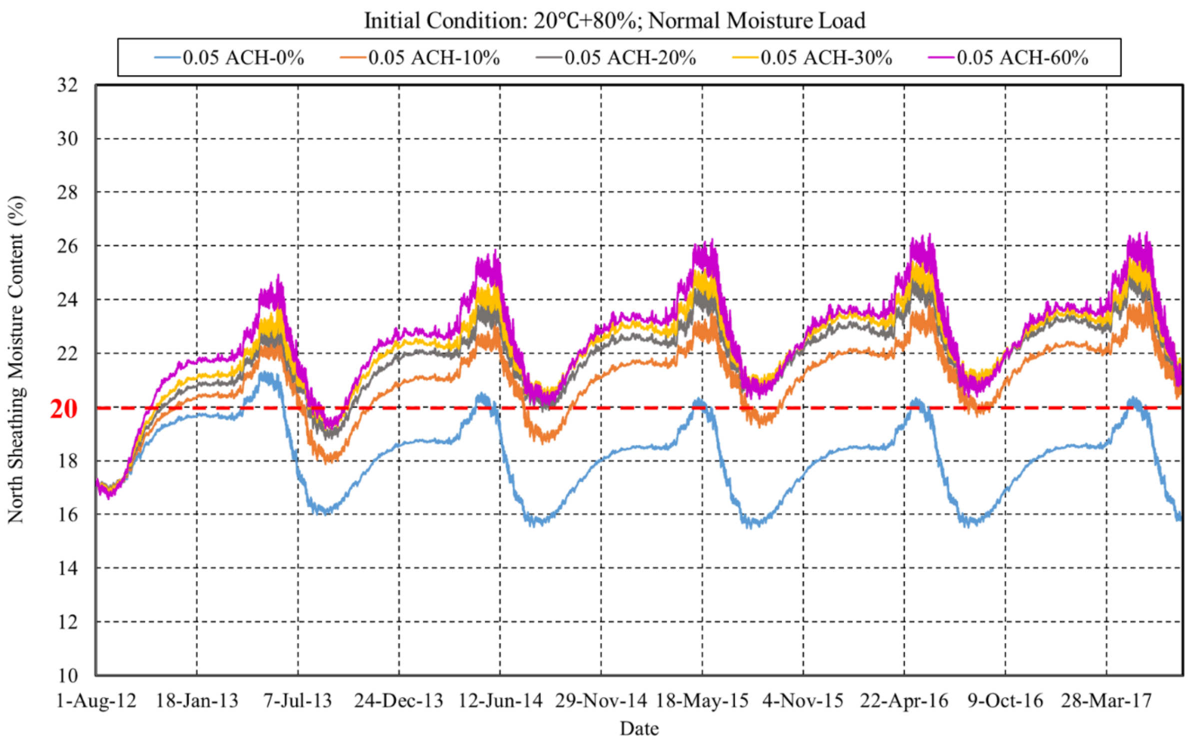
Figure 6-8. Temperature and MC level of South plywood sheathing under different ceiling air leakage rates (initial condition is 20℃/80%, normal moisture load, un-intentional ventilation rate is 0.05ACH) of un-ventilated attic model during the five-year simulation period (Case 6~10).

Figure 6-8-a) & b) show temperature and moisture content of South plywood sheathing under different ceiling air leakage rates (initial condition is 20℃/80%, normal moisture load, un-intentional ventilation rate is 0.05ACH) of un-ventilated attic model during five-year simulation period (from Aug. 1st, 2012 to July 31st, 2017). It's easy to see that temperature profiles of South sheathing in five scenarios almost coincide. The average temperature values of five scenario are -5.69℃, -5.43℃, -5.19℃, -4.95℃ and -4.30℃. The range of temperatures of south sheathing in five scenarios are -38.39℃~34.55℃, -37.76℃~34.02℃, -37.22℃~33.74℃, -36.68℃~33.61℃ and -35.19℃~33.22℃, respectively.

MC levels of South sheathing in five scenarios increase with the increase of ceiling air leakage rates, and MC profiles periodically and slightly increase year by year except for when the ceiling air leakage rate is 0%. When ceiling air leakage rate is 0%, MC level is generally under 20% which is the safety line for mold growth and moisture damages. Maximum MC level of other four scenarios are 24.44%, 26.12%, 26.75% and 27.66% when ceiling air leakage rate are 10%, 20%, 30%, 60%, which means higher risks of moisture related problems as long as there is ceiling air penetration and compared to the initial condition of south sheathing at 20℃/60% with un-intentional infiltration rate of 0.05ACH and normal indoor moisture load.



a) North sheathing temperature (Case 6~10).



b) North sheathing MC (Case 6~10).

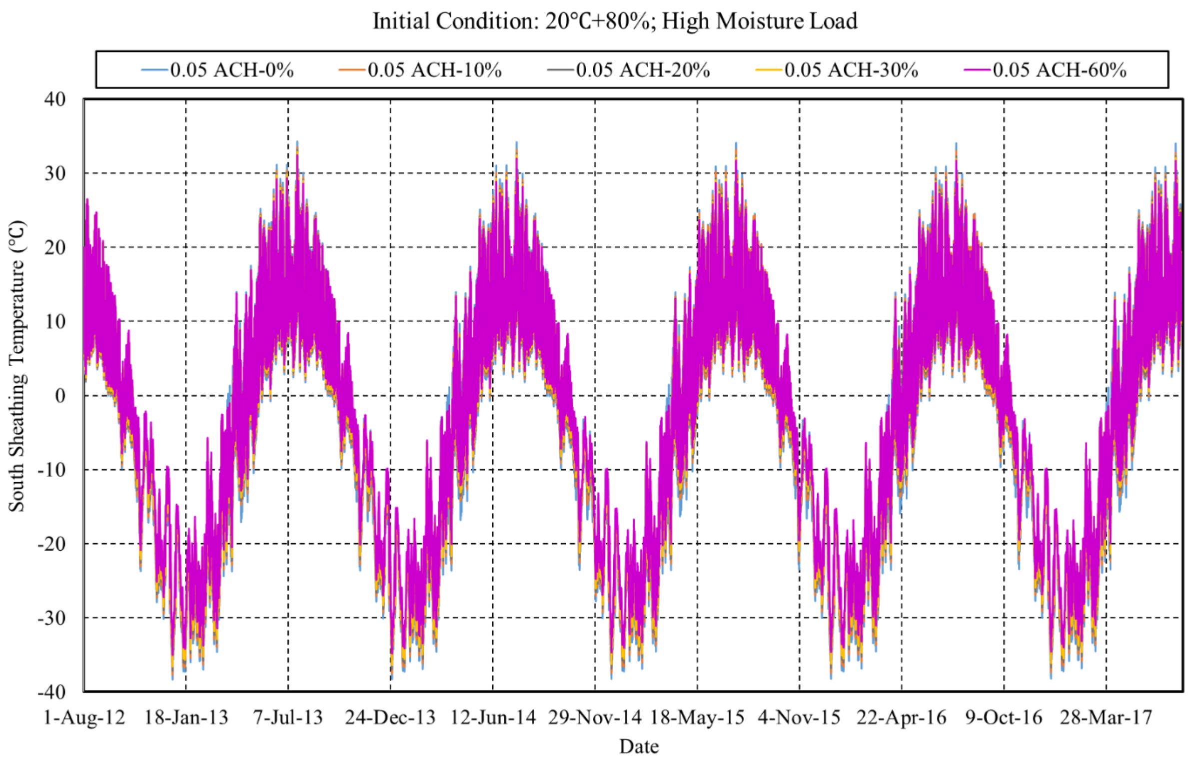
Figure 6-9. Temperature and MC level of North plywood sheathing under different ceiling air leakage rates (initial condition is 20℃/80%, normal moisture load, un-intentional ventilation rate is 0.05ACH) of un-ventilated attic model during the five-year simulation period (Case 6~10).

Figure 6-9-a) & b) show temperature and moisture content of North plywood sheathing under different ceiling air leakage rates (initial condition is 20℃/80%, normal moisture load, un-intentional ventilation rate is 0.05ACH) of un-ventilated attic model during the five-year simulation period (from Aug. 1st, 2012 to July 31st, 2017). It's easy to see that temperature profiles of North sheathing in five scenarios almost coincide. The average temperature values of five scenario are -6.04℃, -5.79 ℃, -5.55℃, -5.31℃ and -4.66℃. The range of temperatures of south sheathing in five scenarios are -38.33℃~32.15℃, -37.70℃~31.62℃, -37.16℃~31.31℃, -36.62℃~31.15℃ and -35.11℃~30.72℃, respectively.

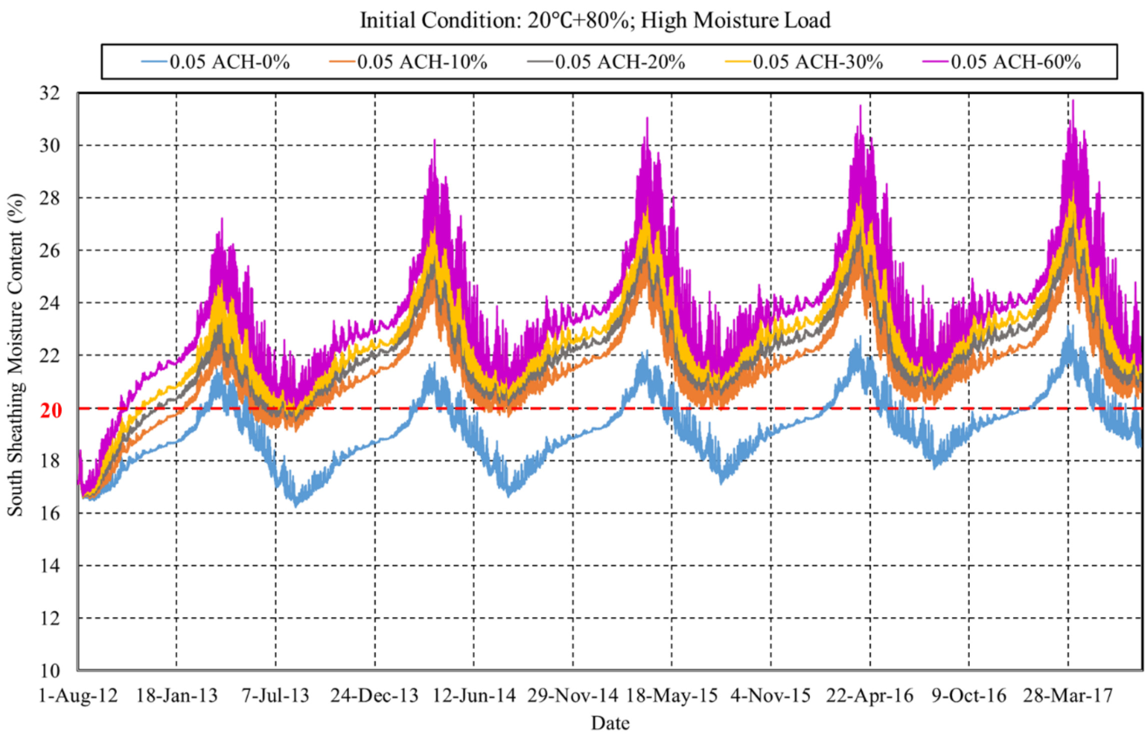
MC levels of North sheathing in five scenarios increase with the increase of ceiling air leakage rates, and MC profiles periodically and slightly increase year by year except for when the ceiling air leakage rate is 0%. When ceiling air leakage rate is 0%, MC level generally under 20% which is the safety line for mold growth and moisture damages. The maximum MC level of other four scenarios are 21.33%, 24.17%, 25.31%, 25.74% and 26.52% when ceiling air leakage rate are

0%,10%, 20%, 30%, 60%, which means moisture related problems have high risks to occur as long as there is ceiling air penetration when initial condition of south sheathing is 20℃/80% and indoor condition is under normal moisture load.

In general, temperatures of South sheathing are slightly higher than which of North sheathing in all scenarios, while MC levels of South sheathing are slightly lower than which of North sheathing in all scenarios. This difference is attributed to the difference in solar radiation, the amount of solar radiation in south orientation is higher than that in north.



a) South sheathing temperature (Case 11~15).

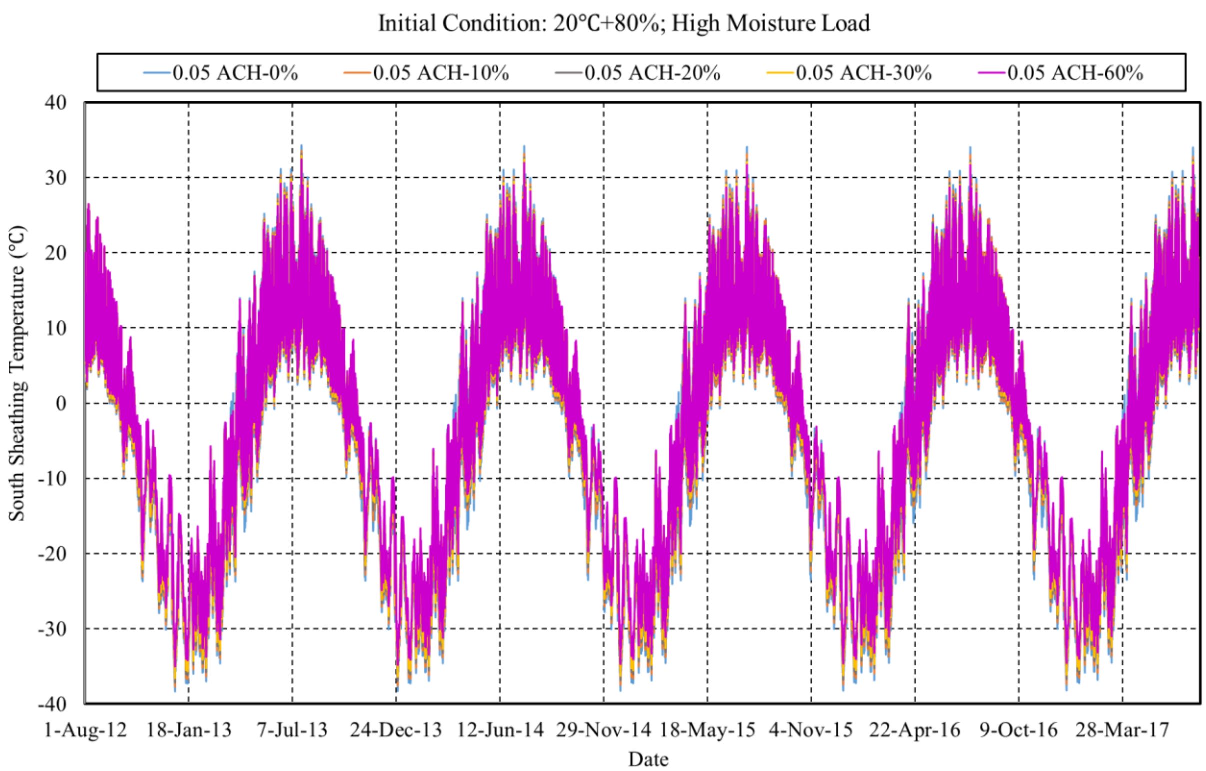


b) South sheathing MC (Case 11~15).

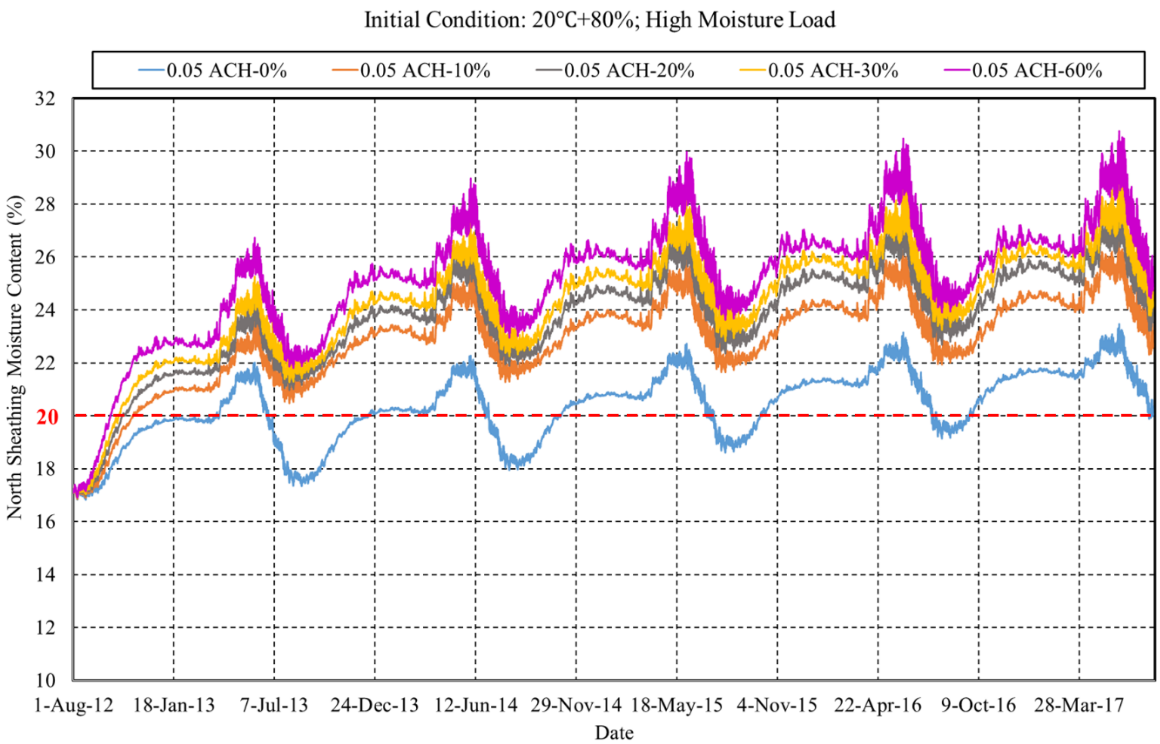
Figure 6-10. Temperature and MC level of South plywood sheathing under different ceiling air leakage rates (initial condition is 20℃/80%, high moisture load, un-intentional ventilation rate is 0.05ACH) of un-ventilated attic model during the five-year simulation period (case 11~15).

Figure 6-10-a) & b) show temperature and moisture content of South plywood sheathing under different ceiling air leakage rates (initial condition is 20℃/80%, high moisture load, un-intentional ventilation rate is 0.05ACH) of un-ventilated attic model during the five-year simulation period (from Aug. 1^{st}, 2012 to July 31^{st}, 2017). It's easy to see that temperature profiles of South sheathing in five scenarios almost coincide. The average temperature values of five scenario are -5.69℃, -5.43℃, -5.18℃, -4.95℃ and -4.30℃. The range of temperatures of south sheathing in five scenarios are -38.37℃~34.66℃, -37.72℃~34.20℃, -37.18℃~33.75℃, -36.65℃~33.67℃ and -35.14℃~33.34℃, respectively.

MC levels of South sheathing in five scenarios increase with the increase of ceiling air leakage rates, and MC profiles periodically and slightly increase year by year except for when ceiling air leakage rate is 0%. When ceiling air leakage rate is 0%, MC level generally under 22% with an increasing trend. The maximum MC level of other four scenarios are 24.80%, 26.36%, 26.74% and 27.64% when ceiling air leakage rate are 10%, 20%, 30%, 60%, which means that much greater risks of moisture related problems under ceiling air infiltration when indoor moisture load is high.



a) North sheathing temperature (Case 11~15).



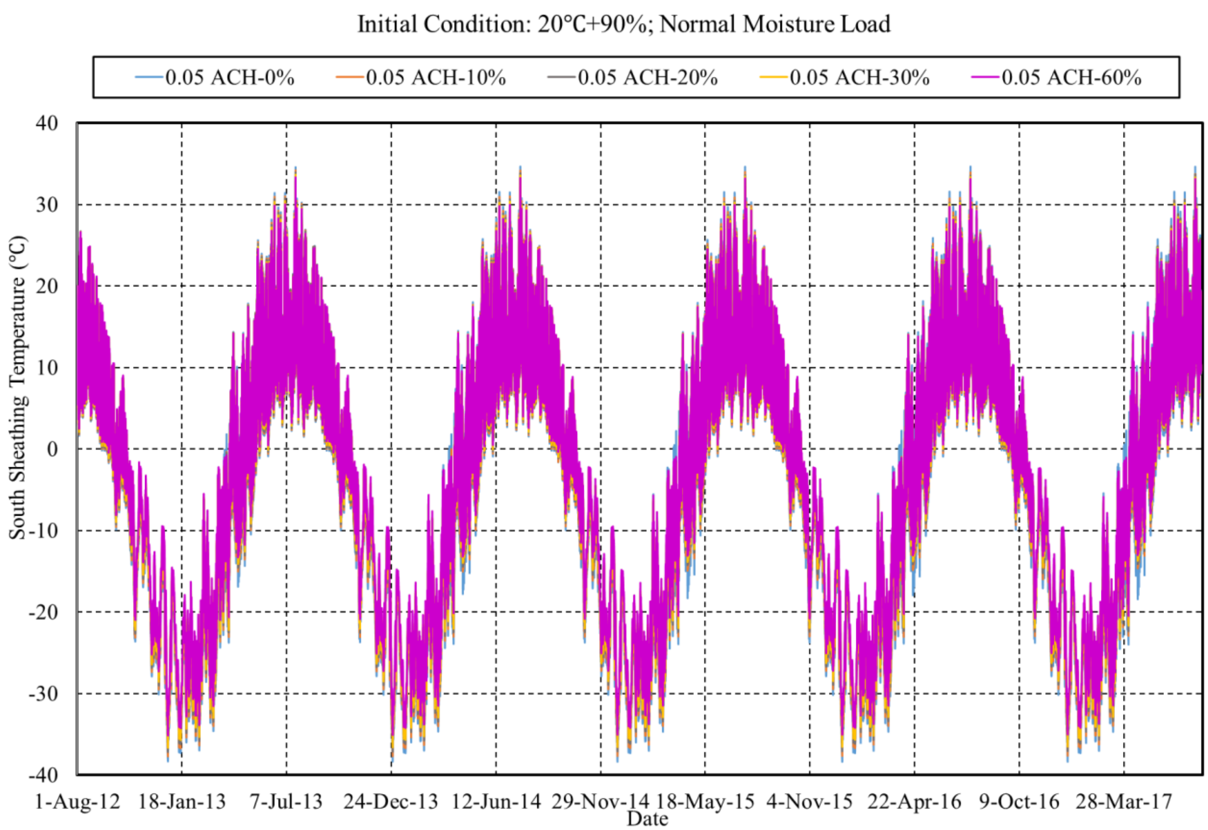
b) North sheathing MC (Case 11~15).

Figure 6-11. Temperature and MC level of North plywood sheathing under different ceiling air leakage rates (initial condition is 20℃/80%, high moisture load, un-intentional ventilation rate is 0.05ACH) of un-ventilated attic model during the five-year simulation period (Case 11~15).

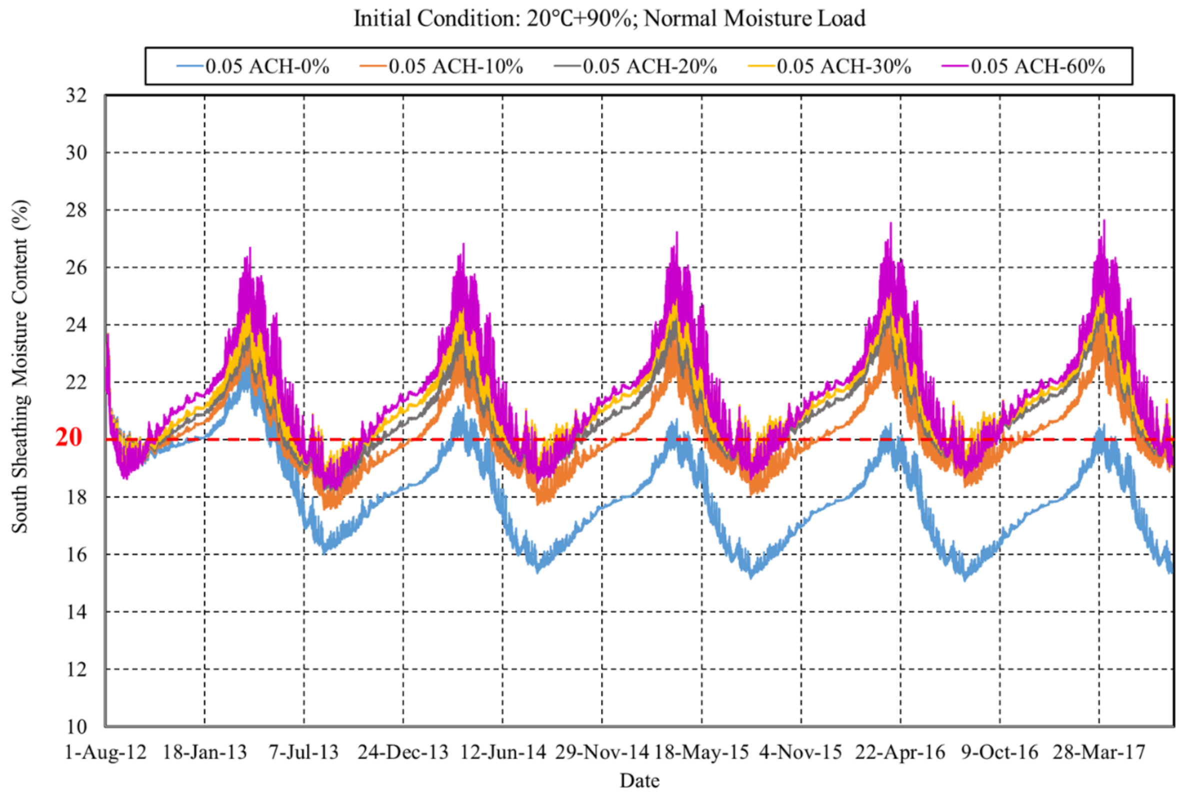
Figure 6-11-a) & b) show temperature and moisture content of North plywood sheathing under different ceiling air leakage rates (initial condition is 20℃/80%, high moisture load, un-intentional ventilation rate is 0.05ACH) of un-ventilated attic model during the five-year simulation period (from Aug. 1st, 2012 to July 31st, 2017). It's easy to see that temperature profiles of North sheathing in five scenarios almost coincide. The average temperature values of five scenario are -6.04℃, -5.78℃, -5.54℃, -5.31℃ and -4.66℃. The range of temperatures of south sheathing in five scenarios are -38.31℃~32.18℃, -37.66℃~31.67℃, -37.12℃~31.41℃, -36.60℃~31.14℃ and -35.09℃~30.76℃, respectively.

MC levels of North sheathing in five scenarios increase with the increase of ceiling air leakage rates, and MC profiles periodically and slightly increase year by year except for when ceiling air leakage rate is 0%. When ceiling air leakage rate is 0%, MC levels are generally under 22% with an increasing trend. Only MC levels in the fourth and fifth years exceed 22%, the maximum MC level can be found in the last year which can reach to around 23%. The maximum MC level of other four scenarios are 24.27%, 25.32%, 25.77% and 26.52% when ceiling air leakage rate are 10%, 20%, 30%, 60%, which means higher risks of moisture related problems as long as there is ceiling air penetration when initial condition of sheathing is at 20℃/80% and indoor condition is under high moisture load.

In general, temperatures of South sheathing are slightly higher than which of North sheathing in all scenarios, while MC levels of South sheathing are slightly lower than which of North sheathing in all scenarios. This difference is attributed to the difference in solar radiation, the amount of solar radiation in south orientation is higher than that in north.



a) South sheathing temperature (Case 16~20).



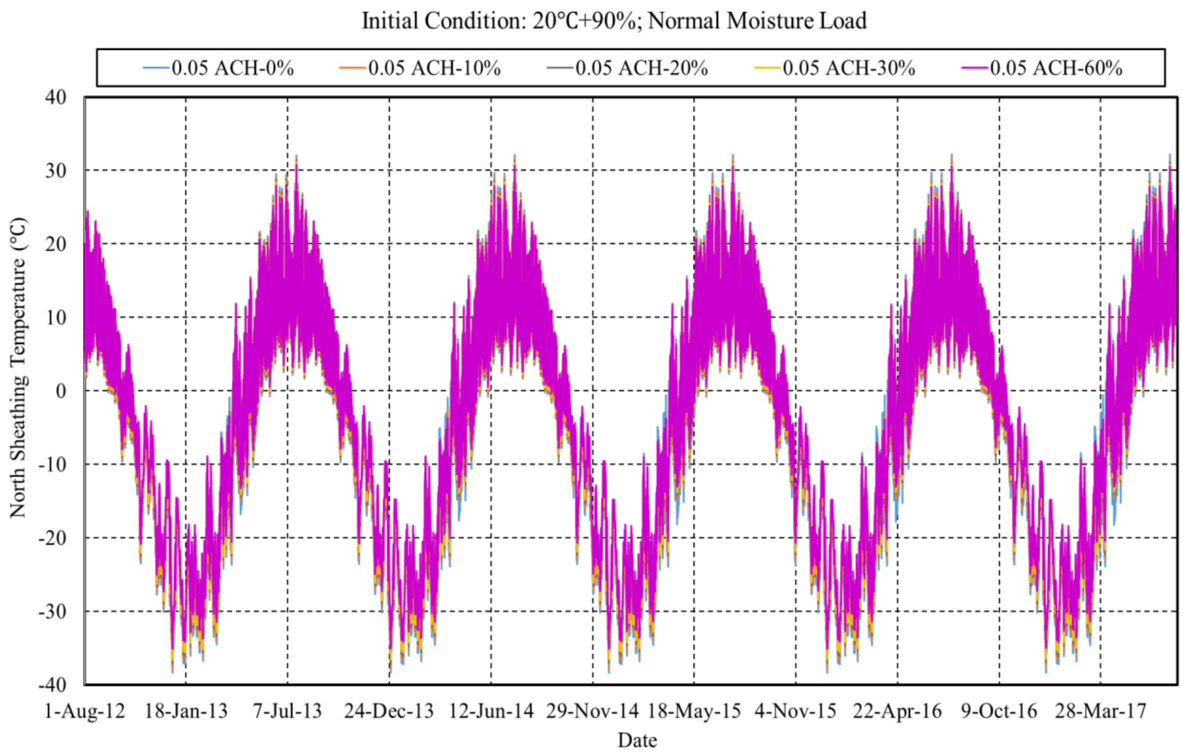
b) South sheathing MC (case 16~20).

Figure 6-12. Temperature and MC level of South plywood sheathing under different ceiling air leakage rates (initial condition is 20℃/90%, normal moisture load, un-intentional ventilation rate is 0.05ACH) of un-ventilated attic model during the five-year simulation period (Case 16~20).

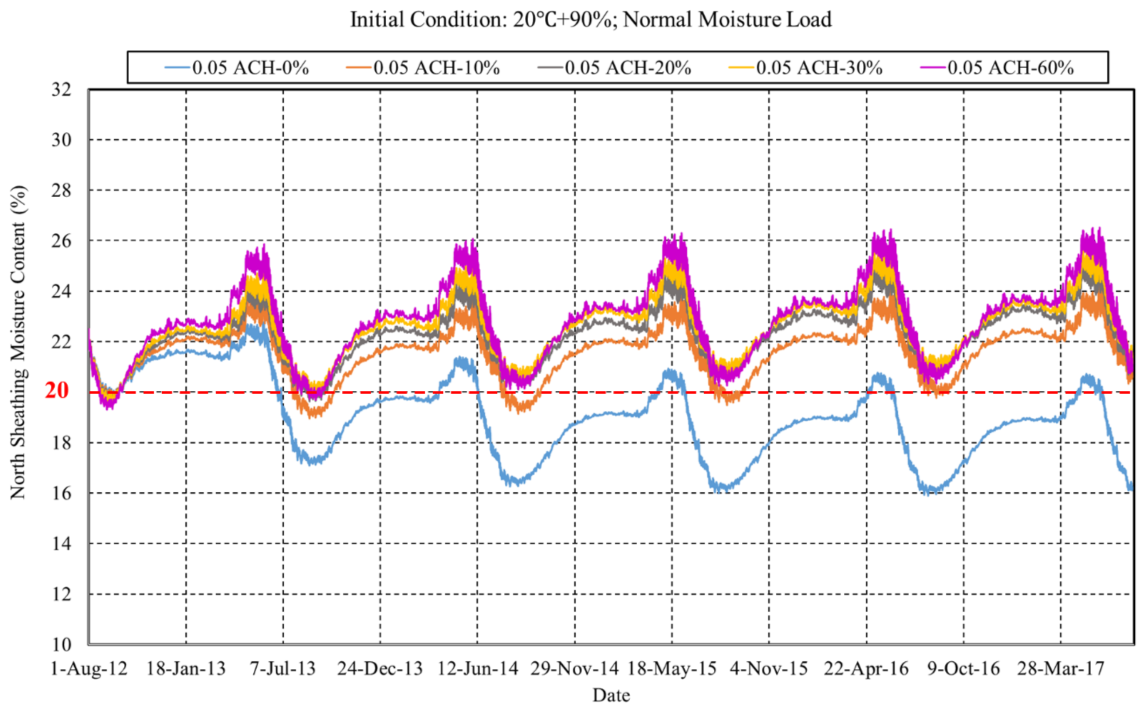
Figure 6-12-a) & b) show temperature and moisture content of South plywood sheathing under different ceiling air leakage rates (initial condition is 20℃/90%, normal moisture load, un-intentional ventilation rate is 0.05ACH) of un-ventilated attic model during the five-year simulation period (from Aug. 1st, 2012 to July 31st, 2017). It's easy to see that temperature profiles of South sheathing in five scenarios almost coincide. The average temperature values of five scenario are -5.69℃, -5.43℃, -5.18℃, -4.95℃ and -4.30℃. The range of temperatures of south sheathing in five scenarios are -38.37℃~34.66℃, -37.72℃~34.20℃, -37.18℃~33.95℃, -36.65℃~33.67℃ and -35.14℃~33.34℃, respectively.

MC levels of South sheathing in five scenarios increase with the increase of ceiling air leakage rates, and MC profiles periodically and slightly increase year by year except for when ceiling air leakage rate is 0%. The maximum MC level of other four scenarios are 24.80%, 26.36%, 26.74%

and 27.64% when ceiling air leakage rate are 10%, 20%, 30%, 60%, which means there is higher risk of moisture related problems as long as there is ceiling air penetration when initial condition of south sheathing is at 20℃/90% and indoor condition is under normal moisture load.



a) North sheathing temperature (Case 16~20).



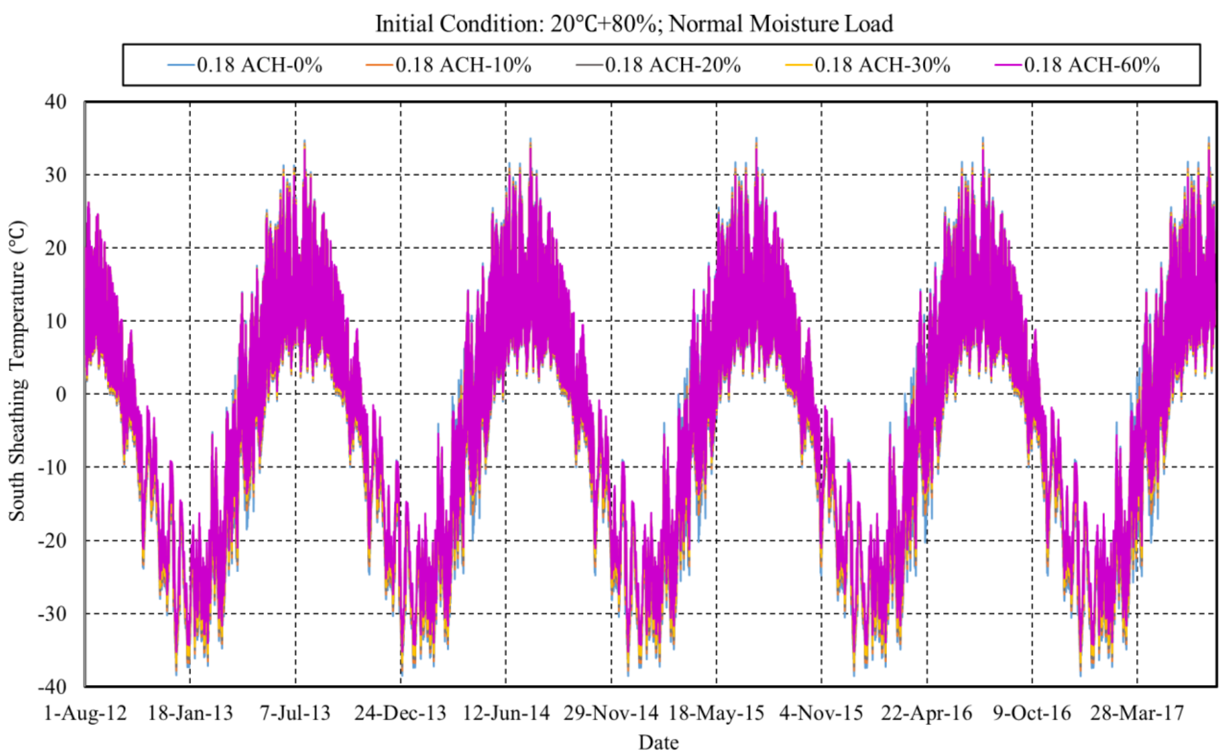
b) North sheathing MC (Case 16~20).

Figure 6-13. Temperature and MC level of North plywood sheathing under different ceiling air leakage rates (initial condition is 20℃/90%, normal moisture load, un-intentional ventilation rate is 0.05ACH) of un-ventilated attic model during the five-year simulation period (Case 16~20).

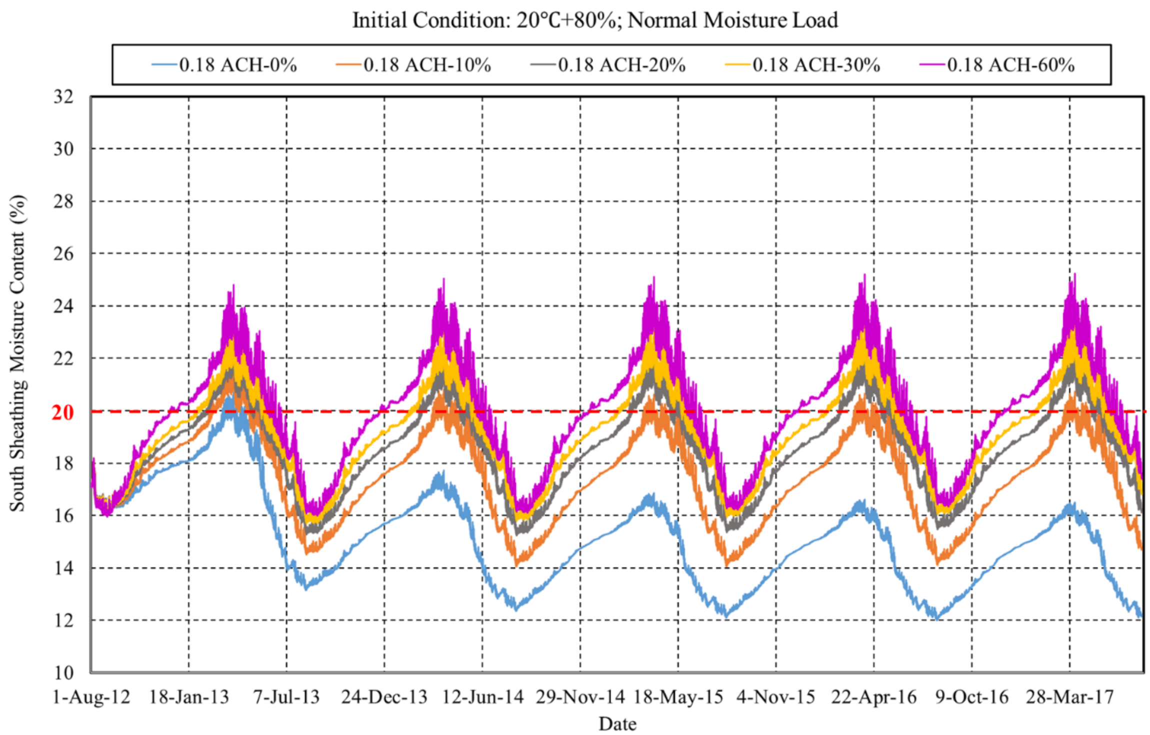
Figure 6-13-a) & b) show temperature and moisture content of North plywood sheathing under different ceiling air leakage rates (initial condition is 20℃/90%, normal moisture load, un-intentional ventilation rate is 0.05ACH) of un-ventilated attic model during the five-year simulation period (from Aug. 1st, 2012 to July 31st, 2017). It's easy to see that temperature profiles of North sheathing in five scenarios almost coincide. The average temperature values of five scenario are -6.05℃, -5.78℃, -5.54℃, -5.31℃ and -4.66℃. The range of temperatures of south sheathing in five scenarios are -38.31℃~32.18℃, -37.66℃~31.67℃, -37.12℃~31.41℃, -36.60℃~31.14℃ and -35.09℃~30.76℃, respectively.

MC levels of North sheathing in five scenarios increase with the increase of ceiling air leakage rates, and MC profiles periodically and slightly increase year by year except for when ceiling air leakage rate is 0%. The maximum MC level of other four scenarios are 24.27%, 25.32%, 25.78% and 26.52% when ceiling air leakage rate are 10%, 20%, 30%, 60%, which means there is higher risk of moisture related problems as long as there is ceiling air penetration. Even ceiling air leakage rate is zero, there is no enough drying potential to dry out plywood sheathing from initial condition 20℃/90%.

In general, temperatures of South sheathing are slightly higher than which of North sheathing in all scenarios, while MC levels of South sheathing are slightly lower than which of North sheathing in all scenarios. This difference is attributed to the difference in solar radiation, the amount of solar radiation in south orientation is higher than that in north.



a) South sheathing temperature (Case 21~25).

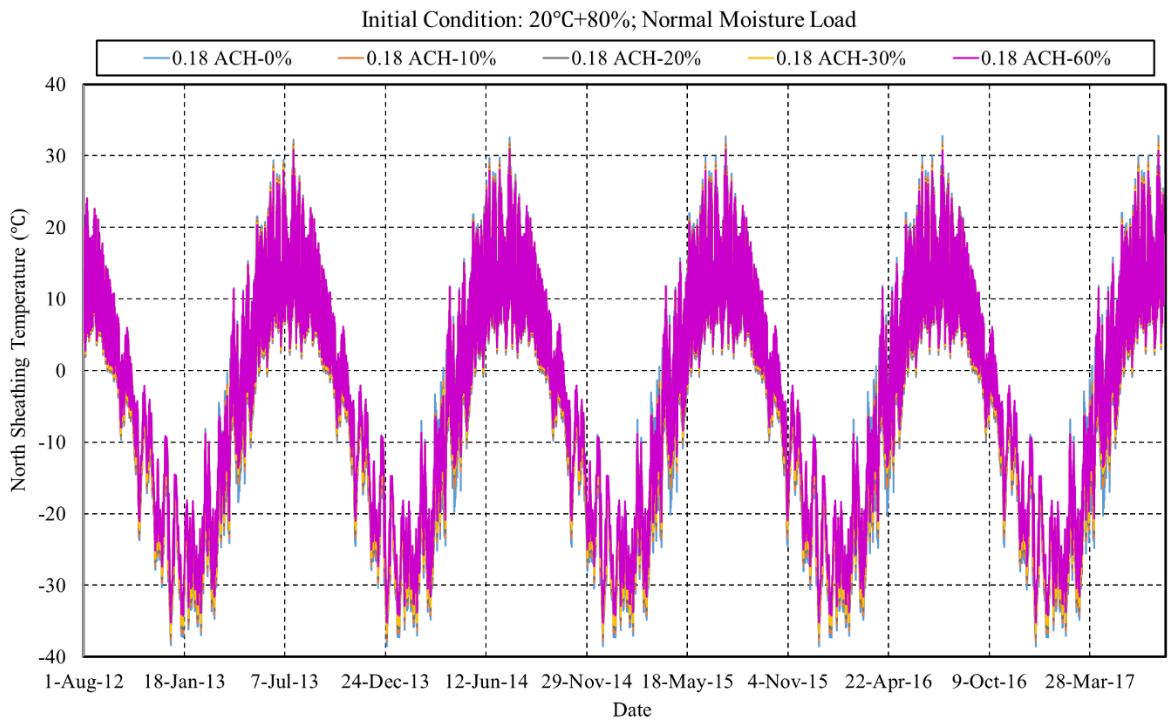


b) South sheathing MC (Case 21~25).

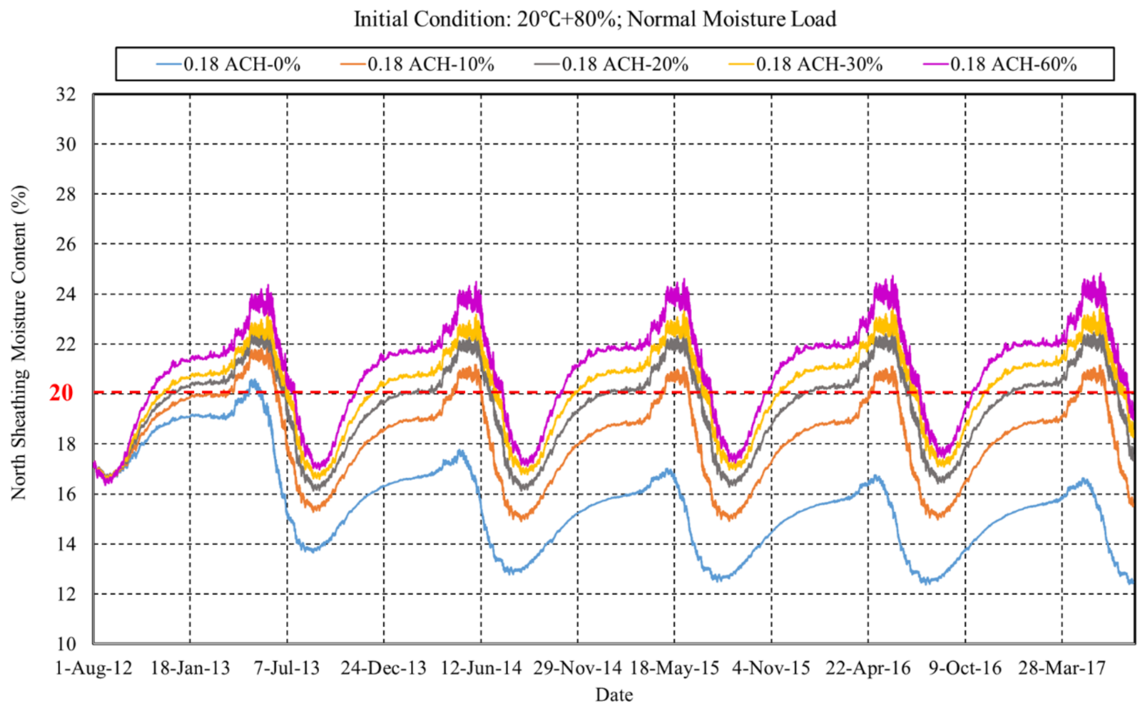
Figure 6-14. Temperature and MC level of South plywood sheathing under different ceiling air leakage rates (initial condition is 20℃/80%, normal moisture load, un-intentional ventilation rate is 0.18ACH) of un-ventilated attic model during the five-year simulation period (Case 21~25).

Figure 6-14-a) & b) show temperature and moisture content of South plywood sheathing under different ceiling air leakage rates (initial condition is 20℃/80%, normal moisture load, un-intentional ventilation rate is 0.18ACH) of un-ventilated attic model during the five-year simulation period (from Aug. 1st, 2012 to July 31st, 2017). It's easy to see that temperature profiles of South sheathing in five scenarios almost coincide. The average temperature values of five scenario are -5.75℃, -5.50℃, -5.26℃, -5.03℃ and -4.38℃. The range of temperatures of south sheathing in five scenarios are -38.55℃~35.11℃, -37.81℃~34.34℃, -37.26℃~34.00℃, -36.74℃~33.81℃ and -35.24℃~33.58℃, respectively.

MC levels of South sheathing in five scenarios increase with the increase of ceiling air leakage rates, and MC profiles periodically and slightly increase year by year except for when ceiling air leakage rate is 0% and 10%. When ceiling air leakage rates are 0% and 10%, MC level generally under 20% which is the safety line for mold growth. Maximum MC level of five scenarios are 20.72%, 21.89%, 22.68%, 23.62% and 25.24% when ceiling air leakage rate are 0%, 10%, 20%, 30%, 60%, which means there is higher risk of moisture related problems when ceiling air leakage rate exceeds 10%. Especially when ceiling air leakage rate is 0%, MC level maintains lower than 16% during five-year simulation period.



a) North sheathing temperature (Case 21~25).



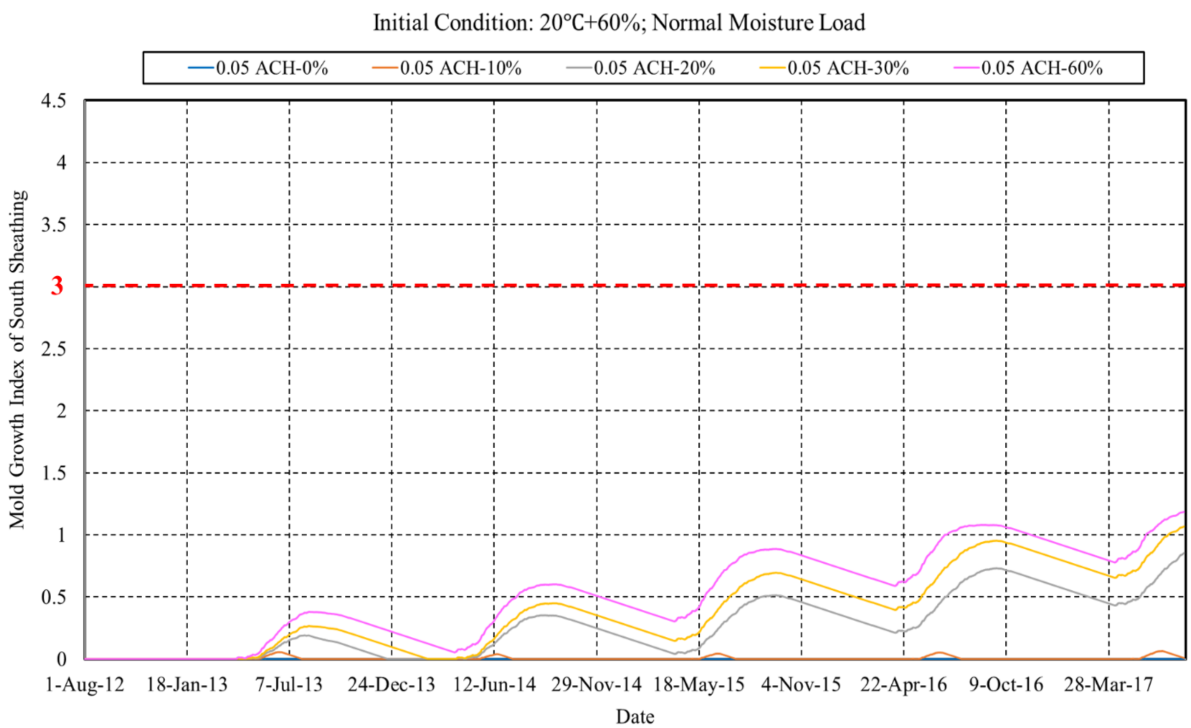
b) North sheathing MC (Case 21~25).

Figure 6-15. Temperature and MC level of North plywood sheathing under different ceiling air leakage rates (initial condition is 20℃/80%, normal moisture load, un-intentional ventilation rate is 0.18ACH) of un-ventilated attic model during the five-year simulation period (case 21~25).

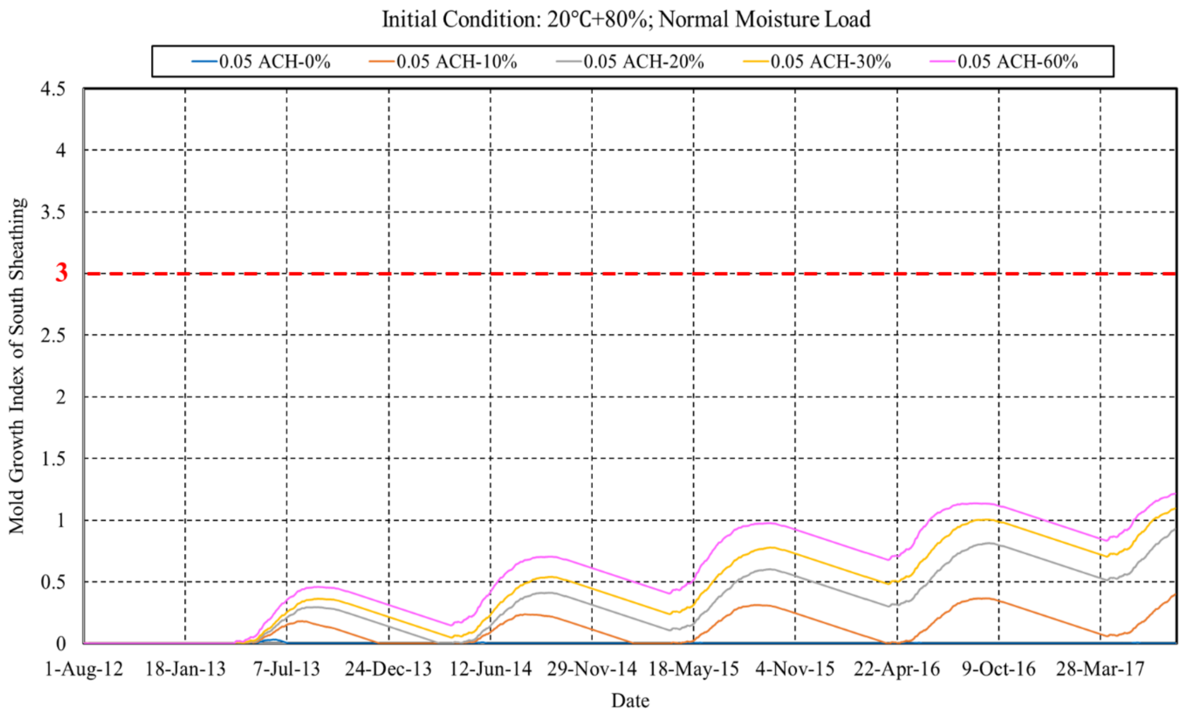
Figure 6-15-a) & b) show temperature and moisture content of North plywood sheathing under different ceiling air leakage rates (initial condition is 20℃/80%, normal moisture load, un-intentional ventilation rate is 0.18ACH) of un-ventilated attic model during the five-year simulation period (from Aug. 1st, 2012 to July 31st, 2017). It's easy to see that temperature profiles of North sheathing in five scenarios almost coincide. The average temperature values of five scenario are -6.11℃, -5.86 ℃, -5.62℃, -5.39℃ and -4.74℃. The range of temperatures of south sheathing in five scenarios are -38.49℃~32.81℃, -37.75℃~31.89℃, -37.20℃~31.54℃, -36.68℃~31.34℃ and -35.19℃~30.97℃, respectively.

MC levels of South sheathing in five scenarios increase with the increase of ceiling air leakage rates, and MC profiles periodically and slightly increase year by year except for when ceiling air leakage rate is 0% and 10%. When ceiling air leakage rates are 0% and 10%, MC level generally under 20% which is the safety line for mold growth. Maximum MC level of five scenarios are 20.60%, 21.87%, 22.62%, 23.54% and 24.83% when ceiling air leakage rate are 0%, 10%, 20%, 30%, 60%. Compared to the cases with 0.05ACH infiltration rate, the increase of background infiltration, which functions as attic ventilation, can reduce the risk of moisture damages although there are moisture damage risks when the ceiling air leakage rate exceeds 10%. When the ceiling air leakage rate is eliminated, i.e. 0%, MC level maintains around 16% during five-year simulation period.

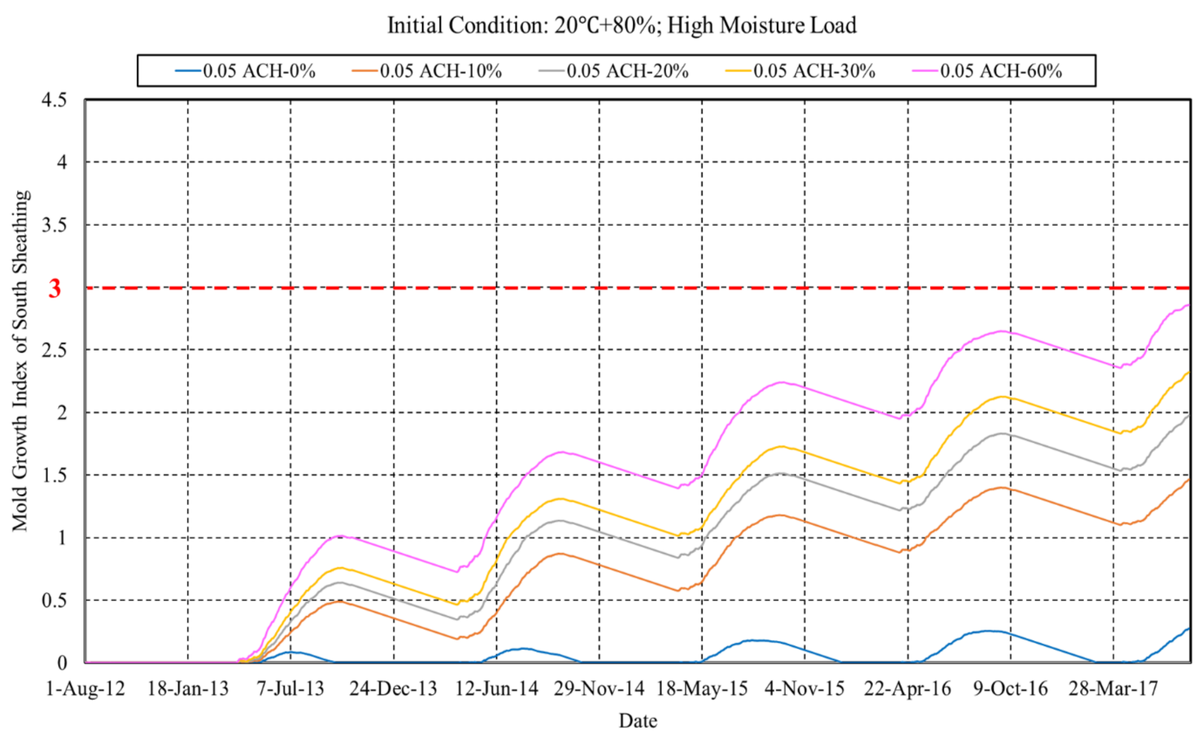
In general, temperatures of South sheathing are slightly higher than which of North sheathing in all scenarios, while MC levels of South sheathing are slightly lower than which of North sheathing in all scenarios. This difference is attributed to the difference in solar radiation, the amount of solar radiation in south orientation is higher than that in north.



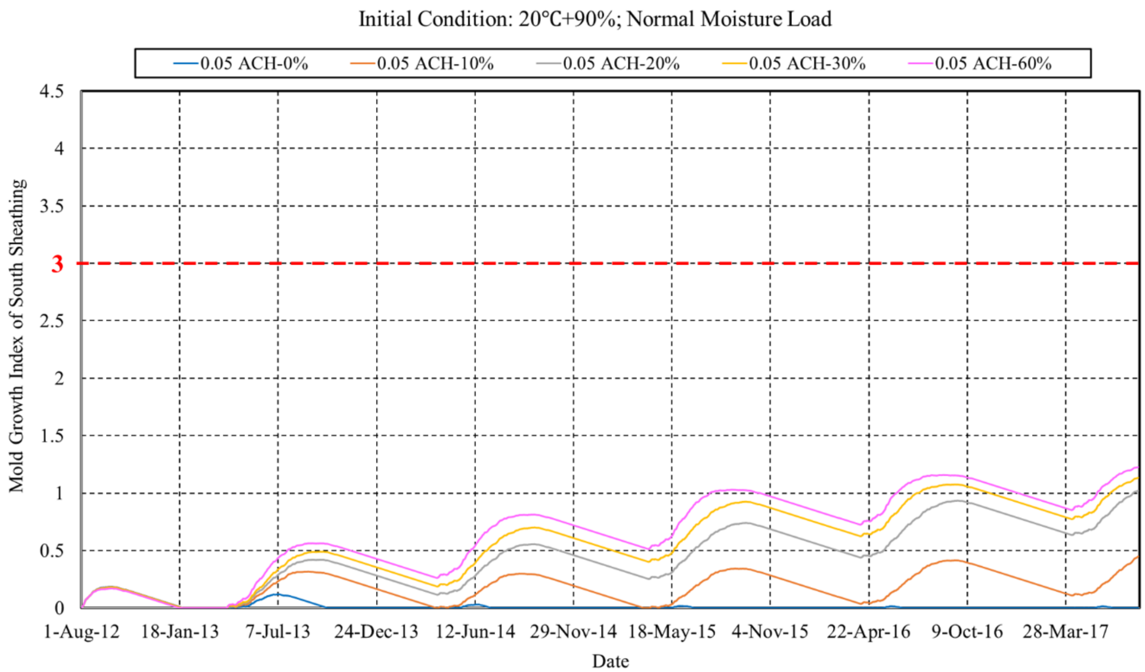
a) Mold Growth Index of South sheathing (initial condition: 20℃+60%; un-infiltration rate:0.05ACH; normal moisture load), (Case 1~5).



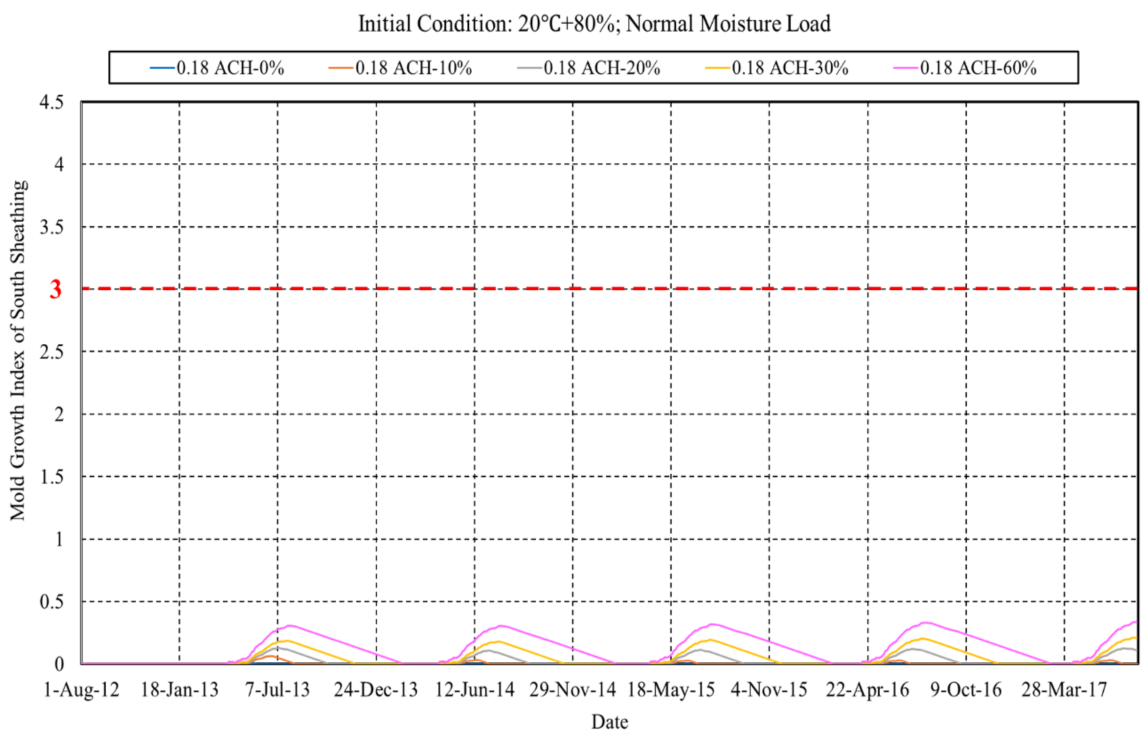
b) Mold Growth Index of South sheathing (initial condition: 20℃+80%; un-infiltration rate:0.05ACH; normal moisture load), (Case 6~10).



c) Mold Growth Index of South sheathing (initial condition: 20℃+80%; un-infiltration rate:0.05ACH; high moisture load), (Case 11~15).



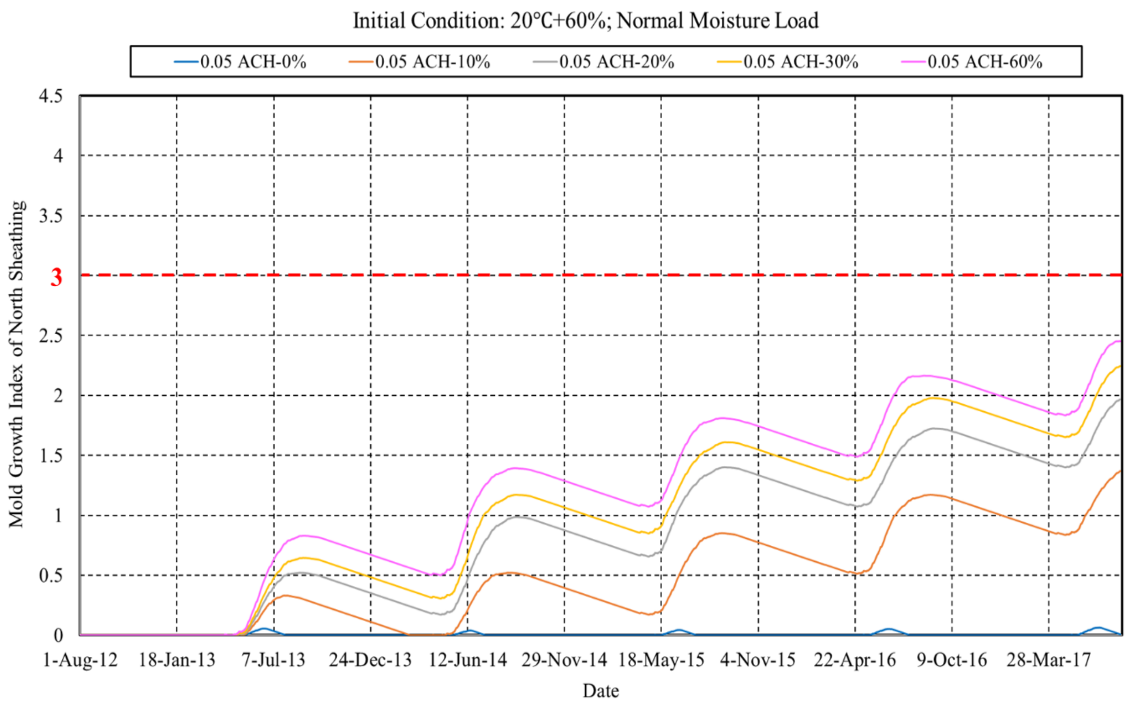
d) Mold Growth Index of South sheathing (initial condition: 20℃+90%; un-infiltration rate:0.05ACH; normal moisture load), (Case 16~20)



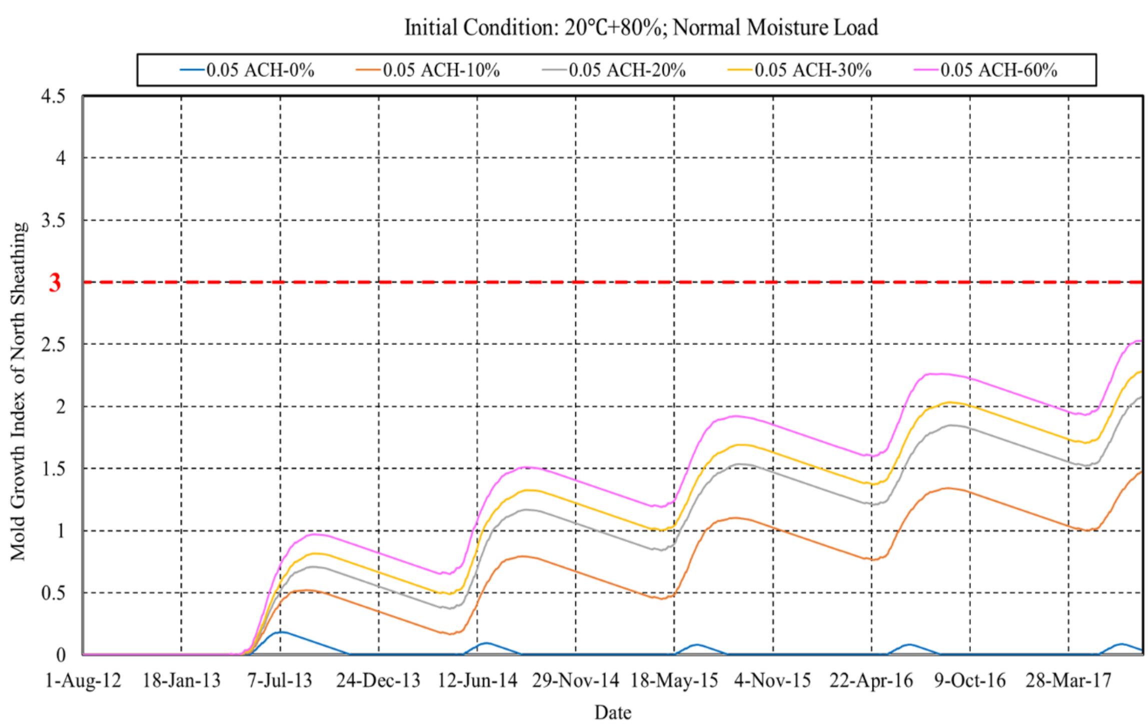
e) Mold Growth Index of South sheathing (initial condition: 20℃+80%; un-infiltration rate:0.18ACH; normal moisture load), (Case 21~25)

Figure 6-16. Mold Growth Index of South Sheathing of un-ventilated attic in different ceiling air leakage rates (0%, 10%, 20%, 30%, 60%) under different combinations of key parameters of 25 typical scenarios.

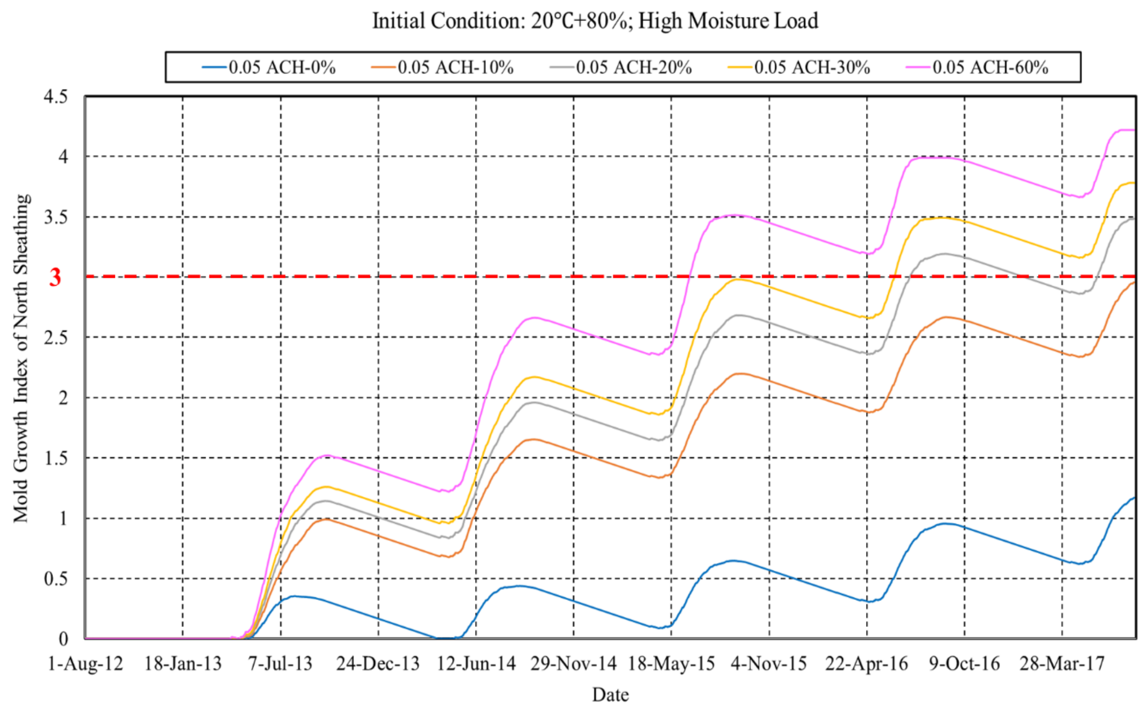
Figure 6-16 shows calculated Mold Growth Index of South Sheathing of un-ventilated attic in different ceiling air leakage rates (0%, 10%, 20%, 30%, 60%) under different combinations of key parameters of 25 typical scenarios. It's easy to see that Mold Growth Index increase with the increase of ceiling air leakage rates of all typical scenarios. All Mold Growth Index profiles of 25 typical scenarios show an annually periodical and slow-rising trend. And all values of Mold Growth Index are lower than three, a threshold recommended by ASHRAE. Mold Growth Index under three means no visible mold growth will be detected. Figure 6-16 a), b) & d) show the effect of initial condition, the mold growth index slightly increases with the increase of initial MC of plywood sheathing. Maximum value of Mold Growth Index can be found when initial MC level is 90%, which is still lower than 1.5 at the end of the simulation period. As a hygroscopic material, plywood sheathing has a cycle of absorbing and releasing moisture with the change of seasons. There is a dynamic moisture balance among plywood sheathing, attic air, indoor condition and outdoor condition. This phenomenon shows that the initial moisture in plywood sheathing in un-ventilated attic can be dried out over time and finally maintain at a relatively stable state. In other words, initial conditions of plywood sheathing have no significant effect on mold growth if other variables are controlled. Figure 6-16 b) & c) show the effect of indoor humidity level, Mold Growth Index have a visibly increase, around two times, from normal moisture load to high moisture load. At the end of the simulation period, Mold Growth Index of high moisture load can reach to around 3 and there is a tendency to continue to increase. That means indoor conditions have a much greater influence on mold growth in plywood sheathing in un-ventilated attic, and there is high risk of moisture damage when indoor condition in a high humidity level if other variables are controlled. Figure 6-16 b) & e) show the effect of un-intentional infiltration rate (background ventilation). Background ventilation is useful method to reduce the risk of mold growth in un-ventilated attic based on the comparison of Mold Growth Index value. Mold Growth Index under 0.05 ACH slowly increase to less than 1.5 until the end of simulation period, while under 0.18 ACH, the Mold Growth Index maintains less than 0.5 during the whole simulation period and no upward trend can be found. This phenomenon illustrates ventilation is a useful method to reduce the risk mold growth, adapt ventilation of attic is good to moisture removal and can reduce moisture-related problems.



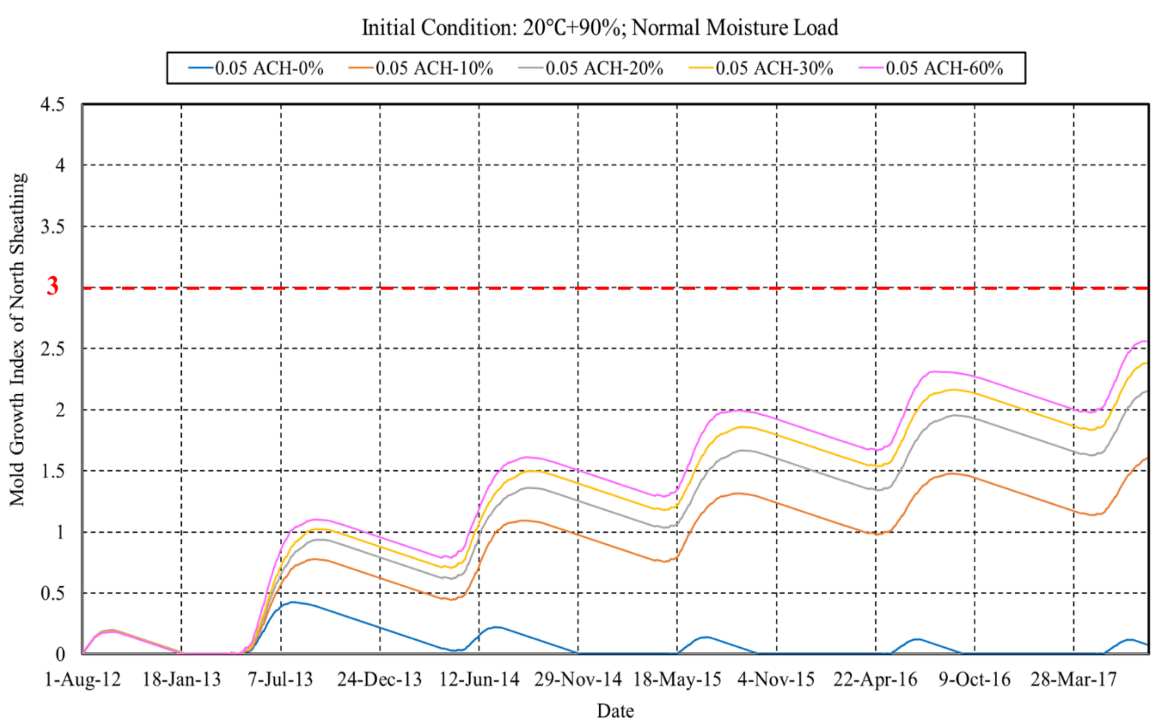
a) Mold Growth Index of North sheathing (initial condition: 20℃+60%; un-infiltration rate:0.05ACH; normal moisture load), (Case 1~5)



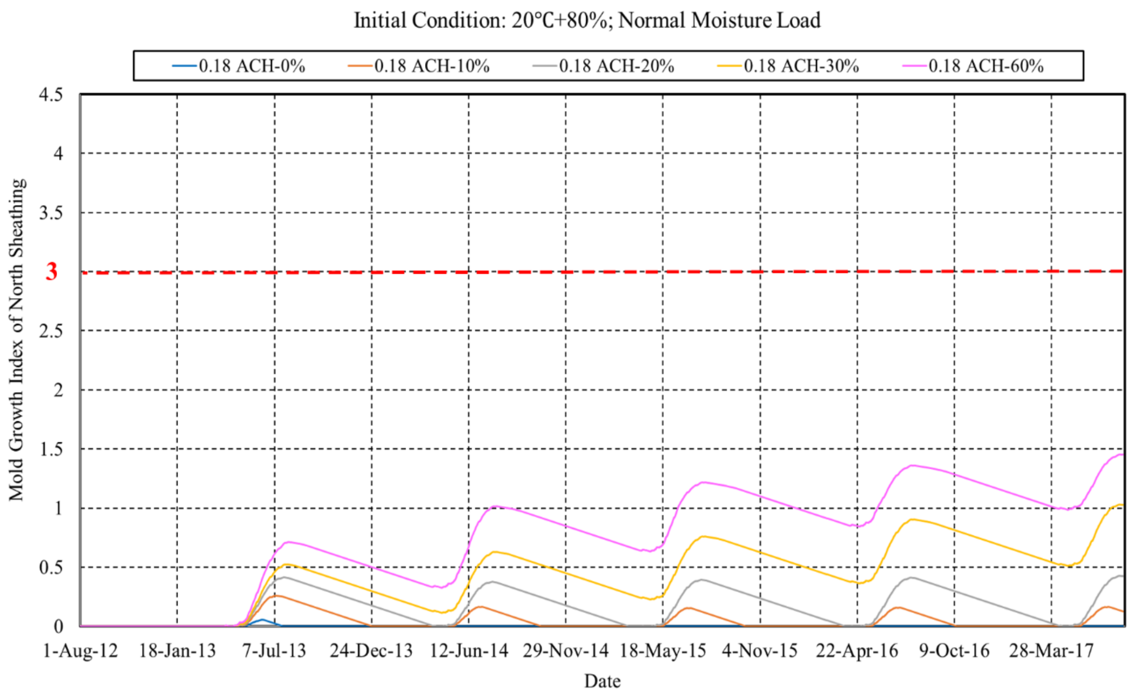
b) Mold Growth Index of North sheathing (initial condition: 20℃+80%; un-infiltration rate:0.05ACH; normal moisture load), (Case 6~10)



c) Mold Growth Index of North sheathing (initial condition: 20℃+80%; un-infiltration rate:0.05ACH; high moisture load), (Case 11~15)



d) Mold Growth Index of North sheathing (initial condition: 20℃+90%; un-infiltration rate:0.05ACH; normal moisture load), (Case 16~20)



e) Mold Growth Index of North sheathing (initial condition: 20℃+80%; un-infiltration rate:0.18ACH; normal moisture load), (Case 21~25).

Figure 6-17. Mold Growth Index of North Sheathing of un-ventilated attic in different ceiling air leakage rates (0%, 10%, 20%, 30%, 60%) under different combinations of key parameters of 25 typical scenarios.

Figure 6-17 shows calculated Mold Growth Index of North Sheathing of un-ventilated attic in different ceiling air leakage rates (0%, 10%, 20%, 30%, 60%) under different combinations of key parameters of 25 typical scenarios. In general, Mold Growth Index of North Sheathing are higher than that of South Sheathing of all scenario cases. This phenomenon is caused by the difference in solar radiation, the amount of solar radiation in south orientation is higher than that in north orientation in Kuujjuaq. Higher solar radiation can provide more drying potential to attic sheathing and then reduce the risk of moisture-related problems, especially for un-ventilated attic The effects of investigated variables of North sheathing are similar to those of South sheathing.

Table 6.7 lists the highest mold growth index values of plywood sheathing (south sheathing and north sheathing) under 25 typical scenarios of un-ventilated attic for further parametric study during the simulation period from Aug. 1st, 2012 to July 31st, 2017. The maximum value of Mold Growth Index is 4.22 which can be found in North sheathing of Case 15. Mold Growth Index of South sheathing of Case 1 and Case 21 maintain 0 which is the lowest value of all scenarios. In general, Mold Growth Index of North Sheathing is higher than that of South sheathing of same case. Highest Mold Growth Index can present the risk of different scenarios and longer simulation period also can be performed for long-term prediction.

Table 6.8. Highest Mold Growth Index of plywood sheathing of un-ventilated attic (25 typical scenarios under further parametric study) during the whole simulation period.

Case Name	**Detailed Case Description**	**Highest Mold Growth Index of South Sheathing**	**Highest Mold Growth Index of North Sheathing**
Case 1	• **0.05 ACH** (Un-intentional Infiltration); • **EN15026 Normal Moisture Load** (Indoor Conditions); • **20 ℃+60%** (Initial Conditions of Plywood Sheathing); • **0%** (Ceiling Air Leakage Rate).	0	0.06
Case 2	• **0.05 ACH** (Un-intentional Infiltration); • **EN15026 Normal Moisture Load** (Indoor Conditions); • **20 ℃+60%** (Initial Conditions of Plywood Sheathing); • **10%** (Ceiling Air Leakage Rate).	0.06	1.37
Case 3	• **0.05 ACH** (Un-intentional Infiltration); • **EN15026 Normal Moisture Load** (Indoor Conditions); • **20 ℃+60%** (Initial Conditions of Plywood Sheathing); • **20%** (Ceiling Air Leakage Rate).	0.85	1.97
Case 4	• **0.05 ACH** (Un-intentional Infiltration); • **EN15026 Normal Moisture Load** (Indoor Conditions); • **20 ℃+60%** (Initial Conditions of Plywood Sheathing); • **30%** (Ceiling Air Leakage Rate).	1.07	2.25
Case 5	• **0.05 ACH** (Un-intentional Infiltration); • **EN15026 Normal Moisture Load** (Indoor Conditions); • **20 ℃+60%** (Initial Conditions of Plywood Sheathing); • **60%** (Ceiling Air Leakage Rate).	1.19	2.45
Case 6	• **0.05 ACH** (Un-intentional Infiltration); • **EN15026 Normal Moisture Load** (Indoor Conditions);	0.03	0.18

	• **<u>20 ℃+80%</u>** (Initial Conditions of Plywood Sheathing); • **<u>0%</u>** (Ceiling Air Leakage Rate).		
Case 7	• **<u>0.05 ACH</u>** (Un-intentional Infiltration); • **<u>EN15026 Normal Moisture Load</u>** (Indoor Conditions); • **<u>20 ℃+80%</u>** (Initial Conditions of Plywood Sheathing); • **<u>10%</u>** (Ceiling Air Leakage Rate).	0.40	1.47
Case 8	• **<u>0.05 ACH</u>** (Un-intentional Infiltration); • **<u>EN15026 Normal Moisture Load</u>** (Indoor Conditions); • **<u>20 ℃+80%</u>** (Initial Conditions of Plywood Sheathing); • **<u>20%</u>** (Ceiling Air Leakage Rate).	0.93	2.08
Case 9	• **<u>0.05 ACH</u>** (Un-intentional Infiltration); • **<u>EN15026 Normal Moisture Load</u>** (Indoor Conditions); • **<u>20 ℃+80%</u>** (Initial Conditions of Plywood Sheathing); • **<u>30%</u>** (Ceiling Air Leakage Rate).	1.96	2.28
Case 10	• **<u>0.05 ACH</u>** (Un-intentional Infiltration); • **<u>EN15026 Normal Moisture Load</u>** (Indoor Conditions); • **<u>20 ℃+80%</u>** (Initial Conditions of Plywood Sheathing); • **<u>60%</u>** (Ceiling Air Leakage Rate).	1.22	2.53
Case 11	• **<u>0.05 ACH</u>** (Un-intentional Infiltration); • **<u>EN15026 High Moisture Load</u>** (Indoor Conditions); • **<u>20 ℃+80%</u>** (Initial Conditions of Plywood Sheathing); • **<u>0%</u>** (Ceiling Air Leakage Rate).	0.27	1.17
Case 12	• **<u>0.05 ACH</u>** (Un-intentional Infiltration); • **<u>EN15026 High Moisture Load</u>** (Indoor Conditions); • **<u>20 ℃+80%</u>** (Initial Conditions of Plywood Sheathing); • **<u>10%</u>** (Ceiling Air Leakage Rate).	1.47	2.96
Case 13	• **<u>0.05 ACH</u>** (Un-intentional Infiltration); • **<u>EN15026 High Moisture Load</u>** (Indoor Conditions); • **<u>20 ℃+80%</u>** (Initial Conditions of Plywood Sheathing);	1.98	3.48

	• **20%** (Ceiling Air Leakage Rate).		
Case 14	• **0.05 ACH** (Un-intentional Infiltration); • **EN15026 High Moisture Load** (Indoor Conditions); • **20 ℃+80%** (Initial Conditions of Plywood Sheathing); • **30%** (Ceiling Air Leakage Rate).	2.32	3.78
Case 15	• **0.05 ACH** (Un-intentional Infiltration); • **EN15026 High Moisture Load** (Indoor Conditions); • **20 ℃+80%** (Initial Conditions of Plywood Sheathing); • **60%** (Ceiling Air Leakage Rate).	2.86	4.22
Case 16	• **0.05 ACH** (Un-intentional Infiltration); • **EN15026 Normal Moisture Load** (Indoor Conditions); • **20 ℃+90%** (Initial Conditions of Plywood Sheathing); • **0%** (Ceiling Air Leakage Rate).	0.19	0.43
Case 17	• **0.05 ACH** (Un-intentional Infiltration); • **EN15026 Normal Moisture Load** (Indoor Conditions); • **20 ℃+90%** (Initial Conditions of Plywood Sheathing); • **10%** (Ceiling Air Leakage Rate).	0.45	1.60
Case 18	• **0.05 ACH** (Un-intentional Infiltration); • **EN15026 Normal Moisture Load** (Indoor Conditions); • **20 ℃+90%** (Initial Conditions of Plywood Sheathing); • **20%** (Ceiling Air Leakage Rate).	1.02	2.15
Case 19	• **0.05 ACH** (Un-intentional Infiltration); • **EN15026 Normal Moisture Load** (Indoor Conditions); • **20 ℃+90%** (Initial Conditions of Plywood Sheathing); • **30%** (Ceiling Air Leakage Rate).	1.13	2.38
Case 20	• **0.05 ACH** (Un-intentional Infiltration); • **EN15026 Normal Moisture Load** (Indoor Conditions); • **20 ℃+90%** (Initial Conditions of Plywood Sheathing); • **60%** (Ceiling Air Leakage Rate).	1.23	2.56
Case 21	• **0.18 ACH** (Un-intentional Infiltration);	0	0.56

	• **EN15026 Normal Moisture Load** (Indoor Conditions); • **20 ℃+80%** (Initial Conditions of Plywood Sheathing); • **0%** (Ceiling Air Leakage Rate).		
Case 22	• **0.18 ACH** (Un-intentional Infiltration); • **EN15026 Normal Moisture Load** (Indoor Conditions); • **20 ℃+80%** (Initial Conditions of Plywood Sheathing); • **10%** (Ceiling Air Leakage Rate).	0.06	0.26
Case 23	• **0.18 ACH** (Un-intentional Infiltration); • **EN15026 Normal Moisture Load** (Indoor Conditions); • **20 ℃+80%** (Initial Conditions of Plywood Sheathing); • **20%** (Ceiling Air Leakage Rate).	0.13	0.43
Case 24	• **0.18 ACH** (Un-intentional Infiltration); • **EN15026 Normal Moisture Load** (Indoor Conditions); • **20 ℃+80%** (Initial Conditions of Plywood Sheathing); • **30%** (Ceiling Air Leakage Rate).	0.21	1.03
Case 25	• **0.18 ACH** (Un-intentional Infiltration); • **EN15026 Normal Moisture Load** (Indoor Conditions); • **20 ℃+80%** (Initial Conditions of Plywood Sheathing); • **60%** (Ceiling Air Leakage Rate).	0.34	1.45

6.3 Design Recommendations

When design criteria are defined as M≤3, key parameters for good attic construction under extremely cold climates of ventilated attic and un-ventilated attics are as follows:

- For ventilated attic, mold growth index values of all simulated scenarios under parametric study maintains zero. It means that ventilated attic is a better choice applied to extremely cold climate, which won’t have any moisture-related problem based on parametric studies as long as a reasonable air-tightness of the ceiling maintained.

- For un-ventilated attic, it's obvious that mold growth index value increase with the increase of ceiling air leakage rate and with the decrease of un-intentional air infiltration rate. The worst scenario of all simulation scenarios is "0.05ACH of un-intentional air infiltration + 60% of ceiling air leakage rate" and the best scenario is "0.18ACH of un-intentional air infiltration + 10% of ceiling air leakage rate". Therefore, it is critical to maintain the air leakage through ceiling to minimum. Un-intentional air infiltration of the un-ventilated attic provides some levels of ventilation and removal of moisture. It is also important to make sure that there is no built-in construction moisture in the attic structure for un-ventilated attic. Minimum moisture load of indoor conditions also can reduce moisture problems. The recommended combination of key parameters for un-ventilated attic design is as follow:
    - **Un-intentional Infiltration Rate:** 0.18ACH or more
    - **Indoor Conditions:** Normal Moisture Load
    - **Initial Conditions of Plywood Sheathing:** 20℃+80% or drier
    - **Ceiling Air Leakage Rate:** 0%~10%

Chapter 7 CONCLUSIONS

This chapter summarizes conclusions, research limitations, contributions and future works of this thesis:

7.1 Conclusions

This thesis investigates hygrothermal performance of ventilated and un-ventilated attics in extremely cold climate through field measurements and hygrothermal simulations. Field measured results indicate ventilated attics (House I and House II) have no moisture-related problems during the whole monitoring period (July 2013 to January 2015), and the MC levels of plywood sheathing is generally less than 20%, within safety range. On the contrary, un-ventilated attic (House III) has mold growth risks at the visually detectable. MC levels of plywood sheathing in un-ventilated attic almost exceed 20% during the whole monitoring period (July 2013 to August 2014). RH/T of attic air in both ventilated and un-ventilated attics have seasonal variations, and the RH levels are at high values (near 100%) during spring and winter periods. It can be concluded that, ventilated attic has a better hygrothermal performance than un-ventilated attic in extremely cold climate. Filter membrane installed in test house with ventilated attics has somewhat success to prevent moisture build-up within the attic space.

WUFI Plus models are setup for House I and House III and the models are validated by comparing to field measurements. Simulation results have a good agreement with field measurements of both ventilated and un-ventilated attics. Mold growth index of 3 is used as performance criteria for parametric study using the validated WUFI Plus models to provide design recommendations for moisture safe attic design in extremely cold climates. For ventilated attic, ceiling air leakage rates (10%, 30% and 60%) and attic ventilation rates (1ACH, 5ACH, 10ACH, hourly variable attic ventilation rates) are set as variables. Mold growth index are near zero under all scenarios of ventilated attic model. For un-ventilated attic, ceiling air leakage rates (10%, 30% and 60%) and un-intentional air infiltration rates (0.05ACH, 0.09ACH and 0.18ACH) are set as variables. Recommended range of these two parameters are 0%~30% and 0.09ACH~0.18ACH based on mold growth index calculation, respectively.

In general, both hygrothermal simulation (WUFI Plus model) and field measurements indicate ventilated attics has a better hygrothermal performance than un-ventilated attics which is a suggested construction that can be used in extremely cold climate. Design recommendations of ventilated and un-ventilated attics are provided to give guideline for low-energy sustainable housing for Canadian North. Validated WUFI Plus models can also be applied to other climates to offer design guideline.

The detailed findings based on field measurements, parametric study for model validation and parametric study for design recommendations are as follows:

1. The analysis of field monitoring of the hygrothermal performance of three attic venting systems in Canadian northern regions shows that:

- Ventilated cold attics with filter membranes have acceptable hygrothermal conditions.
    - House I has one location with MC level remained above 20% for about two months during the winter time from Jan. to end of Feb. 2014 but dried to 11% during the summer;
    - House II has five locations with MC levels remained above 20% for a few months from winter to spring time, typically peaked during the spring time but be able to dry to below 11% during the summer.
    - Hygrothermal performance of attic in House I is slightly better than that in House II. In addition to the difference in venting strategies, other factors such as moisture loads from indoors, the airtightness of the ceilings, and local weather conditions may also have attributed to the difference in the hygrothermal performance of these two attics.
    - For both House I and House II, no mold growth risk was identified on the plywood sheathing surfaces for the monitoring period although some of the surfaces experienced high level of MCs. The duration of favorable conditions is not long enough to sustain considerable mold growth. However, for the long-term performance, whether the seasonal variations of MC levels will pose risks for mold growth and decay needs further investigation.
- Un-ventilated cold attic has high risk of moisture problems.
    - The initial MC levels in plywood sheathing and wood truss were higher in the un-ventilated attic compared to the other two ventilated attics. An increasing trend of MC levels was observed at the end of the first summer;
    - MC levels at most locations remained above 20% year-round with substantial increase in MC during spring from March to end of April 2014;

- Much slower drying in un-ventilated attic was observed during the summer compared to the ventilated attic in House II;
- MC levels at most locations remained above 20-25% at the end of the summer 2014;
- There are much higher risks for mold growth and decay.

2. Parametric study results of hygrothermal performance of ventilated and un-ventilated attics (House I and House III) based on validated WUFI Plus models indicate:

- Attic ventilation rates (1ACH, 5ACH, 10ACH) and ceiling air leakage rates (10%, 30%, 60%) have no significant effect on hygrothermal performance of ventilated attic (House I) in terms of temperature and relative humidity when un-intentional air infiltration and indoor conditions are controlled.

- Ceiling air leakage rates (10%, 30%, 60%) have significant effect on hygrothermal performance of un-ventilated attic (House III), especially the RH level, while un-intentional air infiltration has no significant influence when indoor conditions are controlled.
  - When indoor conditions are controlled, the relative humidity, of un-ventilated attic air has obviously difference, the RH increases with the increase of ceiling air leakage rates (10%, 30%, 60%), under different constant un-intentional air infiltration (0.05ACH, 0.09ACH, 0.18ACH). The RH RMSD values are 8.07%, 14.32% and 5.16%, respectively;
  - When indoor conditions are controlled, the temperature and RH of un-ventilated attic has no significant changes with the increase of un-intentional air infiltration (0.05ACH, 0.09ACH, 0.18ACH), even under different constant ceiling air leakage rate (10%, 30%, 60%). For example, the temperature RMSD values under different constant un-intentional air infiltration when ceiling air leakage rate is 30% are 8.90℃, 8.89℃ and 8.88℃, respectively; and the RH RMSD values are 14.19%, 14.32% and 14.70%, respectively.

3. Parametric study results of hygrothermal performance of ventilated and un-ventilated attics based on mold growth index indicate:

- For ventilated attic, mold growth index maintains zero and the maximum values are less than one during the whole simulation period (from October 17^{th}, 2013 to July 18^{th}, 2015) under all scenarios (different combinations of attic ventilation rates—1ACH & 5ACH & 10ACH & variable hourly attic ventilation rate and ceiling air leakage rates—10%, 30%, 60%).

- For un-ventilated attic, mold growth index increases with the increase of ceiling air leakage rates (10%, 30% and 60%) and the decrease of un-intentional air infiltration rates (0.05ACH, 0.09ACH and 0.18ACH). Different orientations of roof sheathing have significant effect on mold growth values. North-oriented roof sheathing has the highest mold growth index values which can exceed three, especially over the longer period of simulation.

In summary, the design recommendations for attic designs in extremely cold climate are as follows:

- Ventilated attic: As long as the ceiling air tightness remains in a reasonable range, there is no mold growth risk in ventilated attic.
- Un-ventilated attic: The recommended combination of key parameters for un-ventilated attic design is 0.18ACH of un-intentional infiltration rate, normal moisture load of indoor condition, 20℃+80% or drier of initial conditions of plywood sheathing and 0%~10% of ceiling air leakage rate.

7.2 Contributions

This thesis evaluates hygrothermal performance of two types of attic constructions (ventilated attic and un-ventilated attics) in extremely cold climate through field measurements and simulations. Field measured data of attic air (temperature and relative humidity) and plywood sheathing (temperature and moisture content) in testing attic is collected by SMT Wireless Data Acquisition (WiDAQ) system. Validated hygrothermal models are created by WUFI Plus, a whole-building simulation tool with zonal model for the test houses. The main contributions of this thesis are listed as follows:

1. Field measurements demonstrate the actual hygrothermal performance (RH/T of attic air and MC/T of attic plywood sheathing) of both ventilated and un-ventilated attics under extremely cold climates;
2. Recommendations for proper attic design in Northern Canada regions are provided based on field measurements and simulations;
3. Validated WUFI Plus models are established based on House I (ventilated attic) and House III (un-ventilated attic) as base model under extremely cold climates, and these models can be applied to other climates;

4. Parametric study investigates the effects of ceiling air leakage rate and attic ventilation rate on the hygrothermal performance of ventilated attic and the effects of ceiling air leakage rate and un-intentional air infiltration on hygrothermal performance of un-ventilated attic;
5. Validated models also can be used as benchmarks to investigate the effects of global warming and future climates in arctic regions on attic design.

7.3 Future Works

In summary, simulation results follow the trends of field measurements data. The contributing factors to the discrepancy between simulations and measurements could be:

- errors in measurements of MC;
- errors in the measurements of on-site weather data and lack of field measurements data of indoor climate of House III;
- errors in assumed boundary conditions used in the modeling;
- inaccuracy of model itself.

Based on the limitations of this research, recommendations for future studies are stated in experiment and simulation parts as follows, respectively.

1. For experiment part

Field measurement setup of hygorthermal performance of attics can be improved as follow:

1) Further investigation of the appropriateness of un-ventilated attic under extreme cold climates is required through continued field monitoring.
2) The effect of materials of ceiling insulation (thickness, airtightness, thermal conductivity…) on hygrothermal performance of attics can be investigated as future studies.

2. For simulation part

To get more accurate simulation results, the input parameters that need to be measured are listed as follows:

1) On-site outdoor weather data in monitoring houses can be used as boundary condition and input to simulation model;

   Simulation results under field measured weather data can be compared to the result under TMY weather file to verify the reliability of WUFI Plus model.
2) Hourly attic ventilation rate input to WUFI Plus model to get more accurate results;
3) The effects of indoor conditions as variables can be investigated.

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