# MODELLING OF AIR BARRIER CHARACTERISTICS IN PREDICTING THE MOISTURE PERFORMANCE OF BUILDING ENVELOPES

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**A thesis**
**in**
**The Centre for Building Studies**

**Presented in Partial Fulfilment of the Requirements for the Degree of Master of Applied Science at Concordia University Montreal, Quebec, Canada.**

**March 1996**

ISBN 0-612-10815-5

# ABSTRACT

## MODELLING OF AIR BARRIER CHARACTERISTICS IN PREDICTING THE MOISTURE PERFORMANCE OF BUILDING ENVELOPES

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Interstitial condensation is recognized to be the cause of many problems in building envelopes. In multi-layered constructions, the emphasis often has been placed on vapour barrier requirements based on moisture diffusion. Several recent studies have shown that diffusion is only a minor factor in interstitial condensation and that airflow is much more significant in driving moisture through the envelope. For designers, there are no simple methodologies available yet to consider the air leakage phenomenon in the design of envelope components. When airflow is incorporated in simple moisture prediction models, its effect is calculated separately and then added to moisture diffusion effect. This method can lead to important overestimation in results and constitutes a major drawback of the simple models. Another limitation to their use is that they do not calculate the air flow rate through the analyzed section, therefore the user is required to provide input data like the air velocity and flow direction or equivalent leakage area of the section, each of which is difficult to assess.

The present work develops a simple model that predicts condensation in walls due to the combined effect of vapour transfer by diffusion and convection. The flow rate is calculated by making use of the air permeability properties of the materials and elements making up the different layers of the envelope. The proposed methodology to calculate airflow rate through the envelope has been implemented in a computer model used in analyzing a number of common wall sections on a yearly basis. Some of the widely adopted design guidelines related to moisture control have been also investigated.

## AKNOWLEDGMENT

I take this opportunity to express my gratitude to my supervisors, Dr. Krishnan Gowri and Dr. Richard Guy for their guidance, advice and encouragement throughout the course of this thesis.

The financial assistance of NSERC (Natural Sciences and Engineering Research Council) and FRDP (Faculty Research Development Program) provided through the research grants of Dr. K.Gowri is highly appreciated.

Thanks are due to Dr. P. Saathoff and Dr. R. Zmeurreanu at the Centre for Building Studies for their time and help.

Finally, special thanks are due to colleagues who provided valuable help through useful suggestions and criticism.

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## NOMENCLATURE

| | |
|---|---|
| A | Area [m²] |
| C | Flow coefficient [m³/m².s.Paⁿ] |
| $c_L$ | Latent heat of water vaporization or sublimation [J/Kg.°C] |
| $C_p$ | Wind pressure coefficient [dimensionless] |
| $c_p$ | Specific heat of air [J/Kg.°C] |
| J | Julian day |
| h | Distance from neutral pressure level [m] |
| $h_c$ | Convection coefficient [W/m².°C] |
| $h_r$ | Radiation coefficient [W/m².°C] |
| $I_{DN}$ | Solar direct normal radiation [W/m²] |
| $I_h$ | Solar radiation falling on a horizontal surface [W/m²] |
| $I_v$ | Solar radiation falling on a vertical surface [W/m²] |
| K | Thermal conductivity [W/m.°C] |
| L | Site latitude [radian] |
| LON | Site longitude [radian] |
| $P_t$ | Barometric pressure [Pa] |
| Q | Volume flow rate [m³/s] |
| $R_t$ | Total thermal resistance [m².°C/W] |
| $R_v$ | Total vapour diffusion resistance [m².s.Pa/ng] |
| ST | Time zone standard meridian [radian] |

| | |
|---|---|
| t | Temperature [°C] |
| T | Solar time [decimal hours] |
| TH | Thickness of material [m] |
| U | Thermal conductance [W/m².°C] |
| v | air velocity [m/s] |
| V | Wind speed [m/s] |
| $V_g$ | Wind speed at gradient height [m/s] |
| $V_s$ | Wind speed at weather station [m/s] |
| Z | Building height [m] |
| $Z_g$ | Gradient height [m] |
| w | Moisture accumulation rate [ng/s.m²] |
| W | Humidity ratio [kg of moisture/kg of dry air] |
| x | Thermal parameter [dimensionless] |
| y | Vapour diffusion parameter [dimensionless] |

Greek Symbols

| | |
|---|---|
| $\alpha$ | Absorptance of radiant energy [dimensionless] |
| $\beta$ | Solar altitude angle [radian] |
| $\gamma$ | Thermal draft coefficient [dimensionless] |
| $\delta$ | Solar declination angle [radian] |
| $\epsilon$ | Emittance of radiative energy [dimensionless] |
| $\mu$ | Water vapour permeability [ng/m.s.Pa] |

| | |
|---|---|
| $\rho$ | Density of air [kg/m$^3$] |
| $\sigma$ | Stephan Boltzman constant 5.67E-8 [W/m$^2$.K$^4$] |
| $\phi$ | Solar azimuth [radian] |

Subscript

| | |
|---|---|
| dif | Diffusion |
| i | Inside |
| n | Pertaining to layer |
| o | Outside |
| s | Saturation |
| st | Stack |
| surf | Surface |
| win | Wind |

Superscript

| | |
|---|---|
| $\alpha$ | Mean speed exponent |
| n | Flow exponent |

# CHAPTER I

# INTRODUCTION

## 1.1 GENERAL

Building envelopes specially in cold climates play a critical role in protecting and maintaining the indoor environment from the rapidly changing outdoor temperature, relative humidity, wind, rain and snow. The durability and life cycle cost of building envelopes are greatly influenced by the weather barrier materials and construction techniques used to control the flow of heat, air, water and moisture. Throughout the United States and Canada, moisture problems in buildings are a source of numerous complaints and dissatisfaction (Tenwolde,1989). Building designers are becoming aware of the importance of rain screen principle, air tightness levels, and vapour barrier installation techniques to reduce the occurrence of moisture problems. Though several research attempts are made to understand and resolve the moisture induced problems, there is a lack of comprehensive tools and techniques available to practitioners in selecting materials or evaluating construction details.

## 1.2 OVERVIEW OF MOISTURE INDUCED PROBLEMS

Serious moisture damage in buildings is usually the result of a combination of unfortunate circumstances and design/construction deficiencies. As moisture can reach the building envelope from different sources like rain, ground water or air borne humidity, many cases of damage to walls and roofs are complex and difficult to investigate. The present study focuses on the occurrence of condensation within exterior walls of moisture coming from the indoor environment. This occurs when the water vapour is cooled below its dew point. The trend towards increased wall insulation to conserve energy increases the tendency for moisture to condense within the wall (Spolek,1986). In fact, air leakage control measures contribute to the increase of indoor air moisture content and because insulation creates a greater temperature gradient through the wall, it was speculated that there would be an increased opportunity for condensation during the cold winter months. These speculated potential consequences of wall weatherization were based on sound physical principles.

Field observations show that interstitial condensation can be the origin of many building envelope problems. Several case studies of moisture induced problems have been documented by Rose(1986), Merrill and Tenwolde(1989), Tsongas(1985,1995) and others. They range from aesthetic problems like paint peeling, staining or mold growth, to more serious ones including structure failure. Besides its effect on construction durability, interstitial condensation can induce serious problems in the context of energy efficiency and indoor air quality. Moisture induced damage to building envelopes can take place in different forms. For example, the presence of moisture in wooden members under adequate temperature can allow mildew, mold and occasionally wood destroying fungi to attack the structural members (Spray/Hedden,1982). In a field survey by Merrill and Tenwolde(1989), interstitial condensation was demonstrated to cause severe damage in wood sheathing and wall framing. Another form of damage can take place through the seasonal moisture cycling of the outer wall layers which causes wood-based materials to alternately expand and contract. Repeated moisture cycling often leads to warped and bowed boards, delaminated plywood, pushed out nails, the separation of wood members from the structure as well as paint failure by weakening the bond between exterior paint and the substrate material.

## 1.3 PREDICTING MOISTURE BEHAVIOR

Mathematical models are crucial to the development of better practical guidelines for moisture control and remedial measures. During the 1930s and the 1940s, vapour diffusion was considered to be the major cause of condensation in exterior walls (Hutcheon,1963). The earliest mathematical tools like the dew point method and Glaser's diagram were subsequently used to determine the location of vapour barriers based on the thermal and vapour resistance characteristics of the envelope materials. The approaches to moisture control in practice, mathematical analysis and moisture transfer test measurements were all consistent with each other. The installation of vapour barriers reduced the occurrence of moisture problems due to diffusion, but did not prevent air exfiltration and the associated moisture deposition. During the 1970's observations and calculations made it clear that the amount of water vapor carried by air currents could be much larger than the amount delivered by diffusion (Latta,1976). Little doubt remained that many of the condensation problems in buildings are associated with air leaks. Subsequent research efforts were directed towards understanding the air leakage phenomenon and recommendations were developed to incorporate air barriers within the building envelope (Quirouette,1983). The first generation tools mentioned above were inadequate to address the convective moisture transport due to air leakage. The introduction of air flow in moisture calculations posed new research challenges. Several mathematical models concerned with various options and limitations have been developed.

## 1.4 RESEARCH OBJECTIVES

In current design practice, building code requirements for air and vapour barriers form the basis for controlling moisture problems. Designers seldom analyze the construction details for moisture performance unless they encounter difficulty in meeting the code requirements or are faced with a potential problem. This situation exists because current moisture simulation models are not readily available, are too complex to use or have serious limitations. In order to promote a better understanding of the moisture behaviour of building envelopes, simple mathematical models for moisture transfer in buildings need to be developed or derived from existing ones.

The main objectives of this work are to:

i) Develop a methodology to calculate air flow in composite walls using the available air permeability data of building envelope materials and components.

ii) Implement this methodology to represent air barrier characteristics in calculating moisture accumulation using a simple one-dimensional model.

iii) Perform parametric analysis using the above model to assess the moisture performance of wall construction practices and design guidelines.

To achieve the objectives of the research, an extensive literature survey has been carried out and available software models have been reviewed. A software program has been developed along with a database of air permeability values to demonstrate the proposed air flow calculation methodology and the moisture calculation model.

## 1.5 THESIS ORGANIZATION

Chapter II presents a detailed discussion on moisture transport mechanisms, modelling issues and a review of available models.

Chapter III describes the methodology to calculate airflow and the implementation of this methodology in a mathematical model to calculate condensation rates.

Chapter IV presents the mathematical validation of the model and its comparison with three available moisture prediction models.

In Chapter V the developed tool is used to simulate the moisture related behaviour of a series of common wall sections. The results of the analysis are discussed and commented.

Chapter VI presents the conclusion reached by the study, contributions made and recommendations for future work.

Appendix A contains the materials properties database.

# CHAPTER II

# LITERATURE REVIEW

## 2.1 INTRODUCTION

Moisture transport even as a separate branch of building physics, is not yet well understood (Kumaran,1992). As it interacts with heat and air transport, the nature of the moisture transport process becomes very complex. In spite of this, building designers and practitioners have been using calculation methods to develop design guidelines in relation to moisture transport. Some of these methods are very simple, albeit only qualitative, and some so complicated that only well trained researchers can use them. In this chapter an attempt is made to review the physical principles of moisture transfer particularly by air flow, as well as the existing models and practices related to moisture prediction and control.

## 2.2 REVIEW OF MOISTURE TRANSPORT THEORY

Water can exist in three states of matter: Solid, liquid and gas. In the physical conditions that buildings are operated, all these states of moisture may exist. Porous materials have the capability of absorbing moisture from an environment of air that may seem dry to the human. This is mainly due to adsorption forces with which the solid parts of the material even at very low vapour pressures attract molecules of vapour internally in the porous system (Pedersen,1990). Water in building envelopes may be present in the vapour state in the air-vapour gaseous mixture, in the liquid state as absorbed liquid in isolated pockets or in continuous micro channels, or as moisture adsorbed onto the pore surfaces of the solid materials (Spolek,1989). Absorbed moisture is understood in the wringing out of a soaked sponge, while adsorbed moisture is the moisture that remains and can only be removed by evaporation or desorption. Under most conditions, moisture will be present in building materials primarily in the adsorbed and vapour states (Spolek,1989), whilst the saturated liquid may be found on material surfaces.

### 2.2.1 Moisture Transport Mechanisms

Moisture can be transported from one location to another through a porous body in the vapour and liquid states, in addition to the adsorbate state, knowing that in the vapour and liquid states the water molecules are more mobile. However to date, it has not been possible to identify an experimentally realizable single potential that causes moisture transport in various phases (Kumaran,1992). For practical reasons, the driving potential for moisture transport has been considered as a resultant of a set of experimentally realizable driving potentials. This has resulted in the postulation of a variety of moisture transport mechanisms as summarized in table 2.1 (Kumaran,1992). This variety of mechanisms, together with the phase transitions undergone by water make the subject of moisture transport complex. In vapour transfer, thermal diffusion is a minor mechanism (Andersson,1985), and it is generally accepted that moisture migration through even the tightest construction is dominated by the convection of moisture laden air through leakage paths rather than by diffusion or capillary flow (Spolek,1986). In water transfer suction governs the unsaturated flow in porous materials, gravity and external pressure differences are only significant for high saturation ratios (Hens,...).

| PROCESS | STATE | POTENTIAL |
|---|---|---|
| Gas diffusion | Vapour | Vapour pressure |
| Convective flow | Vapour | Air pressure |
| Thermal diffusion | Vapour | Temperature |
| Adsorbate diffusion | Adsorbate | Concentration |
| Liquid diffusion | Liquid | Concentration |
| Thermal diffusion | Liquid | Concentration |
| Capillary flow | Liquid | Suction |
| Gravitational flow | Liquid | Height |
| Poiseuille flow | Liquid | Liquid pressure |

Table 2.1 Moisture transport processes in building materials.

### 2.2.2 Sorption Isotherms

The maximum amount of moisture adsorbed by a given amount of solid depends on the temperature, the partial pressure of water vapour and the surface area (Kumaran,1992). Furthermore, each material has its own characteristic affinity towards water. This affinity is commonly referred to as hygroscopicity. The relationship between the amount of moisture localized on the solid and the vapour pressure of moisture at a given temperature is called the sorption isotherm, see Fig 2.1. Consider the response of a homogeneous fibrous material to water vapour at a fixed temperature. As the vapour pressure in the surrounding air is progressively increased from zero, water molecules are localized on the fibres surface area first in the form of a monomolecular layer and then in multimolecular layers. This continues until the surface layers at various locations grow large enough to form (depending on the local temperature) droplets of water or frost particles. From the absolute dry state to this point, the material is said to be in its hygroscopic range, also called the diffusion regime. Its upper limit corresponds to the *fibre saturation.* Above the fibre saturation, free liquid water exists but not in a contiguous path. In this regime called the transition regime, the capillary attraction between discrete liquid particles and pores is so strong that this liquid cannot be separated from the porous material by ordinary mechanical means. To date different researchers do not agree on the exact moisture transfer mechanism in this regime, especially in an isothermal environment (Burch/Thomas,1991). The moisture content level at which a contiguous path of liquid first exists is termed "irreducible saturation", above it the material is said to be in the capillary regime. Here transfer is by liquid flow. When all pore structures are completely filled with liquid water, the material is said to have attained the maximum moisture content. During desorption (the reverse of sorption), the material retains more moisture than what it can adsorb at any relative humidity. This phenomenon is referred to as hysteresis.

Fibre saturation, also named the *critical moisture content* is generally regarded as the maximum amount of moisture that can be taken on by a wood based material without the risk of degradation. For wood-based products, this criterion corresponds to about 25% to 30% of the dry mass (Burch,1992). The development of wood decay requires high moisture content in the wood, sufficient oxygen and high wood temperatures for periods long enough for the decay to progress. While decay can occur at wood moisture contents as low as 20%, serious decay occurs only when the moisture content of the wood is above the fibre saturation point. Wood decay is relatively slow at temperatures below 10°C and much above 32°C, the optimum temperature being 24°C (Tsongas,1985).

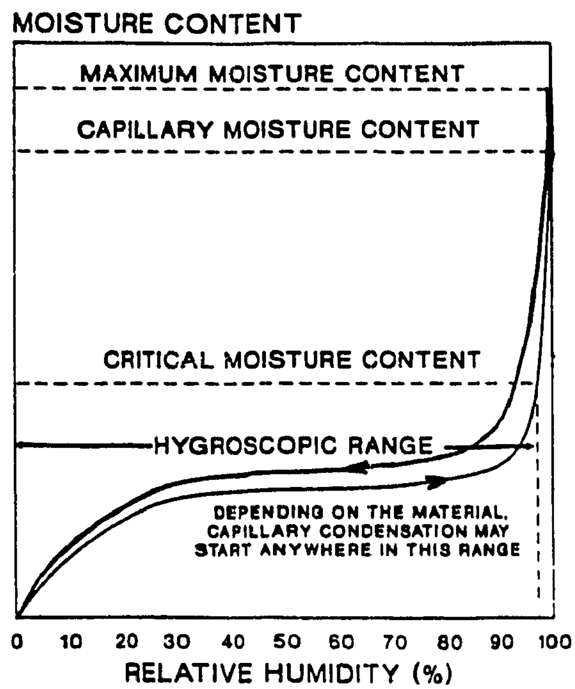



Fig. 2.1 Example of a hygroscopic material sorption isotherm

## 2.3 CHARACTERISTICS OF AIR LEAKAGE IN BUILDING ENVELOPES

Unintentional apertures in building structures occur as a consequence of workmanship and materials used. The amount of air leakage through these apertures depends on the magnitude of the driving forces in combination with the size and shape of the air leakage paths.

### 2.3.1 Impact of Air Flow on Moisture Deposition

It has been theoretically proven that air leakage presents a significant potential for moisture deposition that can be orders of magnitude higher than that due to diffusion. Furthermore, this theory was supported by field observations which confirmed that many moisture problems in houses are caused by the penetration of warm moist household air into the walls. In a field study of 86 new energy-efficient homes reported by Tsongas and Nelson(1991), measurements revealed that in some wooden members the moisture content was high enough to cause wood decay. The investigation carried out at one of these homes found a definite correlation between the location of the wood members with high moisture content and the existence of an adjacent noticeable air leak. This and oth observations led to the conclusion that the moisture build-up in these spots was caused by moist indoor air flowing through an adjacent leak, though the blower door tests revealed a high airtightness of the order of 1.18 ach at 50 Pa. Another field study by Wilson and Garden(1973) examined a masonry-clad, steel-frame, humidified building suffering from disruption of masonry. With the aid of smoke, it was determined that air was leaking outwards through the unplastered portions of the masonry walls and through cracks between structural elements and the masonry. Moisture accumulations (due to condensation) were found to be concentrated adjacent to air leakage paths.

The extent of condensation due to air leakage depends on the quantity of air flow, its initial moisture content, and the reduction in temperature that it undergoes in passing through the building envelope. In general, moisture problems due to exfiltration increase with increasing height, decreasing average temperature, and increasing indoor humidity.

### 2.3.2 Location and Shapes of Air Leaks

Air leaks through (i) materials, (ii) joints between materials, (iii) around openings and service penetrations, (iv) gaps, holes and cracks due to deficiencies in the envelope construction or to damaged materials. A survey of 29 houses around Denver Colorado conducted to study the frequency of occurrence of leakage locations showed that the bottom of drywall leakage was present in 100% of the inspected houses, plumbing fixtures leak in 79% and electric fixture leak in 76% of them (Allen,1985). A similar survey conducted on 35 houses in Finland reported that leakage at the ceiling-wall joint was observed in 29 houses, at the electrical penetrations in 20 houses and at the floor-wall joint in 12 houses (Allen,1985).

Air leakage paths are rarely straight and smooth with a well defined geometry. They are in most cases complex and variable in size, shape, length and roughness. Their shape may even vary with different air pressures (Levin,1991). For example, there could be valve-like leakage paths opening and closing under different air pressures, like plastic film joints if not clamped. In multi-layered building envelopes, long flow paths with directional changes are the most common. But relatively short leakage paths can also occur.

### 2.3.3 Leakage Paths Flow Characteristics

The variety of leakage paths implies different air flow characteristics for every air leakage path. The volume flow rate (Q) is a non-linear function of the pressure difference (ΔP) across it (Hutcheon/Handegord,1989). This is represented by the power law equation:

$$Q = C\,\Delta p^{n}$$

The flow coefficient (C) expressed in $[m^3/s.m^2.pa^n]$, is a constant dependant on the intrinsic air permeability of the material, its thickness, and the dynamic viscosity of air. The flow exponent (n) is dimensionless and ranges in value from 0.5 to 1.0. A value of unity indicates fully developed laminar flow, 0.5 indicates fully rough turbulent flow or orifice flow. Large leakages such as ventilation stacks have values of n close to 0.5 reflecting the normally turbulent flow, while smaller leakages have larger n values (Allen,1985). The air flow characteristics (C) and (n) for some air leakage paths might vary with differential pressure. In multilayered envelope constructions, infiltration flow rates might be different from exfiltration flow rates (CMHC,1991).

### 2.3.4 Theoretical Modelling of Air Flow

Design data input to the air flow models are the result of experiments. The overall air leakage of an enclosure is usually measured by the standardized Fan Pressurization method. Air leakage measurements of individual air leakage paths can be made with the Guarded Pressure Box technique. The power law equation is the most common equation used to fit to measured data. Typically Fan Pressurization tests are carried out at pressure differences between 10-100 Pa, whereas for naturally ventilated houses in the absence of high winds, occurring pressures are in the range of 0-5 Pa (Levin,1991). This brings about the question of whether significant changes in air flow characteristics take place between pressure differences at normal operation and at testing conditions. This is less of a problem for building materials than for joints and construction details. The experiments conducted by Air-Ins Inc. for CMHC (CMHC,1988) to calculate the air permeance values of building materials. confirmed that at pressure differentials of 25 to 100 Pa, the air flow regime through the examined building materials is mainly laminar.

A typical multi-layered building envelope contains several joints, openings and unintentional cracks with a variety of flow characteristics. This makes theoretical air flow rate modelling complicated. Ideally, the size, location and air flow characteristics for each air leakage path should be given as input data to the calculation model. This is rarely possible in practice. An approximation or summation of air flow characteristics has to be made. Attempts have been made to simulate leakage distributions by summing the contribution from the various components in the form of their equivalent leakage areas. The equivalent leakage area is defined as the area of an orifice which would pass the same airflow as the leakage path at a given reference pressure. This reference pressure is 4 Pa in the United States, and 10 Pa in Canada. "There is some doubt of the validity of this approach since it does not allow for the variation of leakage distribution with pressure that occurs when there are leakages with widely differing values of flow exponent" (Allen,1985).

## 2.4 EVALUATION OF AIR BARRIER SYSTEMS

An air barrier is an assembly of materials linked and structurally fastened to parts of the building envelope to form a continuous and air impermeable plane in the roof, walls and below grade components of the building envelope. The specific role of an air barrier is to prevent infiltration of outdoor air and exfiltration of indoor air through the building envelope so as to minimize energy loss. The desired goal of an air barrier is to reduce moisture migration between the inside and the outside in order to prevent the occurrence of condensation within the wall assembly. In order to be effective, an air barrier must possess high resistance to airflow, be strong enough to resist the effects of wind and be durable enough (or maintainable) to last the life of the building. Finally it must form a continuous envelope around the building.

### 2.4.1 Types of Air Barriers

Air barriers can be located anywhere within the wall of an assembly. One approach is to place an air retarder at the interior surface of a building assembly. This is typically achieved by sealing the interior cladding to framing elements (ADA, air dry wall approach) or by installing a continuous sealed polyethylene film between the interior cladding and the framing elements (Poly-wrap approach). Airtightness can also be provided within a building assembly by utilizing a dense cavity fill insulation like dense-pack blown cellulose (integral air retarder). Another approach is to place an air retarder at the exterior surface of a building assembly. This is typically achieved by sealing the exterior sheathing to framing elements (ASA, air sheathing approach) or by installing a continuous sealed building paper over the exterior sheathing (House-wrap approach). Every system has its inherent advantages and disadvantages depending on the cladding, insulation and framing techniques used.

### 2.4.2 Factors Influencing Air Barriers Performance

The performance of an air barrier is dependent on the sealing methods used like tapes, sealants, and caulking. Extended thermal and/or moisture stresses can affect their properties like (loss of adherence or of elasticity, shrinkage or expansion...), and consequently lower the airtightness of the assembly or even cause its total loss. The construction quality plays its part in the effectiveness of an air barrier. In executing theoretically airtight designs, imperfections cannot be avoided under field conditions. This could be caused by the use of damaged materials, unqualified or unsupervised workmanship, unaccommodated differential movements, or a specific difficulty in properly executing certain delicate construction details that are prone to air leakage. The probability of imperfections increases with an increasing number of joints and penetrations. Finally, as building envelopes are subject to a wide range of air pressures, an air barrier system should be able to support part of this load after completion of the construction as well as during construction. The proportion of the air pressure load carried by the air barrier is partly affected by its location in the wall assembly and by the adjacent materials which might provide it with structural support. Air pressures even at low values might cause damage to the weak parts of an air barrier like sealed or stapled spots if they are not executed properly. Membranes lacking rigid supports might undergo ballooning which increases the air leakage area, and can cause damage to the membrane after repeated loading.

The assessment of each of the above mentioned factors requires the collection and the analysis of a great deal of experimental and field data. This does not fall within the scope of this thesis, but the existence of those factors shows that there is a gap between theoretical modelling of the physical phenomena of air transfer and the uniqueness of each real case. It is also an indicator that the high mathematical accuracy of certain complex models cannot fulfil its objective if appropriate field data is not available.

## 2.5 MODELLING OF MOISTURE BEHAVIOUR

Understanding and predicting moisture movement through the envelope is of fundamental importance in cold climates where moisture is one of the most important factors affecting building envelope performance.

### 2.5.1 Review of the Evolution of Moisture Modelling

In the past, for practical evaluation of the moisture behaviour of construction, simple analysis have been carried out based on the Dew point method or on Glaser's method. Both these methods compare vapour pressures within the envelope as calculated by simple vapour diffusion equations, with saturation pressures, which are based on temperature gradients (Pedersen,1992). If the calculated vapour pressure is above the saturation pressure at any point within the envelope, condensation is indicated. The main difference between these two methods lies in the graphical procedures. This type of analysis is still used today. It parallels that used for conductive heat transport; phase changes are assumed to occur at materials interfaces, desorption/adsorption by hygroscopic materials and liquid phase transfer are ignored. A major shortcoming of the Dew point and Glaser's methods is that omitting vapour transfer by convection is so far reaching that many constructions may be misjudged by using these methods.

In early literature, constructions were condemned if interstitial condensation was possible. This led to the vapour barrier chase of the sixties (Hutcheon,1963). In the 1960s, the importance of air leakage began to be recognized, this led to design recommendations that focused primarily on airflow control, such as the Airtight Drywall Approach (ADA). Improved mathematical models were developed to include heat and moisture transport by convection, (Cunningham,1983). In Cunningham's analytical model diffusion and convection are assumed to act independently and are additive. Spolek (1989) mentions that other developed models also proposed to calculate the aggregate effect by adding diffusion and convection components; (Burch & al.1979; Stewart 1981). This approach was criticized by Tenwolde (1985) who demonstrated that it is not correct to treat diffusional and convective flows as independent and sum the separate effects as this may lead to significant overestimates of moisture accumulation rates. In fact, vapour pressure and temperatures within the envelope are greatly influenced by air leakage. The alternative to this approach is proposed by Tenwolde in his mathematical model Moistwall-2 (Tenwolde,1985), where equations are developed for moisture accumulation in a multi-layered wall with air movement through the wall. In recent years, attention has been focused on extending the existing models to account for all the possible mechanisms important to heat and mass transfer. Recent models like (MOIST and MATCH) include latent heat effects due to phase changes and de/adsorption. In the past, these have been assumed to be negligible. As mentioned by Spolek (1989), the effects of adsorption of water vapour at wood surfaces have been examined experimentally and mathematically in a study by (Burch and Lemay 1984). They concluded that latent heat effects due to adsorption play an important role in preventing condensation.

All models have encountered some common difficulties. The most serious, is the lack of reliability of the experimentally determined values for materials properties. Vapour diffusion coefficients as a function of moisture content and temperature through building materials are one example of data that is difficult to obtain. "*It seems that the most interesting range of moisture content from the point of view of moisture damage is around 98% RH, and not at very high moisture content. With existing measurement methods, it is very difficult to obtain data here, both for moisture retention curves and transport coefficients*" (Andersson,1985). Another difficulty encountered in experimentally measured properties is the anisotropicity of building materials. As stated by Pedersen (1992), "There is also an appreciable spread in the material properties even within different specimens of what appears to be the same material".

### 2.5.2 Review of the Existing Models and Practices

In 1993, 29 codes from 10 different countries were documented by the International Energy Agency (IEA,Annex 24). They cover the whole Heat-Air-Moisture (HAM) transport domain and range from simplified to very complex models. Of the twenty-six models that address moisture transport, six are steady-state, nineteen are transient, and one is a combination. Four of the simple models deal only with heat and vapour transport, they are one dimensional and based on the steady-state Glaser's scheme of heat conduction and vapour diffusion with constant materials properties (*WAND* and *GLASTA* from Belgium, *HYGRO* from The Netherlands and *BRECON2* from the U.K. ). The other two simple models (*EMPTIED* and *KONVEK*) incorporate air transport. *EMPTIED* (Canada) considers stack effect as the only air driving potential. Input requirements include the identification of the condensation planes and also an equivalent leakage area for the analyzed construction. Another draw back of this model is that it is only applicable to one-storey high walls with no internal vented cavities. In both models (*EMPTIED* and *KONVEK*), diffusion and convection are assumed to act independently and their results are additive.

Another model *WALLDRY* (Canada) deals with steady-state heat and air transfer and non-steady state vapour transfer. It was developed for a specific purpose which is to study the wetting and drying of the outer part of insulated wood-frame walls. It only applies to strapped siding. Air transport is limited to convection loops through the cavity and input requirements regarding air transport are complicated.

Within this category of simple codes that incorporate airflow, falls Moistwall-2, the computer program developed by Tenwolde. It assumes a homogenous one-dimensional airflow. The velocity and direction of the airflow are required as input data from the user. The model uses this information to determine the location and the amount of condensation.

Sixteen of the transient models do not include air transfer (*LATENITE* from Canada, *MOIST* from USA, *MATCH* from Denmark). The transient models show a wide variation in the assumptions, the driving potentials addressed, the materials properties used and the boundary conditions modelled. Heat, air and moisture transfer in its overall complexity appears intensively analyzed and modelled in the most sophisticated models (*TCCC2D* and *TRATMO2* from Finland). Like other transient models they encountered difficulties in dealing with materials properties and the continuity of moisture content at interfaces.

For instance in *TCCC2D* "freezing water and the water flow at interfaces of the material layers could not be simulated" (Kumaran,1992).

In design practice, we notice that Glaser's diagram is commonly used in Europe (Tenwolde,1994). Glaser's method has been adopted by the German code DIN as the recommended way to verify the moisture related performance of constructions (Pedersen,1992). Similar though perhaps not graphical methods are used in most countries as the standard way to calculate moisture migration in building constructions. The dew point method is used in North America and adopted by ASHRAE. The IEA investigation (IEA, annex 24) showed that out of ten participating countries, only three had standards for the calculation method for interstitial condensation. Five countries used the Glaser's method in engineering practice though three more countries used the related "saturation-line/vapour-pressure-line intersection method". Only one country reported that "advanced methods" were used. Of the ten countries, engineering practice in only three of them took solar gains and long wave radiation into account to formulate the boundary conditions. In seven countries, annual mean conditions were used for the boundary conditions.

### 2.5.3 Discussion and Commentary on Existing Models

Most of the existing models are research oriented tools, more or less easy to use for the researcher/developer but difficult to work with for designers and practioners. The results of the enquiry conducted by IEA for ten different countries (IEA,annex 24) revealed a remarkable lack in practice linked tools and models to evaluate moisture problems and to aid in design and performance judgment.

The most sophisticated models are supposed to provide the most accurate results. But the current water vapour transfer test methods do not provide material property data for these models. On the other hand, the complex and large amount of input required by these models are obvious drawbacks to their use by the practitioner, in addition to the difficulty a typical designer has to face whether in choosing the appropriate model or in interpreting the output. Another limitation to their use is that they are rarely available. They have been developed and used mainly within the research community. The knowledge gained from the use of these models has only been available when results of model analyses were published in reports and articles. Consultants, building designers and manufacturers in the building industry have not had access to the models themselves, and therefore the models do not yet constitute real design tools.

The most widely adopted tools in engineering practice are based exclusively on diffusion. The few attempts to incorporate airflow in simple moisture prediction models fall into the trap of treating diffusion and convection as independent. As mentioned previously, Tenwolde's mathematical model (Tenwolde,1985) avoids this trap by accounting for the influence of convection on temperature and moisture diffusion. But on the other hand, its input requirements include air velocity and flow direction which are difficult to assess. This limitation can be overcome by developing a methodology which allows the modelling of air barrier systems. This methodology can therefore be used to calculate air flow rates that reflect the wall design and its air permeability properties.

## 2.6 SUMMARY

From the literature review, the main points important to the core of the thesis can be summarized as follows:

(i) There is a remarkable lack of tools and models available to design practitioners to evaluate potential moisture problems. Building codes addressing moisture control are based on rather simplistic methods like the Glaser's diagram. With this method, interstitial condensation as a cause for moisture problems has been overemphasized.

(ii) There is no simple available model that addresses moisture diffusion and convection as interdependent and at the same time incorporates the envelope's air barrier characteristics in evaluating its moisture performance.

(iii) An already existing mathematical model (Tenwolde,1985) can serve as a basis for constructing the required model, as it is based on differential equations that address the effect of air leakage on temperature and vapour diffusion.

(iv) Air flow modelling in the proposed model should be able to simulate the pressure induced variations of leakage distribution in building envelopes.

The above findings drawn from the literature review consolidate the importance and the potential of the present work.

# CHAPTER III

# MODEL DEVELOPMENT

## 3.1 INTRODUCTION

This chapter details the development of an air flow calculation method which evaluates airflow rates through multi-layered exterior walls. This method uses the available air permeability data of building materials and components. An already developed mathematical model, Moistwall-2 (Tenwolde,1985) has been selected to serve as the basis for heat and moisture flow calculations. The air flow module and the heat and moisture flow modules constitute the two main parts of the model.

## 3.2 ASSUMPTIONS

The mathematical model developed here applies to multilayered walls subject to one-dimensional heat, air and moisture transport and to time-varying temperatures and vapour pressures on each side. The model is applicable only for the analysis of wood frame constructions where the effect of thermal bridging can be neglected. The mathematical model is based on the following assumptions and conditions:

1) Layers are assumed to be in perfect contact, so that film or contact resistances are negligible.

2) Material properties are assumed for simplicity to be independent of temperature and moisture content.

3) Heat transfer through the materials is by conduction and convection, and it is assumed to occur by convection and radiation at the boundary surfaces. Vapour transfer is by diffusion and convection.

4) Heat and moisture flow are assumed to be at right angle to the plane of the structure and the highest potential difference for heat, vapour and air pressure are assumed to exist across the wall.

5) Air flow is assumed to be at a right angle to the plane of the structure and uniformly distributed over the whole area of the analyzed section.

6) Heat storage in the materials is not considered. Also, the storage of moisture in hygroscopic materials is not accounted for.

7) Phase changes of vapour (condensation/evaporation) are assumed to occur only at boundaries and layers interfaces.

8) The model is pseudo-dynamic in that it uses hourly weather data, including outdoor dry bulb and dew point temperatures, solar radiation and wind speed and direction. Consequently, a one-hour time step is adopted for temperature, air and moisture flow calculations.

Other assumptions related to more specific aspects of the model are mentioned through the course of this chapter.

### 3.3 AIR FLOW MODEL

The objective of the air flow model is to define the direction and velocity of the air flow through a wall assembly. They depend on the driving potential acting across the wall and on the air permeability of the wall. Once calculated, the air velocity and direction are used by the heat and moisture flow model to determine the amount and location of condensation / evaporation within the envelope.

#### 3.3.1 Mechanisms of Airflow

The total air pressure differential $\Delta p_{tot}$ across the wall is considered as the summation of the pressure differentials due to stack, wind and mechanical ventilation (Walker/Wilson,1993). Δp caused by mechanical equipment can be provided by the user, whereas the pressure differentials caused by stack effect and wind are calculated based on the weather data, indoor conditions, building geometry and terrain conditions.

i) Stack pressure

The stack pressure at a distance h from the neutral pressure level expressed in meters is given by (Hutcheon/Handegord,1989):

$$\Delta p_{st} = \gamma * 0.034169 * h * P_t * \left(\frac{1}{T_i} - \frac{1}{T_o}\right) \qquad \textbf{(1)}$$

Where:

- $\gamma$ is the thermal draft coefficient which represents the ratio of the actual pressure to the theoretical stack effect. It varies between 0 and 1, and depends on the resistance to flow via vertical shafts connected to floors and also on the resistance to flow between floors. The default value for it is 1.

- The constant 0.034169 represents the ratio of g (acceleration due to gravity, 9.81 m/s²) over Ra (gas constant for air, 287.1 J/kg.K)
- $P_t$ is the barometric pressure [Pa].
- $T_i$ and $T_o$ represent the indoor and outdoor air dry bulb temperatures in Kelvin degrees.
- h is chosen to be the distance from the neutral pressure plane to the point with the highest exfiltrative pressure during the heating season. h is equal to: H*(1-r) where:
  - H is the clear height between two floors that are assumed airtight. It could represent the floor height if its upper and lower slabs are airtight and it is not connected to a vertical shaft. Or it could represent the total building height in the case where the floor slabs are not airtight.
  - r is the ratio of the height of the neutral pressure plane to the total height H of the storey or the building. It is dependent on the distribution and the areas of the openings. For a 2-storey house r varies between 0.49 and 0.75 (NRC,1994).

ii) Wind pressure

The calculation of Δp due to wind effect is given by (Hutcheon/Handegord,1989):

$$\Delta p_{win} = 0.5 * C_p * \rho * V^2 \qquad (2)$$

Where:

- $C_p$ : wind pressure coefficient. [dimensionless]

  It can have negative or positive values, and it depends on the building shape, geometry (length to width ratio), height, wind direction and the influence of nearby buildings and vegetation. The user can choose to enter a constant value of $C_p$ for the simulation period, or the program can calculate hourly values of $C_p$ for a particular building shape and terrain conditions using a $C_p$ file. The model provides a wind $C_p$ file applicable to a low-rise building with a length to width ratio equal to two, and an exposed terrain category. The user can input his own wind $C_p$ file.

- ρ : air density [kg/m$^3$]
- V : the wind speed at the building height. V is calculated using the following formula (Hutcheon/Handegord,1989) :

$$V = V_g * (\frac{Z}{Z_g})^{\alpha} \tag{3}$$

Where:

- Z : building height [m]
- $Z_g$ and α are the gradient height and the mean speed exponent respectively. They depend on the terrain category and have to be input by the user.

$V_g$ : velocity at gradient height calculated as follows:

$$V_g = V_s * (\frac{300}{10})^{0.15} \tag{4}$$

Where:

$V_s$ : wind speed provided by the weather station. Typically it is recorded at an anemometer mounted 10 m above ground at an airport. 300 and 10 are respectively the gradient height and the mean speed exponent corresponding to the terrain category of an airport.

### 3.3.2 Methodology to Determine the Air Flow Rate

i) Breaking down the wall section into components

The assumption of one-dimensional air flow enables one to divide the envelope horizontally into independent sections, such that vertical air flow from one section to the other is assumed zero. These divisions are based on the number of layers making up each section, their sequence, thicknesses and material properties. Consequently, each section will have different air permeability properties and air flow rates are calculated through each section independently.

Air temperature, relative humidity and air pressure on both sides of the wall are assumed to be the same for different sections in the same wall. The air flow velocity is assumed to be uniform through the same section of the wall. Every section is broken down into layers, and each layer into components (such as panels, joints ...) each with a given air permeability. This process enables data to be entered describing a multi-layer wall assembly and its air barrier system. Also by this process the envelope is transformed into a network of resistances where the airflow resistances of the layers work in series, and the resistances of components making up each layer work in parallel. Consider for example a wall made of two layers; gypsum boards gasketed to the floor making up the first layer and rigid insulation panels with taped joints making the second. The air flow resistances of the gypsum boards and the gaskets (which are two different components) of the first layer work in parallel as do the taped joints and the rigid insulation panels making up the second layer of the wall. But the resistance of the first layer as a whole works in series with the resistance of the whole second layer.

ii) Writing the equations

Based on mass conservation theory, the mass flow of air is the same through each layer. Assuming that the change in air density from layer to layer is negligible, the volume flow of air is the same through each layer. The air volume flow rate through a certain layer is equal to the sum of the air volume flow rates through different components that make up this layer. For example the flow rate through taped rigid insulation panels is equal to the sum of the flow rates through the insulation and through the taped joints. Therefore to express the air flow rate through a certain layer comprising "m" components, one can write:

$$Q_{layer} = \sum_{i=1}^{m} Q_{component} \tag{5}$$

Air flow calculations are based on the power law equation:

$$Q = A * C * \Delta p^{n} \tag{6}$$

Where:

Q = Volumetric flow rate of air $[m^3/s]$

A = Normal cross-sectional area of the material $[m^2]$

C = flow coefficient $[m^3/s.m^2.Pa^n]$

$\Delta p$ or $\Delta p_{tot}$ = static pressure differential across the material [Pa]

n = flow exponent

Data on the air permeability of materials are taken from laboratory tests conducted under specific air pressure differentials (referred to as $\Delta p_{test}$). In order to use these data for other pressure differentials, it is assumed that the flow coefficient and exponent "C" and "n" are independent of the air pressure fields. The ratio of two different flow rates through the same material can be expressed by:

$$\frac{Q_1}{Q_2} = (\frac{\Delta p_1}{\Delta p_2})^n \tag{7}$$

Consequently one can write:

$$Q_{component} = Q_{test} * (\frac{\Delta P_{actual}}{\Delta p_{test}})^n \tag{8}$$

In this equation, ($Q_{test}$) is the air flow rate through the component at ($\Delta P_{test}$), ($\Delta P_{actual}$) and ($Q_{component}$) are respectively the actual pressure differential across the component and the corresponding actual flow rate through the component. ($Q_{test}$), ($\Delta p_{test}$) and "n" are provided by the materials database of the model, whereas ($\Delta P_{actual}$) and ($Q_{component}$) have to be calculated. Depending on the type of the component, the air flow through it, ($Q_{test}$) for given ($\Delta P_{test}$) can be expressed in $m^3/m^2.s$, $m^3/m.s$ or $m^3/unit.s$. Using equation (8), one can write the following:

- For a panel component:

$$Q_{component} = Area * Q_{test(m^2)} * (\frac{\Delta p_{actual}}{\Delta p_{test}})^n \tag{9}$$

If the panel used has a thickness ($TH_{actual}$) different from the thickness ($TH_{test}$) of the tested specimen, then assuming that air permeability is inversely proportional to thickness one can write:

$$Q_{component} = Area * (\frac{TH_{test}}{TH_{actual}}) * Q_{test(m^2)} * (\frac{\Delta p_{actual}}{\Delta p_{test}})^n \tag{10}$$

Rearranging:

$$Q_{component} = \left(\frac{Area * Q_{test(m^2)} * TH_{test}}{\Delta p_{test}{}^{n} * TH_{actual}}\right) * \Delta P_{actual}{}^{n} \tag{11}$$

- For a joint component:

$$Q_{component} = length * Q_{test(m)} * \left(\frac{\Delta p_{actual}}{\Delta p_{test}}\right)^{n} \tag{12}$$

Rearranging:

$$Q_{component} = \left(\frac{length * Q_{test(m)}}{\Delta p_{test}{}^{n}}\right) * \Delta p_{actual}{}^{n} \tag{13}$$

- For a unit component:

$$Q_{component} = No_{units} * Q_{test(unit)} * \left(\frac{\Delta p_{actual}}{\Delta p_{test}}\right)^{n} \tag{14}$$

Rearranging:

$$Q_{component} = \left(\frac{No_{units} * Q_{test(unit)}}{\Delta p_{test}{}^{n}}\right) * \Delta p_{actual}{}^{n} \tag{15}$$

For simplification, products of the form;

$$\left(\frac{Area * Q_{test(m^2)} * TH_{test}}{\Delta p_{test}{}^{n} * TH_{actual}}\right); \left(\frac{length * Q_{test(m)}}{\Delta p_{test}{}^{n}}\right); \left(\frac{No_{units} * Q_{test(unit)}}{\Delta p_{test}{}^{n}}\right) \tag{16}$$

as seen in equations 11, 13 and 15 are referred to as "$C_{component}$", so that for different components we have different values of "C" denoted $C_a$, $C_b$, $C_c$....

For a wall with n layers, each with a certain number of components, there will be n flow equations which according to equation (5) will be similar to the following:

$$Q_1 = C_a*(P_i-P_1)^{n_a} + C_b*(P_i-P_1)^{n_b} + C_c*(P_i-P_1)^{n_c} + .... \quad (17)$$

$$Q_2 = C_e*(P_1-P_2)^{n_e} + C_f*(P_1-P_2)^{n_f} + .... \quad (18)$$

.

.

$$Q_n = C_r*(P_{n-1}-P_o)^{n_r} + C_s*(P_{n-1}-P_o)^{n_s} + ..... \quad (19)$$

Where, $Q_1$ through $Q_n$ represent the volume flow rates through layer 1 to layer n. $P_i$ and $P_0$ represent respectively the indoor and the outdoor air pressures which are assigned the values of $\Delta P_{tot}$ and zero respectively. $P_1$ through $P_{n-1}$ represent the air pressures at the materials interfaces. They have to be calculated in order to determine the air flow rate through the wall.

iii) Solving the equations:

As mentioned earlier, the net volume flow rate is the same through each layer, so by subtracting two consecutive equations from each, one has:

$$Q_2 - Q_1 = 0 \quad (20)$$

$$Q_3 - Q_2 = 0 \quad (21)$$

.

.

$$Q_{n-1} - Q_n = 0 \quad (22)$$

This provides a set of (n-1) non-linear equations with (n-1) unknowns that can be solved using numerical methods such as the Newton-Raphson technique. The model adopted a globally convergent Newton's method (Numerical recipes,1992).

In the case where there is an air cavity behind the siding, it is assumed to be an equalized pressure cavity. Therefore the resistance to air flow of the last two layers (siding and cavity) is negligible and the air pressure at the inner face of the cavity is considered by the program as equal to the assigned outdoor pressure. In this case the total number of layers is reduced by two, and the number of non-linear equations to be solved will be equal to (n-3).

When the air pressures at the interfaces are determined, the air flow volume can be calculated through any selected layer and then divided by the area to obtain the air flow velocity through the section. This procedure is then repeated for each section of the wall.

### 3.3.3 Identification of a Wall Section Permeability Equation

One of the features of the program is its identification of the flow exponent "n" and coefficient "C" of a composite wall. In fact, the air permeability of the section as a whole can be represented by an equation of the form:

$$Q = C * \Delta p^{n} \tag{23}$$

By calculating the logarithm of both sides of this equation we get:

$$\log_e Q = \log_e C + n * \log_e \Delta p \tag{24}$$

Rearranging:

$$(\log_e Q) = n(\log_e \Delta_p) + (\log_e C) \tag{25}$$

This equation is of the straight line form: Y = aX + b.

where "a" equals "n" and "b" equals $\log_e$ of "C".

To determine the values of "a" and "b", the air flow rate through the section is calculated for twenty values of total differential air pressure $\Delta p$. These pressure values are chosen between 1 and 100 Pascals which is the usual operating range. In the process of air velocity calculation, the $\Delta p$ values generating residuals of an absolute value higher than $10^{-8}$ are rejected so that an acceptable accuracy is assured. Then the logarithms of the retained $\Delta p$s and of the corresponding air flow rates are calculated and assigned to X and Y coordinates of a point "P". The least square method is applied to find the equation that best fits a straight line through these points. The slope of this line is equal to the value of "a", and the y coordinate of the intersection of this line with the y-axis is equal to the value of "b". Knowing "a" and "b", the values of "n" and "C" can be determined, where "n" is equal to the coefficient of "X" and "C" is equal to the exponent of the constant. We can now write the airflow equation of the wall section. This equation is then used by the program to calculate the hourly values of the air velocity through the wall.

## 3.4 HEAT AND MOISTURE FLOW MODELS

Temperature and vapour pressure gradients in a multilayered construction are greatly affected by air flow. Also, the occurrence of condensation/evaporation can affect the temperature profile through the generated/absorbed latent heat. Solar radiation can give rise to substantial increase in a wall's exterior surface temperature above air temperature, specially in winter. This can decrease the chance for interstitial moisture condensation to happen. The boundary conditions for heat and moisture flow models include:

- Air temperature and relative humidity and a surface convection coefficient of 0.121 for the interior.

- Air temperature and relative humidity, solar radiation, radiation of the surroundings and surface convective coefficient for the exterior.

### 3.4.1 Determining the Exterior Surface Temperature

Long-wave radiation exchange is assumed to take place between the external wall surface and the sky and surroundings considered as black bodies at air temperature. Using a steady state approach (Pedersen,1992), the surface temperature is calculated for a precise hour as:

$$T_{surf} = \frac{(\alpha * I_v + h_c * T_o + h_r * T_o + U * T_i)}{(h_c + h_r + U)} \tag{26}$$

Where:

- $\alpha$ = absorptance of the outside surface.
- $I_v$ = Solar radiation falling on a vertical surface. [W/m²]
- $T_i$, $T_o$ and $T_{sky}$ are the interior air, exterior air and sky temperatures respectively.
- U = The thermal conductance of the construction calculated from the outside surface to the indoor air. [W/m².°C]
- $h_c$ is the convective coefficient. [W/m².°C]

  $h_c = 5.82 + 3.96*v$ for $v \leq 5$m/s , $h_c = 7.68*v^{3/4}$ for $v > 5$m/s
- $h_r$ is the equivalent radiative coefficient. [W/m².°C]

$$h_r = \sigma * \varepsilon * (T^2_{surf} + T^2_o) * (T_{surf} + T_o) \tag{27}$$

For simplification:

$$h_r \approx \frac{1}{2} * \sigma * e * (T_{surf} + T_o)^3 \qquad (28)$$

where:

- $\epsilon$ = emittance of the external surface.
- $\sigma$ = Stephan Boltzman constant; 5.67E-8 [W/(m².K⁴)]
- v = wind velocity [m/s]

In the calculation of $h_c$, the angle between the wind direction and the surface of the wall is assumed to have no effect. By considering equations (26) and (28), we have two equations with two unknowns (surface temperature and radiation coefficient) that can be solved by a numerical method, like the Newton-Raphson technique adopted in the model.

Calculation of solar radiation:

To calculate the hourly amount of solar radiation falling on a vertical surface knowing the amount falling on a horizontal surface, we need to determine the sun position from its altitude and azimuth both expressed in radians. This is done by the following procedure:

The solar time of the day, T is obtained as a function of: (i) SM the time zone Standard Meridian (73° or 0.4166Π radians for Montreal), (ii) ST the standard time at which the sun position needs to be determined and (iii) ET the equation of time (in decimal hours). The equation of time gives (IES,1984):

ET = 0.17 * sin [4 * Π/373 * (J-80)] - 0.129 * sin [2 * Π/355 * (J-8)]

Where, J is the Julian day.

Then the solar time expressed in decimal hours (IES,1984) is calculated by:

$T= ST + ET + 12(SM-LON) / \Pi$

Where LON is the longitude of the site (73°.45' or 0.408Π radians for Montreal).

The solar declination angle $\delta$ (expressed in radians) which accounts for the change of the earth's axis tilt with respect to its elliptic orbit throughout the year can be determined by:

$\delta = 0.4093 \sin [(\Pi/184) * (J-81)]$

Then the solar altitude $\beta$ is calculated as:

$\beta = \sin^{-1} (\sin L * \sin\delta - \cos L * \cos\delta * \cos(\Pi*T/12))$

Where L is the site latitude (45°.28' or 0.25155Π radians for Montreal). A negative value of $\beta$ means that the sun is below the horizon.

The solar azimuth $\phi$ measured from due south, is determined from the following equations (Hutcheon/Handegord,1989):

If $T \leq 12$ then:

$\phi = [\cos^{-1} (\cos L * \sin\delta + \sin L * \cos\delta * \cos(\Pi * T/12))/\cos\beta] - \Pi$

If $T>12$ then:

$\phi = \Pi - \cos^{-1} [(\cos L * \sin\delta + \sin L * \cos\delta * \cos(\Pi * T/12))/\cos\beta]$

Now that the position of the sun is determined, the total short wave radiation reaching a vertical surface is given by (Hutcheon/Handegord,1989).

$I_v = I_{DN} * \cos \theta v + Id + Ir$

By neglecting Id and Ir which are respectively the diffuse sky radiation and the short-wave radiation reflected from the surroundings, we will have:

$I_v = I_{DN} * \cos \theta v$

Where $I_{DN}$ is the direct normal radiation and $\theta v$ is the angle of incidence (angle between the incoming solar rays and a line normal to the receiving surface).

$I_{DN}$ can be calculated from:

$I_{DN} = I_h / \cos \theta h$

Where $I_h$ is the solar radiation reaching a horizontal surface (hourly values given by the Ashrae WYEC), $\theta h$ is the incidence angle on the horizontal surface.

knowing that $\cos \theta h = \sin \beta$, we have:

$I_{DN} = I_h / \sin \beta$

Knowing that $\cos\theta v = \cos\beta * \cos\gamma$

where the angle $\gamma = \phi - \Psi$, $\Psi$ being the vertical surface azimuth measured from due south, and $\phi$ the solar azimuth calculated earlier, we can calculate the solar radiation as:

$I_v = (Ih/\sin\beta) * \cos\beta * \cos (\phi - \Psi)$

### 3.4.2 Mechanisms of Heat and Moisture Flow

The heat and moisture flow calculations are based on the equations developed by Tenwolde (1985).

Heat flow:

The calculation of temperature in the model uses the equation derived by Berlad et al for exfiltrative and infiltrative airflow from the steady-state energy conservation equation:

$$\rho * c_p * v * \frac{dt}{dl} = K * \frac{d^2t}{dl^2} \qquad (29)$$

Where:

- $\rho$ = density of air [kg/m$^3$ ]
- $c_p$ = specific heat of air [J/kg.°c]
- K = thermal conductivity of insulation
- l = distance from the inside boundary of the insulation
- t = temperature
- v = velocity of air flowing; +ve for exfiltration and -ve for infiltration.

This equation applies only to a single layer of homogenous material. However, Tenwolde has shown that a similar differential equation that can be used for multilayered walls has the form:

$$\rho * c_p * v * \frac{dt}{dx} = \frac{1}{Rt} * \frac{d^2 t}{dx^2} \tag{30}$$

Where x is a thermal parameter which represents a fraction of the total thermal resistance of the wall, Rt.

The solution for equation (30) is:

$$t = t_i - (t_i - t_o) * \frac{e^{Ax} - 1}{e^A - 1} \tag{31}$$

Where:

$$A = \rho * c_p * v * Rt \tag{32}$$

$t_i$ and $t_o$ represent the indoor and outdoor temperatures respectively. In the absence of air movement, temperatures across the wall section are a linear function of x:

$$t = t_i - x * (t_i - t_o) \tag{33}$$

Vapour flow:

In vapour transport, conservation of mass gives:

$$\rho * c * v * \frac{dp}{dy} = \frac{1}{Rv} * \frac{d^2p}{dy^2} \tag{34}$$

Where:

- c = W/P is a constant; W being the humidity ratio
- v = air velocity
- p = water vapour pressure
- Rv = total vapour diffusion resistance of wall

The solution for equation (34) is:

$$p = p_i - (p_i - p_o) * \frac{e^{By} - 1}{e^{B} - 1} \tag{35}$$

Where:

$$B = \rho * c * v * Rv \tag{36}$$

- y is a vapour flow parameter similar to x.
- $p_i$ and $p_o$ represent the interior and exterior vapour pressures respectively.

Without air movement, vapour moves by diffusion only, and vapour pressures in the wall are a linear function of y:

$$p_{diff} = p_i - y * (p_i - p_o) \tag{37}$$

### 3.4.3 Determining Moisture Accumulation

The accumulation or evaporation rates at a material surface or interface can be found from the following equation :

$$w = \frac{B}{Rv} * \left( \frac{(p_i - p_s) * e^{By_s}}{e^{By_s} - 1} - \frac{(p_s - p_o)}{e^{B(1-y_s)} - 1} \right) \quad (38)$$

Where $p_s$ is the saturation vapour pressure at this location and $y_s$ is the y calculated for the location in question.

In a pure diffusion case:

$$w_{diff} = \frac{1}{Rv} * \frac{p_i - p_s - y_s(p_i - p_o)}{y_s(1 - y_s)} \quad (39)$$

The accumulation rate at an interface represents the difference between the vapour flows to and from the condensing surface. The latent heat of condensation / evaporation has sometimes a significant effect on the temperature profile. The increase/ decrease in temperature $\Delta t_L$ attributable to latent heat can be expressed for the case of diffusion as:

$$\Delta t_{Ldiff} = c_L * w_{diff} * Rt * x_s * (1 - x_s) \quad (40)$$

Where $c_L$ is the latent heat for vaporization or sublimation.

In a case of combined diffusion and convection $\Delta t_L$ is expressed as:

$$\Delta t_L = \frac{Rt * c_L * w}{A} * \frac{(e^{x_s A} - 1) * (e^{1 - x_s A})}{(e^A - 1)} \quad (41)$$

In case of evaporation $\Delta t_L$ is negative.

## 3.5 MODEL IMPLEMENTATION

The airflow and moisture calculation models have been implemented in a computer program. This software is developed using Fortran 77 programming language available for the IBM personal computer.

### 3.5.1 Input and Output Requirements

The user specifies the starting day of the simulation which will then run for a whole year. The user also chooses to run the program for the simple case of diffusion or for the case of combined diffusion and airflow. In the last case, the user is asked to choose between defining a constant wind $C_p$ value or using the wind $C_p$ file of the model or providing his own wind $C_p$ data file.

The other input requirements include the following:

i) Description of the Building and terrain conditions: This includes the building's height, the height of the storey or the height between two airtight floors, the orientation of the wall to be analyzed, the absorptivity and emissivity of the exterior finish, in addition to the two parameters that describe the surrounding terrain category; the wind gradient height and mean speed exponent.

ii) Description of the wall section: This includes the number of layers in the wall and their sequences, the number of components in each layer, the identification of each component and its quantity.

iii) Description of the internal climate of the building: This includes monthly values of internal dry bulb temperature, relative humidity and mechanical pressure.

The program calculates the hourly values of air velocity, temperature, partial pressure and the amount of cond./evap. at the materials surfaces and interfaces and deduces the cumulative condensate quantities at interfaces at the end of every week. It provides weekly averaged values for temperature and relative humidity at the materials interfaces, in addition to weekly averaged values of the outside and inside temperatures and relative humidity values, air pressure differentials and velocities. The program also calculates the total thermal and diffusion resistances of the wall, its air permeability at 75 Pa along with the air permeability of each layer separately at 75 Pa. It also identifies the flow exponent and coefficient of the composite wall.

### 3.5.2 Database

Materials properties database:

The materials data base used by the program comprises 57 components grouped in three categories according to the characteristics of their air permeability data. The first category represents (panel materials) through which air flow is expressed per $m^2$. These materials are provided with diffusion permeability, thermal conductivity, and air permeability for a defined thickness and pressure differential. The air flow type through these materials is laminar. The second category represents components for which air permeability is expressed per unit (like an electric outlet). The third category represents the components that make up the joints between two materials or between a material and a fixture (like a gasket around an electrical outlet). Their permeability is expressed per meter length. The diffusion and thermal properties of the components belonging to the second and third categories are assumed to be insignificant. Their effect on heat and moisture transfer is only through their permeability to air.

The air permeability of the items in the data base whether expressed per area, unit or length always represent flow rates under a known test pressure differential, (75 Pa for most of the cases). These values are the results of experiments usually conducted on a single material or element (CMHC,1988;1991a,1991b,1993), (Levin,1991).

Though this database includes the most common components, it does not cover all the components that might be found in a construction. This arises because of construction variability, limited laboratory tests describing the construction details and also because of the huge number of components that could be found in a multilayered construction such as cracks and joint materials. Therefore, choices from the database to represent specific details are subject to interpretation. This is illustrated in the examples analyzed in Chapter V.

Weather data:

The ASHRAE WYEC (Weather Year for Energy Calculations) is used by the model to generate hourly values of the following parameters for the city of Montreal:

Outdoor air dry bulb temperature, outdoor air dew point temperature, wind speed, wind direction and horizontal solar radiation.

### 3.5.3 Software Architecture

The program consists of several independent modules for each aspect of calculation, data retrieval and input/output processing. Fig 3.1 shows how the airflow and heat and moisture routines are integrated in the model. Fig 3.2 shows the process used to generate the wall section air permeability equation and how the accuracy is controlled. Fig 3.3 is a detailed view of the moisture accumulation routine.

### 3.5.4 Program Features

The model can predict the air velocity through multi-layered walls where joints, connections and perforations are modeled. This air velocity is then used to predict the transfer of heat and moisture in these walls. The model can determine the location(s) of condensation (one additional condensation location on each side of the originally identified surface) and calculate the time-varying moisture accumulation rate in the wall. The model predicts the rate of potential evaporation of the condensed moisture. It is suitable for analysis of winter heating as well as summer cooling conditions. The model may be used to study the effects of different parameters on moisture condensation, like the design of the wall, the climate, the wall orientation. By identifying the air flow coefficients of a multi-layered wall, the model allows comparison in terms of air permeability between different wall designs and for variable differential pressure ranges. By permitting the division of a wall section into smaller sections, the model allows the user to investigate the effect of the ratio of joints length to the total area of the wall section on the hygric performance of the wall.

### 3.5.5 Model Limitations

The primary objective of the model is to incorporate air flow in one-dimensional, steady-state moisture flow calculations, thereby improving the accuracy and capabilities of the analysis. The proposed methodology is not based on transient finite difference methods and hence does not require extensive input data. However, the simplicity and the underlying assumptions limit the applicability of the results. These results cannot be used to accurately assess the long-term performance of a wall system and should be regarded as rather qualitative. The user being aware of the assumptions and limitations, must therefore exercise professional judgement in interpreting the results.

At this time the model can only be applied to walls, though it could be modified to consider roofs provided that the air permeability of roofing systems can be obtained. The one-dimensionality of the model limits the forms of air leakage problems it can address, and also makes it only applicable to wood frame constructions, where thermal bridge effects are less significant than in concrete and steel constructions. This last limitation restricts its application to low-rise buildings.

Air convection loops within the cavity or between the cavity and the indoor or outdoor are not specifically handled in this model. Addressing this particular problem constitutes a suggestion for a future research work.

**Fig 3.1 GENERAL FLOW CHART**

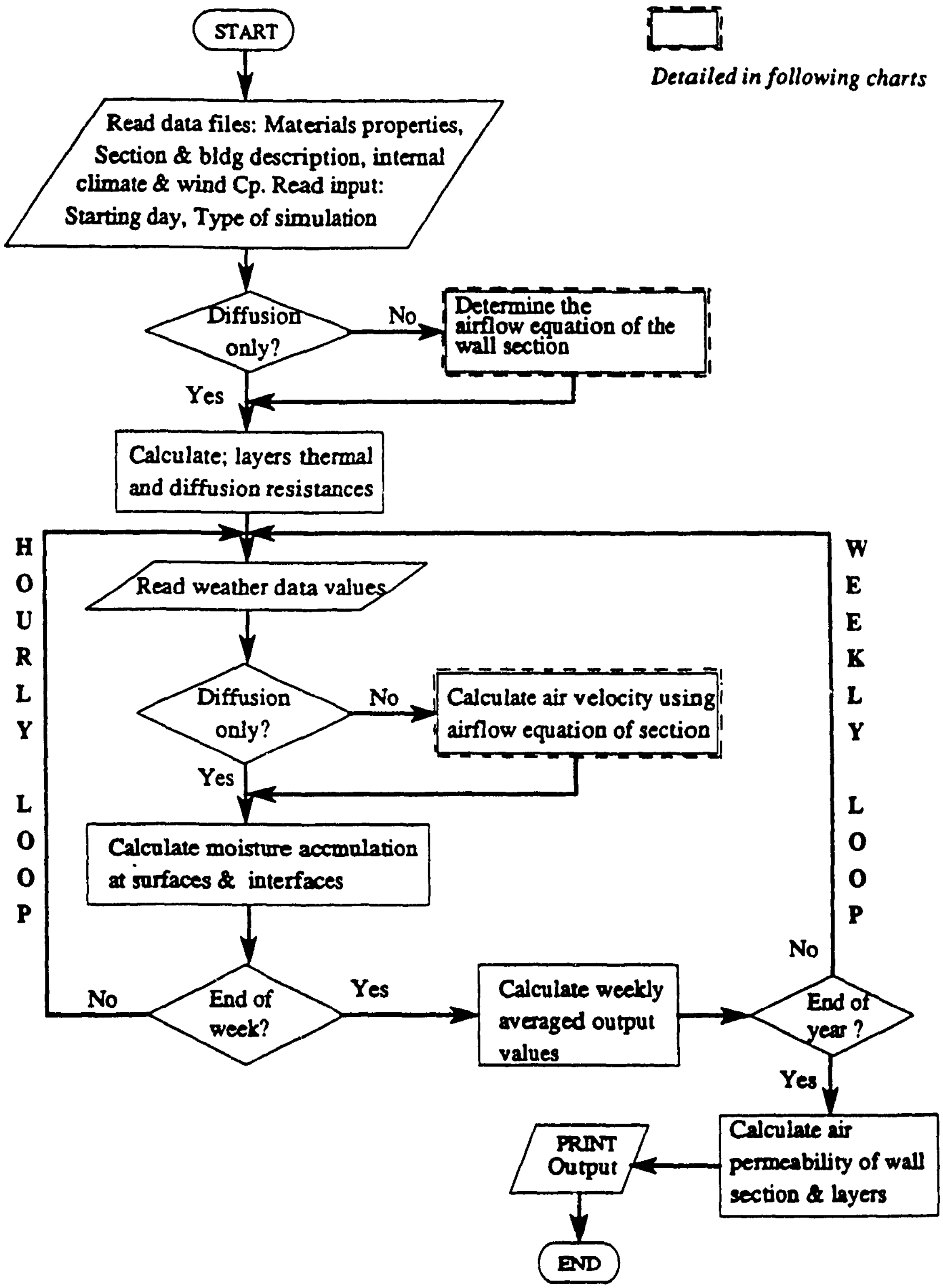
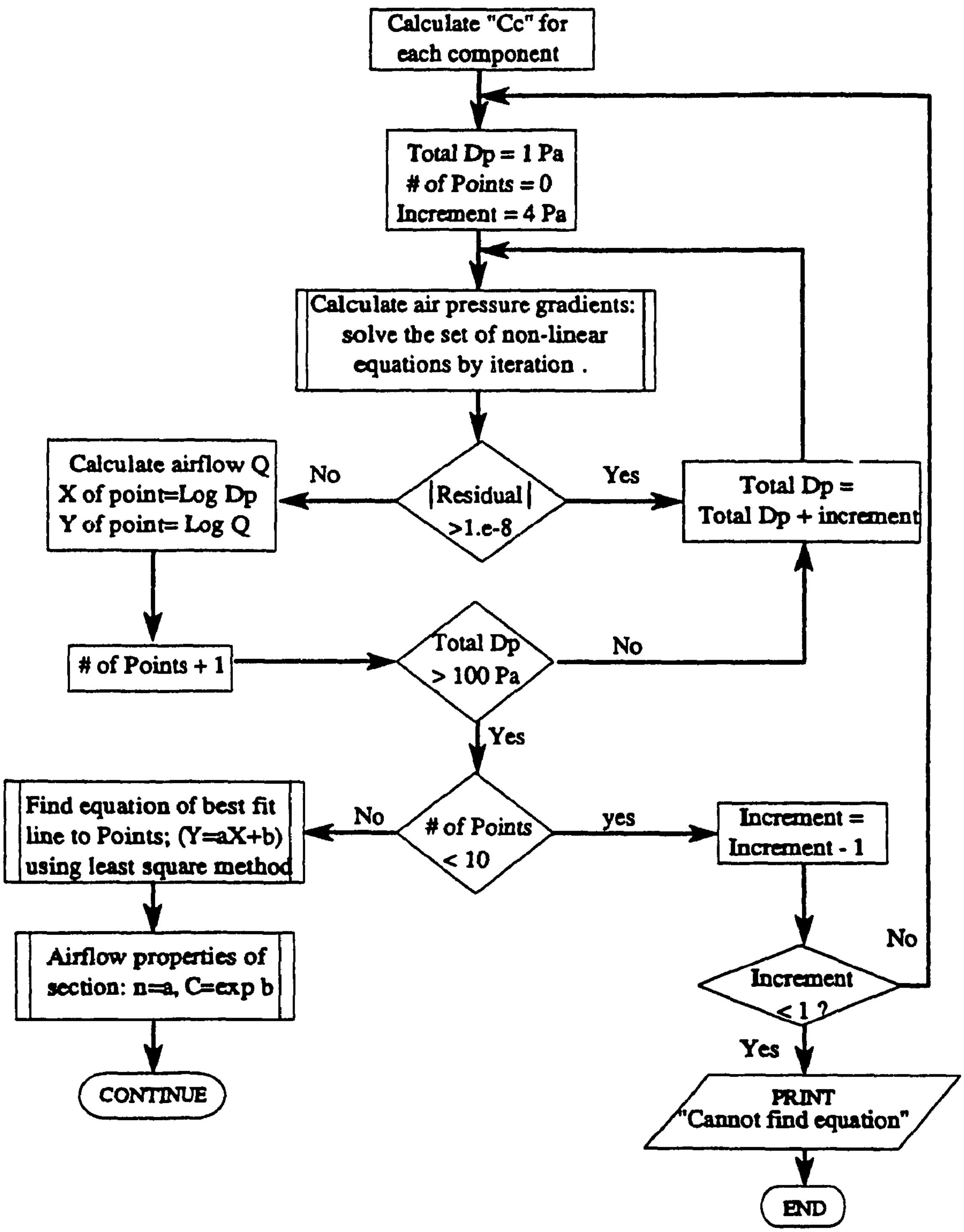
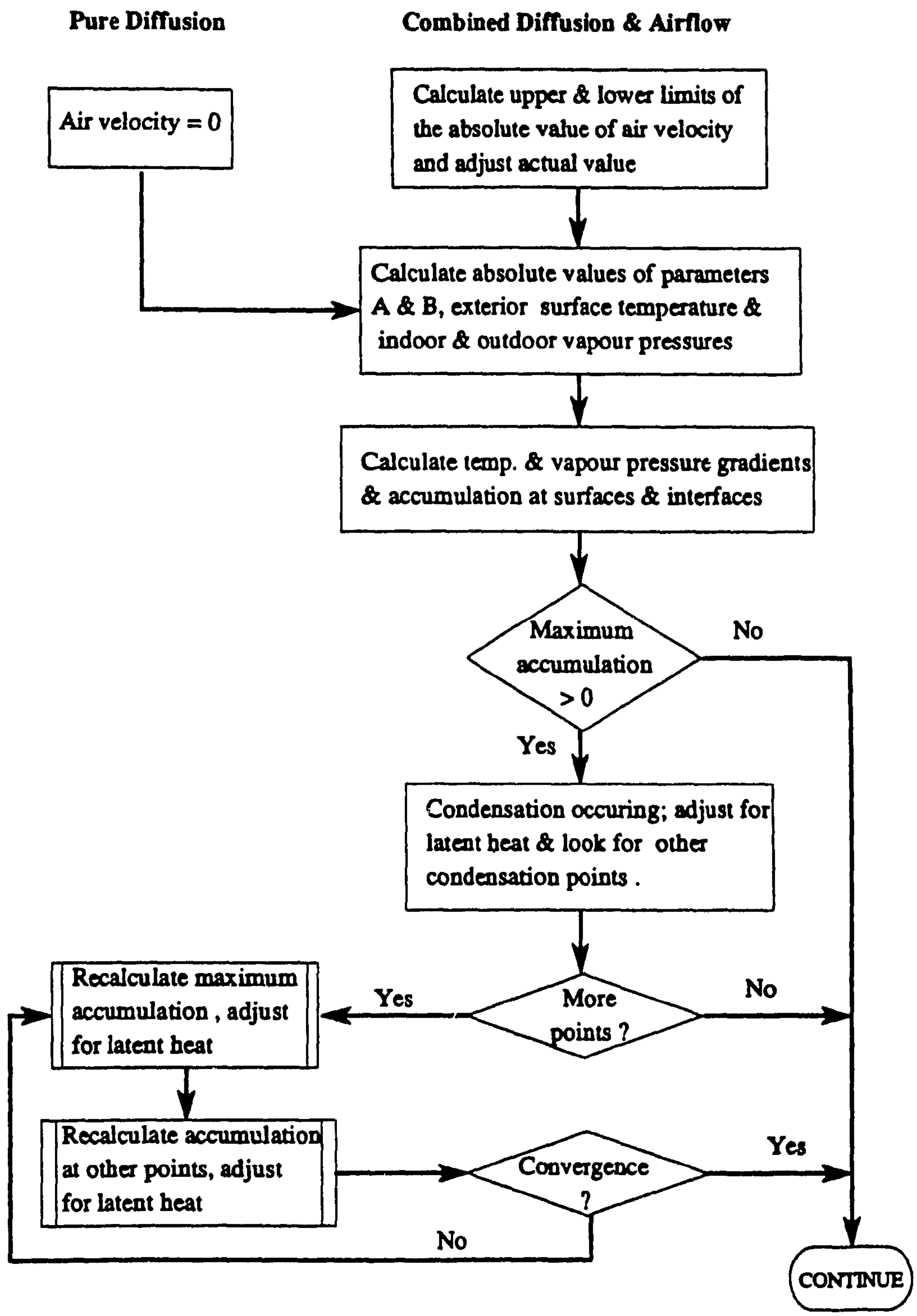


**Fig 3.2 FLOW CHART OF THE AIRFLOW ROUTINE**



## Fig 3.3 FLOW CHART OF MOISTURE ACCUMULATION ROUTINE



# CHAPTER IV

# MODEL VALIDATION AND ASSESSMENT

In this chapter, a mathematical validation is conducted for the purpose of ensuring consistency in the relations between different interdependent parameters and verifying the accuracy of the numerical methods used by the model. In addition, the model results are compared with those of three available models: Condense, EMPTIED and MOIST.

## 4.1 MATHEMATICAL VALIDATION

The net moisture accumulation calculated by the "moisture flow routine" of the model depends on a number of variables such as, the air flow rate through the wall as calculated by "the airflow routine", the internal vapour pressure and the outdoor temperature. The air flow rate value depends on the wall section "airflow equation" and the total differential pressure across the wall. In this section the airflow model is addressed through the verification of the method used to determine a wall section "airflow equation" as described in section 3.3.3. The moisture flow model is addressed through the examination of the effect of the interior vapour pressure on moisture accumulation.

Test Problems:

i) Method to determine the airflow equation of a wall section:

The two variables examined here are the differential air pressure and the air volume flow rate. The wall chosen for the analysis is described in section 5.2 (stud wall section). For twenty values of total differential pressure ($\Delta P_{tot}$) between 1 and 100 Pa with 4 Pa interval, the air flow rate through the analyzed section was calculated and plotted in Fig 4.1a as dark triangles. We notice that as expected an increase in the absolute value of pressure leads to an increase in the absolute value of air velocity. The next step consists in generating the air permeability equation of the (stud section) using these twenty determined points and following the process detailed in section 3.3.3. The equation determined is:

$$Q = 2.691E\text{-}05\ \Delta p^{0.703}$$

Where Q is the air volume flow rate per $m^2$.

The graph of this equation was traced using 99 points representing 99 values of $\Delta p$ between 1 and 99 Pa. Fig. 4.1a shows the perfect match between the curve traced by the equation (empty squares) and the twenty points used to generate this equation (dark triangles). This proves the validity and the mathematical accuracy of the approach used.

ii) Calculation of moisture accumulation:

The two variables examined here are the independent internal vapour pressure and the dependent cumulative condensation calculated at the end of the week. If a constant internal temperature is maintained, then a higher vapour pressure means a higher relative humidity. For the same wall section and the same weather data, an increase in the internal relative humidity is expected to lead to an increase in the amount of accumulation. The time of year chosen for the analysis is the first week of January where the outdoor conditions are adequate for condensation.

The wall chosen for the analysis is described in section 5.6. Fig 4.1b shows the results of the test, and as expected moisture accumulation increases steadily with relative humidity.

## 4.2 COMPARISON WITH OTHER MODELS

Three available computer models were chosen for comparison with our model:

- Condense (version 2.0), based on the dew-point method which is one of the most widely used traditional methods for determining the condensation location.
- Emptied, a steady-state model developed for C.M.H.C. (1990). It incorporates air flow in a simplistic way.
- Moist (version 2.0) developed by NIST, is one of the very few available transient models and probably the most widely used one in the United States.

### 4.2.1 Condense

Condense is a one-dimensional steady-state model that calculates temperature and vapour pressure gradients across a given wall assembly (QBEC,1993). The input includes the selection of material for each layer, indoor and outdoor design temperatures and relative humidity values. The model estimates the potential of moisture condensation due to diffusion.

Description of the analyzed wall section:

- Gypsum board, 13mm thick, 0.08 R-value, 0.0005 diffusion resistance. Paint with

0.039 diffusion resistance.

- Fiberglass batt, 89mm thick, 2.1 thermal resistance, 0.00067 diffusion resistance.
- Extruded polystyrene, 50mm thick, 1.75 thermal resistance and 0.0405 diffusion resistance.
- Wood siding, 12mm thick, 0.141 thermal resistance and 0.02 diffusion resistance. Paint with 0.039 diffusion resistance.

Boundary conditions:

Outdoor: Air film convection coefficient = 0.03. Temperature = -23°C. RH = 90%.

Indoor: Air film convection coefficient = 0.24. Temperature = 22°C. RH = 30%.

Results:

- Condense predicts condensation in the last quarter of the batt insulation with a rate of 0.4072E+04 ng/s.m$^2$. Refer to Fig 4.2.
- Our model predicts condensation on both faces of the siding with a total rate of 0.84E+04 ng/s.m$^2$ which is double the amount predicted by Condense.

This discrepancy in the predictions between the two models is due to the fact that Condense based on the dew point method reports only the first condensation location found. To avoid inaccurate conclusions about the rate and condensation location, the calculation procedure should be repeated until the vapour pressure does not exceed the saturation vapour pressure anywhere in the construction.

### 4.2.2 EMPTIED

EMPTIED is the abbreviation for Envelope Moisture Performance Through Infiltration, Exfiltration and Diffusion (CMHC,EMPTIED). The program estimates the potential amount of moisture that is likely to accumulate, month by month in a specified building envelope through air leakage and vapour diffusion. It utilizes the hourly "bin" weather data for a particular locality to represent the outdoor conditions, but the user selects the indoor conditions for the analysis. The input also includes an equivalent leakage area for the section, the identification of the condensation planes, and the maximum absorption of water for these planes in kg/m$^2$. The calculations are based on steady-state thermal and moisture equilibrium.

Description of the analyzed wall:

The wall section chosen for the comparative analysis is assumed to be facing North so that sun radiation effect on temperature is ignored. The section is made of the following layers:

- Gypsum board, 13mm thick with a vapour retarder type II paint.
- Batt, 89mm thick.
- Fiber board, 8mm thick.
- Air cavity, 19mm thick.
- Painted wood siding 19mm thick.

Total R-value = 2.831. Total diffusion resistance = 0.0596.

Total height of section = 2.8m. Neutral pressure plane at mid-height.

Input data:

The air permeability equation of this section as determined by our model is expressed by:

$$Q = 2.2723E{-}05 * \Delta p^{0.84}$$

Where Q is the volume flow rate per $m^2$.

This equation is used to calculate the equivalent leakage area of the section as follows:

For $\Delta p$ = 10Pa, Q = 0.0001572 $m^3/m^2.s$.

$$Q = C * A_{eq} * \sqrt{\frac{2}{\rho} * \Delta p}$$

Where C is the orifice flow coefficient given the value of 0.6, Aeq is the equivalent leakage area to be calculated and $\rho$ is the air density given the value of 1.2kg/$m^3$.

Solving the equation, we get: $A_{eq}$ = 0.64 $cm^2$.

This value is input into EMPTIED. The condensation plane to be input into Emptied was chosen to be similar to the one predicted by our model and which is the cavity/siding interface. The maximum water absorption for the siding was assumed to be equal to 2.3kg/$m^2$. Monthly values of indoor air temperature and relative humidity as presented in Table 5.1 are used to describe the indoor environment.

Our model was modified so as to ignore wind effects in the air pressure calculations, therefore the results reflect only the stack effect in a single storey building. Also the output was modified to yield monthly values for condensation/evaporation and cumulative condensation instead of weekly values. The analysis was run for an air exfiltration case for a whole year starting with the beginning of January.

Results:

The output generated by EMPTIED is presented in table 4.1. In this table, the "condensation breakdown" shows that the diffusion component of moisture accumulation as calculated by Emptied is negligible in comparison to the air leakage component although the vapour control in the analyzed section is fulfilled by a vapour barrier type II paint. This makes us question the sensitivity of Emptied to the vapour resistance values. The comparison between Emptied output and our model's (presented in Fig 4.3) shows that Emptied predicts higher moisture accumulation and also higher evaporation rates. This is partly due to the fact that Emptied ignores the effect of air convection on diffusion, where warm exfiltrating air causes an increase in the temperatures of the wall section which tends to decrease the potential for condensation. Emptied results tend to reflect an upper limit for moisture deposition. The program does not seem to simulate a realistic drying. The user of this program should be aware of these drawbacks so as not to jump to erroneous conclusions.

### 4.2.3 MOIST

Moist is a transient one-dimensional finite difference model developed to predict the coupled transfer of heat and moisture in a multi-layered wall under non-isothermal conditions. It can predict moisture transfer in the diffusion through the capillary flow regimes (Burch/Thomas,1993). The model does not incorporate air flow through walls. Materials properties are a function of temperature and moisture ratio.

Description of the analyzed wall:

- Gypsum board 13 mm with paint.
- Batt insulation 140 mm.
- Fiberboard sheathing 11 mm thick.
- Tyvek (weather barrier).
- Painted waferboard siding 15 mm thick.

Total thermal resistance: 3.87

Total diffusion resistance: 0.024

Input data:

i) Materials properties:

The choice of the wall section materials was dictated by the materials database available in both software. The thermal conductivity values of the materials making up the wall are the same in both models. However, in MOIST the permeability of what are considered to be storage materials is a function of the relative humidity. In order to facilitate meaningful comparison of the models, some approximations have been made to establish equivalence in vapour diffusion resistance values of materials.

- For the gypsum board, the permeability (for R.H. between 50-100%) is 40-43.07 ng/m.Pa. We chose the value of 40 for our model.
- For the fiber board, the permeability (for relative humidity values between 50-100%) is 32.1-30 ng/m.Pa. The value of 32 was chosen for our model.
- For the wafer board siding, the permeability (for relative humidity values between 50-

100%) is 0.395-25.5. A value of 1.25 corresponding to a relative humidity of 72% was judged reasonable.

- The inside paint has a permeance of 575, the external paint has a permeance of 115.
- Fiberboard density = 2.92 kg/m². Wafer board siding density = 10.59 kg/m².

ii) Boundary conditions:

Outdoor: Weather data of Montreal (hourly values) for air temperature and R.H. Convection coefficient at the outside surface is 25. Wall is facing North.

Indoor: Temperature = 23°C, R.H. = 33%. Convection coefficient at the interior surface is 8.25.

The simulation duration is one year starting with the beginning of September.

Results:

- The weekly averaged relative humidity values at the fiber/tyvek interface were plotted for both software in Fig.4.4. We notice that the R.H. generated by our model start at higher values than those generated by MOIST. The results are very close during the peak of the winter season with the most serious deviations occurring in the Spring. In fact, drying with our model starts earlier than with MOIST, but for the last few weeks of the year, the R.H. results of both models become very close. The discrepancy between the results generated by the two models is due to the fact that MOIST accounts for the moisture sorption and the calculated R.H. values reflect the moisture content of the hygroscopic materials.

- From the graph drawn by MOIST and representing the time varying moisture content of the three storage materials; gypsum board, sheathing and siding, we notice:

  i) At the end of week 29 from the start of the simulation, the fiberboard sheathing reaches its highest moisture content which is equal to 37.03 % of its dry mass, thus equivalent to 1.083 $kg/m^2$. Referring to our model, we see that at the end of week 29, the moisture accumulation values predicted at the inner and outer faces of the sheathing are equal to 0.0916 and 0.981 $kg/m^2$ respectively. They sum up to 1.072 $kg/m^2$. This value represents the highest accumulation sum at both faces of the sheathing and is very close to the above mentioned value generated by MOIST.

  ii) The wafer board siding reaches its highest moisture content at the end of week 34. It is equal to 16.5% of its dry mass, thus equivalent to 1.75 $kg/m^2$, (maximum sorption for this material being equivalent to 22.5% of its dry mass). The highest accumulation at the tyvek/siding interface predicted by our model is three times the value predicted by MOIST. This discrepancy might be partly due to the fact that in MOIST the vapour permeability of the siding is a function of relative humidity. Another reason for this discrepancy might be the difference between the convergence criteria in both models.

## Mathematical validation

Fig 4.1a

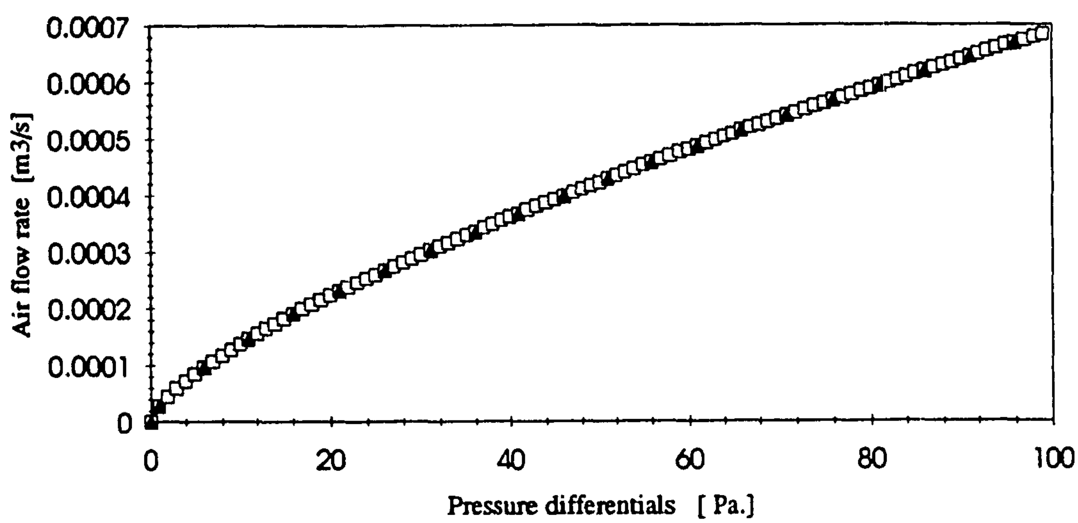
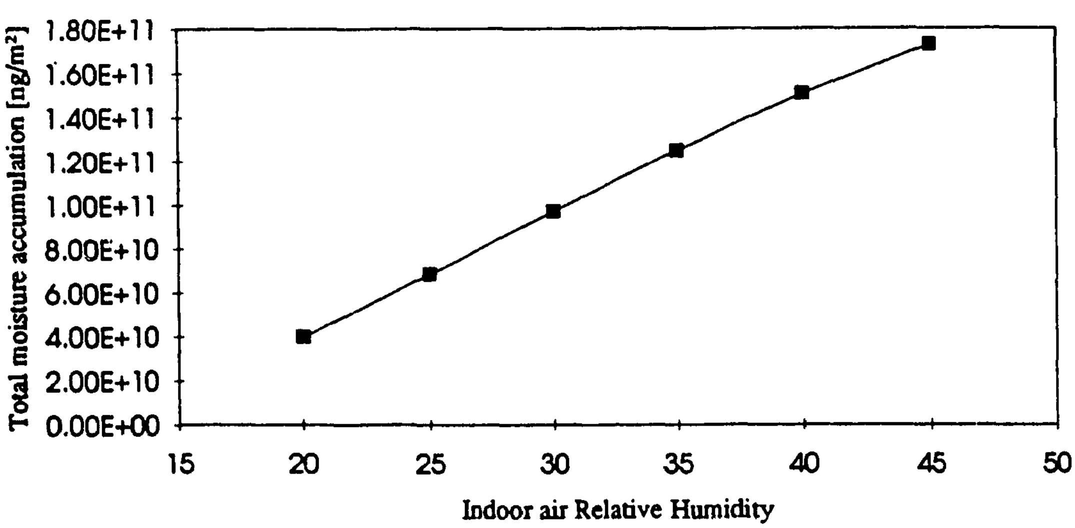



Fig 4.1b



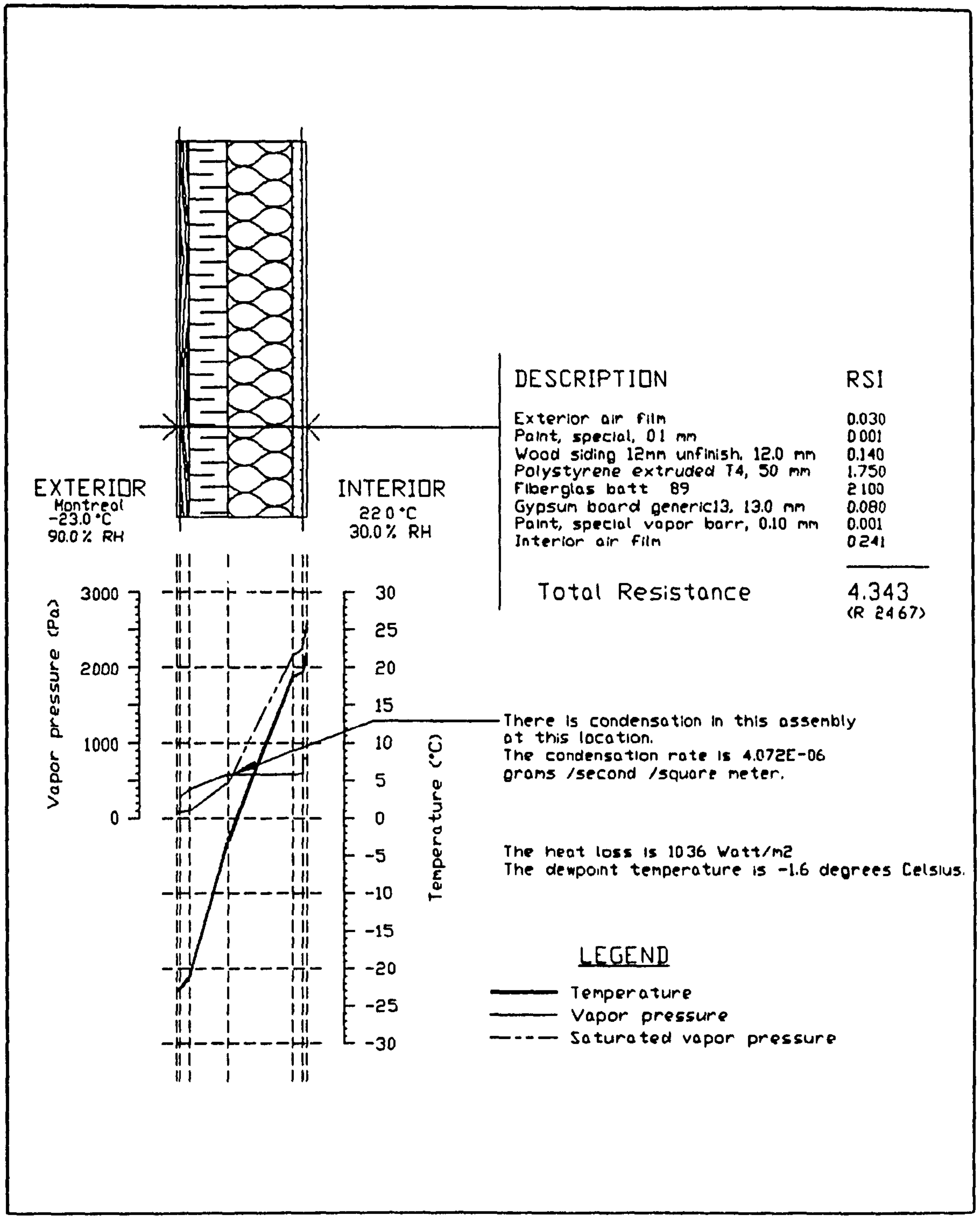



Fig. 4.2 Condense output

| MON | Plane 1 - kg/m2 Conden | Evap | Drain | Absorb | Plane 2 - kg/m2 Conden | Evap | Drain | Absorb |
|---|---|---|---|---|---|---|---|---|
| Jan | 0.6148 | 0.0108 | 0.0000 | 0.6040 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Feb | 0.5265 | 0.0104 | 0.0000 | 1.1202 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Mar | 0.2954 | 0.0766 | 0.0000 | 1.3389 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Apr | 0.0386 | 0.2812 | 0.0000 | 1.0964 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| May | 0.0110 | 0.4789 | 0.0000 | 0.6285 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Jun | 0.0000 | 0.6315 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Jul | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Aug | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Sep | 0.0159 | 0.5293 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Oct | 0.0103 | 0.4219 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Nov | 0.0802 | 0.1895 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Dec | 0.4055 | 0.0098 | 0.0000 | 0.3957 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |

Output for MONTREAL, QUEBEC
leakage area = 0.64 cm2/m2

PLANE1 = siding
Max absorb plane1 = 2.30 Kg/m2

CONDENSATION BREAKDOWN - AIR LEAKAGE vs VAPOUR DIFFUSION

| MON | Plane 1 - kg/m2 Air Lkge | Diffusion | Total | HAFZ | HBFZ | Plane 2 - kg/m2 Air Lkge | Diffusion | Total | HAFZ | HBF |
|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 0.5793 | 0.0355 | 0.6148 | 278 | 466 | 0.0000 | 0.0000 | 0.0000 | 0 | |
| Feb | 0.4960 | 0.0306 | 0.5265 | 246 | 426 | 0.0000 | 0.0000 | 0.0000 | 0 | |
| Mar | 0.2818 | 0.0136 | 0.2954 | 523 | 221 | 0.0000 | 0.0000 | 0.0000 | 0 | |
| Apr | 0.0384 | 0.0002 | 0.0386 | 720 | 0 | 0.0000 | 0.0000 | 0.0000 | 0 | |
| May | 0.0103 | 0.0007 | 0.0110 | 744 | 0 | 0.0000 | 0.0000 | 0.0000 | 0 | |
| Jun | 0.0000 | 0.0000 | 0.0000 | 720 | 0 | 0.0000 | 0.0000 | 0.0000 | 0 | |
| Jul | 0.0000 | 0.0000 | 0.0000 | 744 | 0 | 0.0000 | 0.0000 | 0.0000 | 0 | |
| Aug | 0.0000 | 0.0000 | 0.0000 | 744 | 0 | 0.0000 | 0.0000 | 0.0000 | 0 | |
| Sep | 0.0149 | 0.0010 | 0.0159 | 720 | 0 | 0.0000 | 0.0000 | 0.0000 | 0 | |
| Oct | 0.0102 | 0.0000 | 0.0103 | 744 | 0 | 0.0000 | 0.0000 | 0.0000 | 0 | |
| Nov | 0.0772 | 0.0030 | 0.0802 | 652 | 68 | 0.0000 | 0.0000 | 0.0000 | 0 | |
| Dec | 0.3853 | 0.0202 | 0.4055 | 373 | 371 | 0.0000 | 0.0000 | 0.0000 | 0 | |

Legend:
HAFZ: hours above freezing
HBFZ: hours below freezing

Table 4.1 EMPTIED output

Fig . 4.3 Comparison with EMPTIED

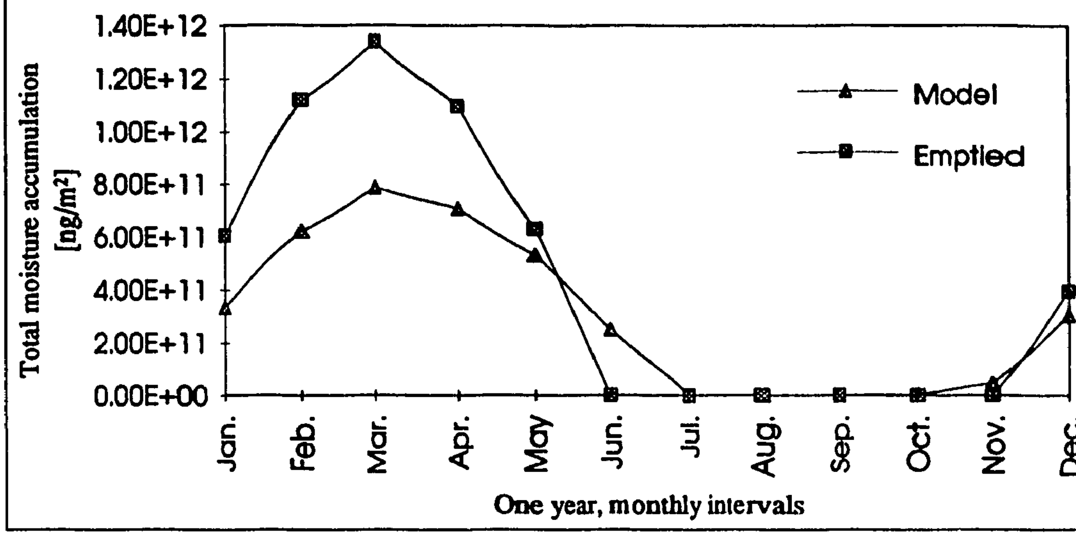
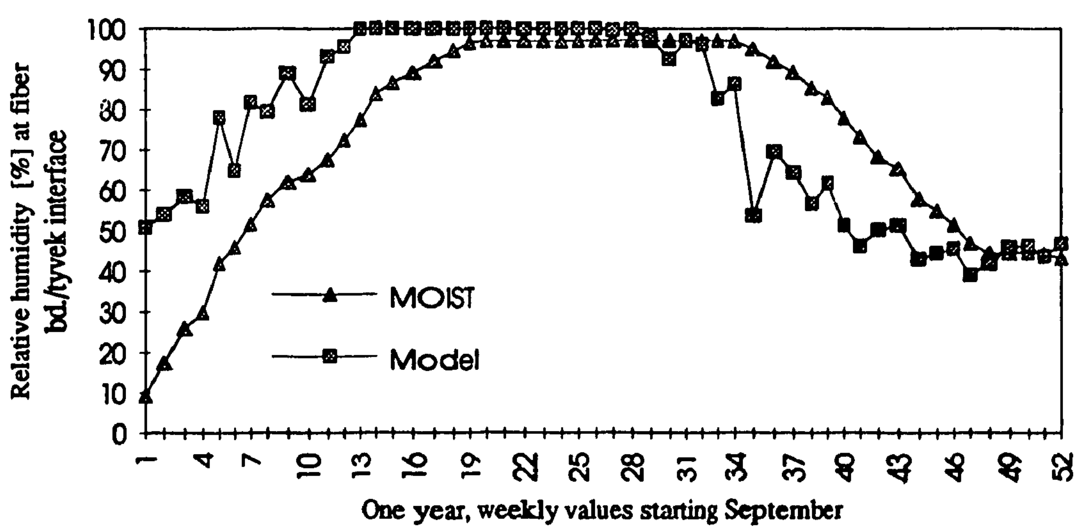



Fig. 4.4 Comparison with MOIST



# CHAPTER V

# PARAMETRIC ANALYSIS

## 5.1 AIM OF THE ANALYSIS

The objective of the parametric analysis is to show the capabilities and the uses of the model and to investigate the effects of different parameters handled by the model on the final output. For this purpose, a number of wall sections that are commonly used in construction have been analyzed in different situations, where the variations in air flow rate, interior relative humidity, thermal and diffusion resistance of the sheathing were studied regarding their impact on the location and the amount of interstitial condensation, as well as on drying. Some of the building code requirements have been also examined in order to develop an understanding of the factors governing the performance of building enclosures and of the problems addressed by these codes.

All the simulations were run for a period of one year starting with the beginning of September which corresponds to the end of the drying season. The outdoor climate conditions represent the city of Montreal. The monthly values of indoor air temperature and relative humidity presented in table 5.1 were adopted for all the simulations unless otherwise stated.

## 5.2 ANALYSIS OF A STOREY-HIGH WALL

The purpose of this analysis is to show the procedure by which a storey high wall can be analyzed by sub-dividing it into horizontal sections according to the wall design. The analysis also shows how by allowing the division of a wall section into smaller sections, the user can investigate the effect of joints to total area ratio on the hygric performance of the wall. The wall chosen for the analysis represents a standard 38x89 mm wood framing system where two different sections are identified; the header joist section and the stud wall section. The analyzed wall was chosen to be facing South, and parallel to the roof ridge of a building with the following characteristics: Height equal to 10 m, length to width ratio equal to 2, terrain category represented by a gradient height of 300 m and a mean wind speed exponent of 0.15. The wind coefficient hourly values used in calculating the wind pressures were derived from the default wind $C_p$ database file.

<u>Description of the analyzed sections:</u>

The three analyzed wall sections are illustrated in Fig 5.1a and Fig 5.1b which show a vertical section through the wall, an elevation of the sheathing and detailed views of the different components.

1) The Header Joist section is composed of the following layers:

- 38mm thick pine wood rim joist. The gaps between the joist and the upper plate and between the joist and the upper storey sub-floor are modelled as similar to "unattended joints between gyp.boards with no nailing strip behind."

- A tyvek film is used to wrap the exterior face of the joist and act as an air barrier.
- 50 mm thick semi-rigid fibreglass panel with no joints in this area.
- 19 mm strapping space.
- 19 mm wood siding with two coats of exterior paint.

Area of the section: 0.3408 $m^2$.

2) The stud wall section is composed of the following layers:

- 13 mm thick gypsum board with a coat of latex. The joints between the boards are assumed to be perfectly airtight. The horizontal gaps between the boards and the upper and lower plates are modelled as "unattended joints between gyp. boards with no nailing strip behind".
- 6mil polyethylene membrane acting as a vapour/air barrier, and connected to the tyvek film at the top and bottom of the stud wall with a bead of acoustic sealant.
- 89 mm thick fibreglass batt.
- 50 mm thick semi-rigid fibreglass with horizontal and vertical joints between panels modelled as "0.5mm gaps".
- 19 mm strapping space.
- 19 mm painted wood siding.

Area : 5.76 $m^2$.

3) One partial area of the stud wall (equal to 0.96 $m^2$) was chosen to be analyzed separately. It is concentrated around a succession of joints; the first one (starting from the inside) is the joint between the gypsum board and the floor or the bottom

plate, followed by the joint between the polyethylene and the tyvek, and then by the horizontal and vertical joints between adjacent fibreglass panels.

Results:

Fig 5.2 shows the weekly moisture accumulation in each of the three analyzed sections. By comparing the two graphs corresponding to the stud wall section and the concentrated section, we see that the concentrated section shows a much higher accumulation rate (almost double) and also a higher drying rate. This is due to its higher joint length to surface area ratio and consequently higher air permeability. In illustrating the air flow path and moisture behaviour, the case of a concentrated section is closer to reality than the case where airflow through the whole wall section (stud section) is assumed to be uniformly distributed.

| Month | Air temp.°C | Air R.H.% |
|---|---|---|
| January | 22 | 30 |
| February | 22 | 30 |
| March | 23 | 30 |
| April | 23 | 30 |
| May | 25 | 35 |
| June | 25 | 35 |
| July | 25 | 40 |
| August | 25 | 40 |
| September | 25 | 35 |
| October | 23 | 30 |
| November | 22 | 30 |
| December | 22 | 30 |

Table 5.1 Indoor climate data

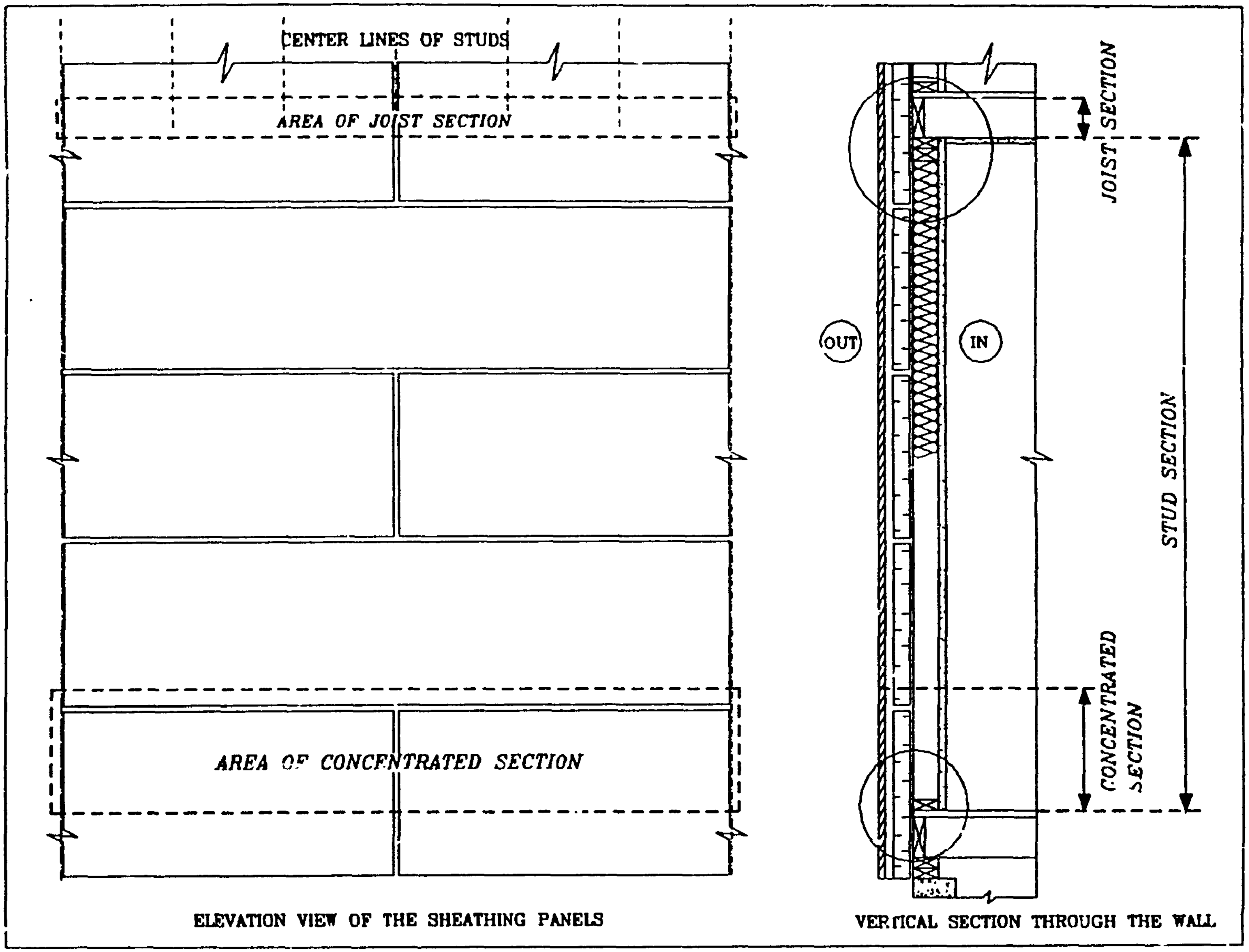

CENTER LINES OF STUDS
AREA OF JOIST SECTION
AREA OF CONCENTRATED SECTION
ELEVATION VIEW OF THE SHEATHING PANELS
OUT
IN
JOIST SECTION
STUD SECTION
CONCENTRATED SECTION
VERTICAL SECTION THROUGH THE WALL

Fig. 5.1a

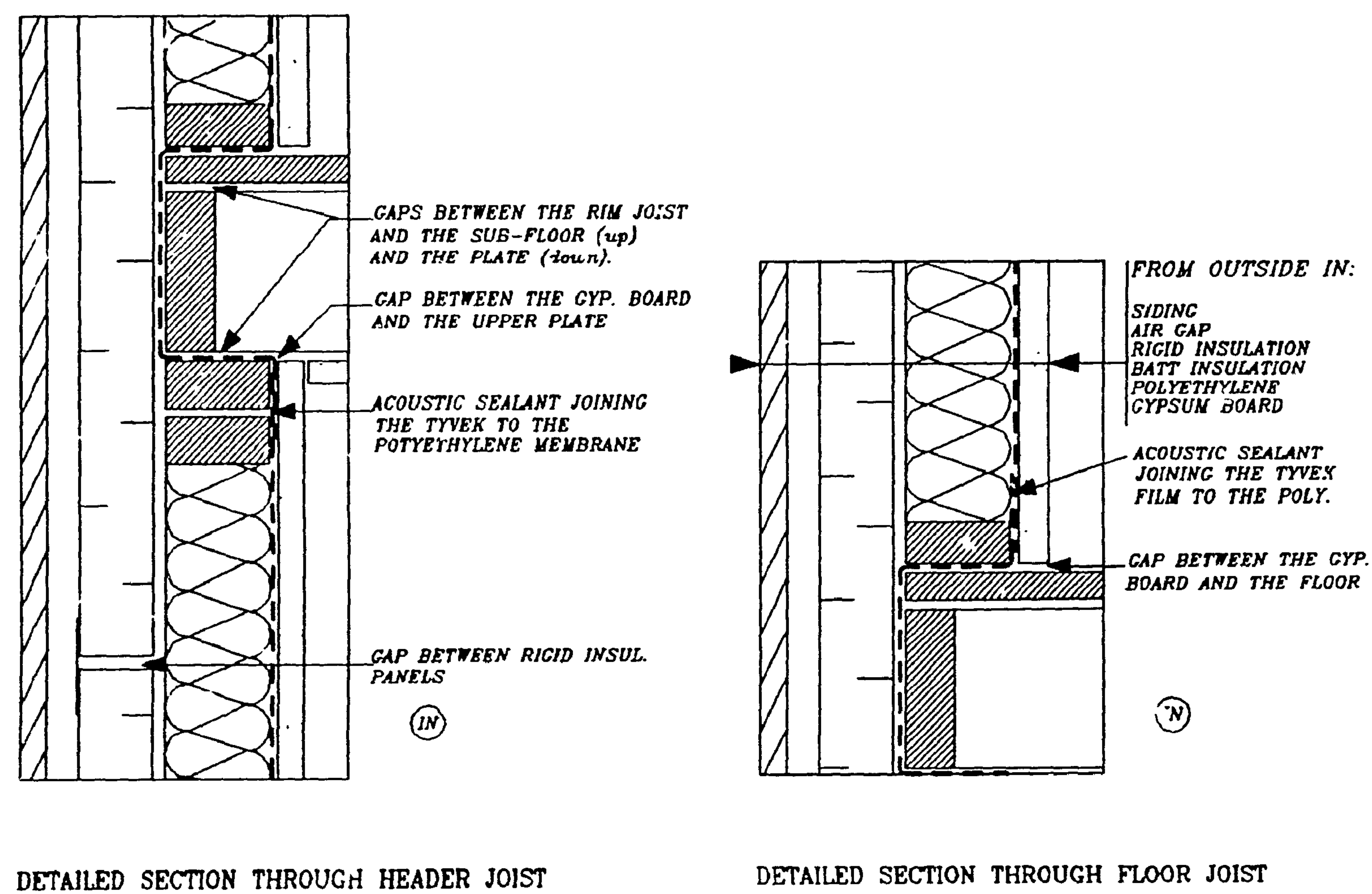

GAPS BETWEEN THE RIM JOIST
AND THE SUB-FLOOR (up)
AND THE PLATE (down).
GAP BETWEEN THE GYP. BOARD
AND THE UPPER PLATE
ACOUSTIC SEALANT JOINING
THE TYVEK TO THE
POTYETHYLENE MEMBRANE
GAP BETWEEN RIGID INSUL.
PANELS
IN
DETAILED SECTION THROUGH HEADER JOIST
FROM OUTSIDE IN:
SIDING
AIR GAP
RIGID INSULATION
BATT INSULATION
POLYETHYLENE
GYPSUM BOARD
ACOUSTIC SEALANT
JOINING THE TYVEK
FILM TO THE POLY.
GAP BETWEEN THE GYP.
BOARD AND THE FLOOR
N
DETAILED SECTION THROUGH FLOOR JOIST

Fig. 5.1b

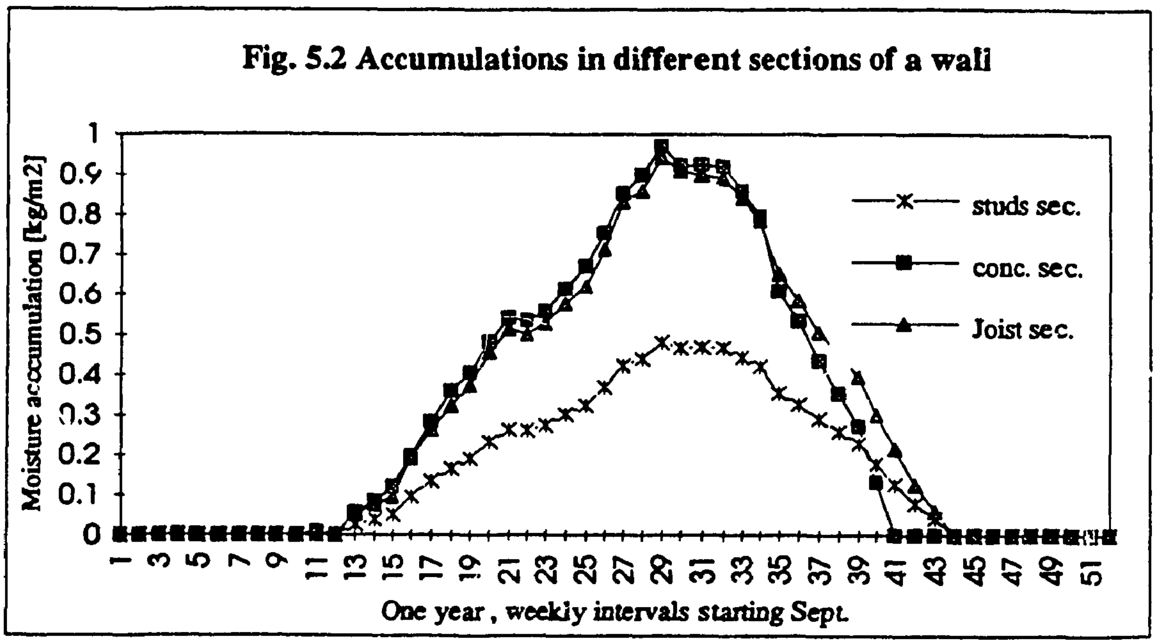


Fig. 5.2 Accumulations in different sections of a wall
Moisture accumulation [kg/m2]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51
One year , weekly intervals starting Sept.
studs sec.
conc. sec.
Joist sec.

## 5.3 IMPACT OF SHEATHING MATERIALS PROPERTIES

The primary objective here is to study how moisture accumulation in a wall is affected by the vapour permeance and insulation value of the sheathing for different air permeability values of the sections. The analysis covers four wall sections with different sheathing materials; extruded polystyrene, semi-rigid fibreglass, plywood and fibreboard. The walls have the same height and width equal to 2.4 m. which corresponds to an area of 5.76 $m^2$. The wind coefficient is assumed to be independent of the wind direction and a constant value of -0.8 is assigned to it. Knowing that the stack pressure is calculated for a single storey, it is negligible compared to wind pressure, and therefore the results illustrate an air exfiltration case.

### 5.3.1 Wall with Insulating / Vapour Barrier Type II Sheathing

Description of the wall section:

The section illustrated in fig 5.3 (I) is composed of the following layers:

- Gypsum board 13 mm thick with a type II vapour barrier paint (one coat of latex and one coat of acrylic).
- 38x89 mm studs @ 400 mm o.c. with batt insulation.
- Extruded polystyrene 50mm thick.
- Air cavity 19mm thick (horizontal strapping)
- Wooden siding 19mm thick with two coats of exterior paint.

In this section the function of weather/air barrier is fulfilled by the sealed extruded polystyrene which also constitutes a vapour barrier type II.

Total thermal resistance = 4.429 m².°C/W

Total diffusion resistance = 0.099 m².s/ng

The joints between the gypsum boards and the floor as well as the joints between the gypsum boards and the upper plates are modelled as "unattended joints between gypsum panels with nailing strip behind". The joints between the sheathing panels are modelled differently for each of the considered alternatives.

Analysis:

The program was run for the case of pure diffusion (air velocity = 0) and for three different air permeability values of the section, reflecting different modelling of the imperfections in sealing joints between sheathing panels as follows:

Alt.no.1: 12 m of horizontal and vertical joints between sheathing panels modelled as similar to "0.5 mm gap". This yields an air flow rate of 0.21 L/m² at 75 Pa.

Alt.no.2: 24 m of horizontal and vertical joints between sheathing panels modelled as similar to "0.5 mm gap". This yields an air flow rate of 0.35 L/m² at 75 Pa.

Alt.no.3: 12 m of horizontal and vertical joints between sheathing panels, modelled as similar to "0.7 mm gap" which yields an air flow rate of 0.6 L/m² at 75 Pa.

Results:

- Moisture was found to accumulate mainly on the air cavity/siding interface. For higher air permeability values of the section, important condensation is observed at the polystyrene/air cavity interface. Insignificant condensation occurs at the batt/poly. interface. In the case of pure diffusion, condensation occurs exclusively at the inner face of siding.

- The weekly moisture accumulation (for all condensation locations) are plotted for the three alternatives. Fig 5.4a shows that the accumulations increase with air permeability. The drying rate is also seen to increase with air permeability.
- The increase in air permeability does not affect the condensation at the poly/batt interface which remains negligible in all cases. The outer surface of the sheathing is where the accumulation rate is most sensitive to increase in air leakage rate.
- The comparison between moisture accumulation values at a relatively low airflow rate (0.21 $L/m^2$ at 75 Pa) to the values obtained with pure diffusion where the maximum does not exceed 0.033 $kg/m^2$, shows that exfiltrative airflow can highly increase the rate of moisture accumulation within a wall.

### 5.3.2 Wall with Insulating / Vapour Permeable Sheathing

Description of the wall section:

The extruded polystyrene in the previously analyzed case was replaced by a 57 mm thick rigid fibreglass with the outer side faced with "tyvek" providing a weather and air barrier. This section has the same thermal resistance value as the previous one, but its different diffusion resistance is equal to 0.0595 $m^2.s/ng$ due to the higher diffusion permeability of the sheathing.

Refer to fig 5.3 (I) for illustration.

Analysis:

The simulation was run for two air permeability values of the section induced by two different modelling of the gaps between the gypsum boards and the upper and lower plates, and the gaps between the semi-rigid fibreglass panels with respect to width and length.

Alt.no.1 yields an air flow rate of 0.35 L/m$^2$ at 75 Pa.

Alt.no.2 yields an air flow rate of 0.6 L/m$^2$ at 75 Pa.

Results:

- The condensation occurs exclusively at the tyvek/air cavity and the air cavity/siding interfaces with the amounts at the tyvek/air cavity being less important but increasing with air permeability. The weekly amounts of cumulative condensation are shown in Fig 5.4b.
- Unlike the previous case study, no condensation is occurring at the batt/sheathing interface. This is due to the high diffusion permeability of the sheathing which causes a relatively low vapour pressure at that location and eliminates the condensation potential in the very cold hours.

### 5.3.3 Wall with Non-insulating / Vapour Barrier Type II Sheathing

Description of the wall:

- Gypsum board 13mm thick with a type II vapour barrier paint.
- 38x89 mm studs @ 400 mm o.c. with batt insulation.

- Plywood sheathing, 8mm thick.

- Air block (trowel applied); weather barrier/air barrier.

- Air cavity 19mm thick (strapping).

- Wooden siding 19mm thick with two coats of exterior paint.

Thermal resistance : 3.934

Diffusion resistance : 0.0942

Refer to fig 5.3 (II) for illustration.

Analysis:

In addition to a pure diffusion case, two cases representing different air permeability values of the section have been analyzed.

Alt.no.1: The gaps between the gypsum boards and the upper and lower plates are modelled as 4.8 m long "unattended joints between gyp.bd. with no nailing strip". Gaps between the plywood panels are modelled as 14.4 m long "0.7 mm gap". The air bloc layer is assumed to be discontinuous on 4.8 m. This yields an air flow rate of 0.27 L/m$^2$ at 75 Pa.

Alt.no.2: It represents a partial area of alt.no.1, equal to 1.2 m$^2$ and concentrated around successive joints. It yields an air flow rate of 0.58 L/m$^2$ at 75 Pa.

Results:

- In case air velocity is equal to zero (pure diffusion), accumulation occurs at one location: the inner surface of the plywood sheathing.

- For cases including airflow, condensation occurs at three locations; the batt/plywood, the plywood/airbloc and the air cavity/siding interfaces. The most important accumulation being at the batt/plywood interface.
- Accumulations at all locations increase with the air permeability of the section. At the batt/plywood interface, with higher air permeability, the time needed for drying becomes longer. Fig 5.4c illustrates the weekly accumulations for both alternatives at that location.

From the above results, we notice that this kind of assembly has potential problems due to the moisture accumulation at the batt/plywood interface. Part of the water present at this location could be wetting the insulation and thus decreasing its insulating value. If we assume that the condensate will be totally absorbed by the plywood, we notice that by mid May (which corresponds to week 37 from the beginning of the simulation), the plywood in alt.no.2 will still be holding about 1.0 $kg/m^2$ of water. This corresponds to 25% of its mass, the critical moisture content being located around 27% of the dry mass.

### 5.3.4 Wall with Non-Insulating / Vapour Permeable Sheathing

Description of the wall section:

The plywood in the previous case study was replaced by an 8 mm thick fibreboard.

Thermal resistance = 4.024 $m^2.°C/W$

Diffusion resistance = 0.0632 $m^2.s/ng$

Refer to fig 5.3 (II) for illustration.

Analysis:

The simulation was carried out for two alternatives representing two air permeability values of the section. They are achieved by varying the width of gaps between the sheathing panels and by adding a leaky component (an electrical outlet) to the first layer of the wall section (alt.no.2).

Alt.no.1: Yields an air flow rate of 0.27 L/m$^2$ at 75 Pa.

Alt.no.2: Yields an air flow rate of 0.58 L/m$^2$ at 75 Pa.

Results:

- Condensation takes place at two locations; the fibre board/airbloc and the cavity/siding interfaces. Accumulations at the first location being the most important. They are plotted in Fig 5.4d.
- Comparing to the previous case study (5.3.3), we notice that by replacing the plywood sheathing by a more permeable material, the condensation location moved outwards from the inner to the outer face of the sheathing.

### 5.3.5 Observations

From the comparison of the results generated by the four analyzed cases including airflow; two with insulating sheathing and two others with non insulating sheathing, we notice that the common condensation location to all cases is the inner face of the siding. Accumulation at the batt/sheathing interface which can be considered as the most critical permeance of the sheathing. In walls with sheathing of no significant R-value, the diffusion permeability of the sheathing plays a decisive role in inducing condensation at this critical location. Accumulation at this location is shown to be very sensitive to exfiltrating airflows, therefore in this specific case, low permeance sheathing can create a potential for moisture problems . On the other hand, in walls with insulating sheathing, the diffusion resistance of the sheathing is less significant in influencing the hygric performance of the wall. From the analyzed cases, it was noticed that, if condensation is induced at the batt surface by a low permeance sheathing, it is negligible in quantity, does not accumulate and does not increase with exfiltrative airflow. With non-absorptive sheathing like polystyrene, this condensed water will run down the face of the sheathing to the bottom plate of the wall. Due to its small amount, the plate is not likely to reach its fibre saturation. Another observation is that substantial increase in accumulation is induced by air flow on the outer surface of the sheathing. This is noticed in walls with insulating sheathing, and walls with vapour permeable non-insulating sheathing. The impact of this condensate on the durability of the wall depends on several factors like the sheathing capacity for water absorption, and its drying capability.

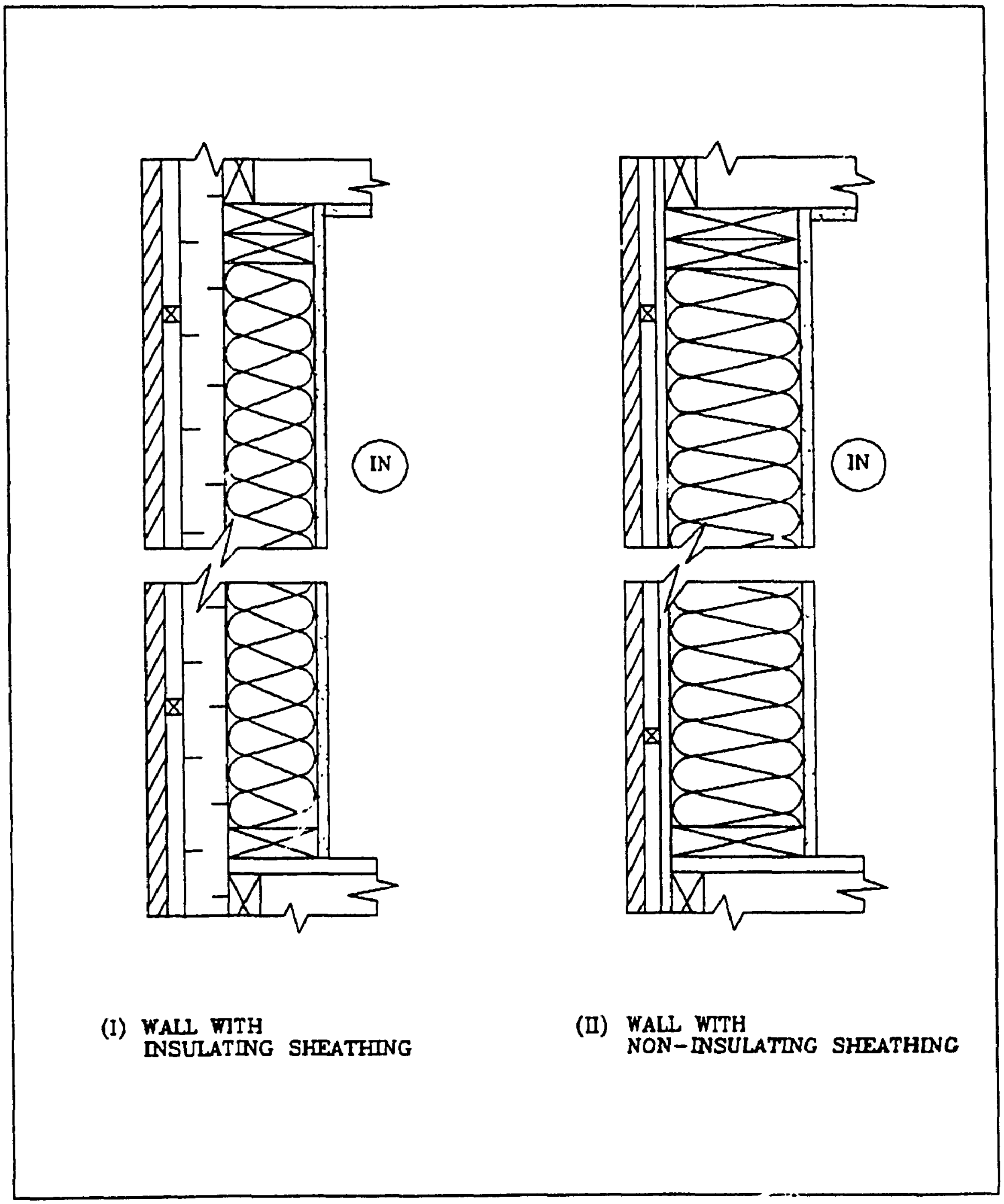
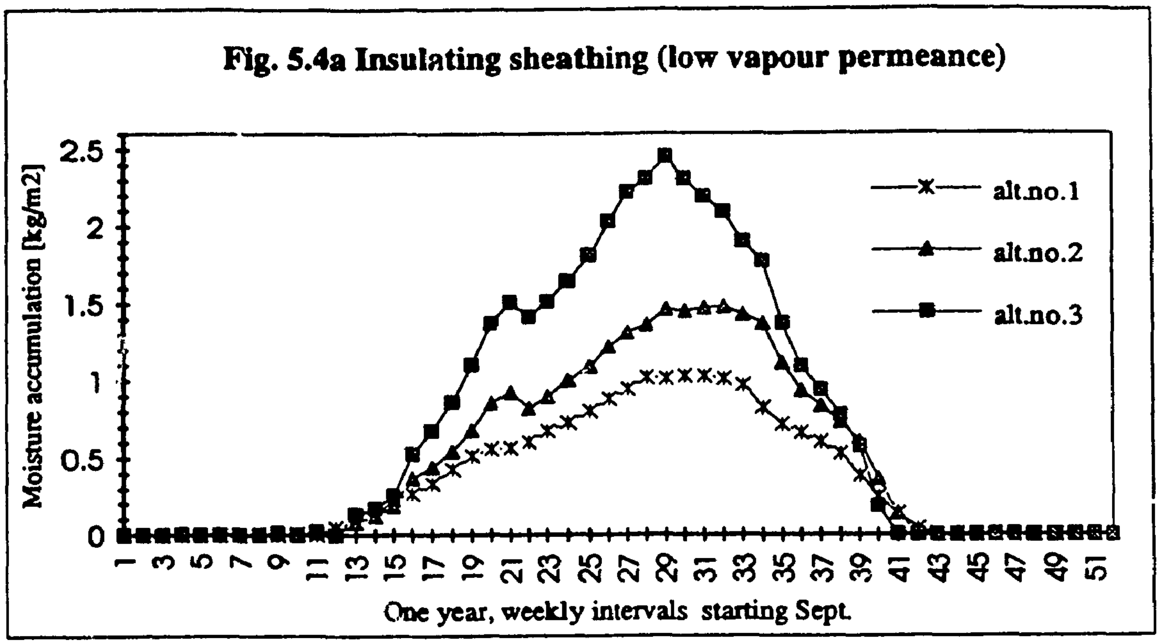
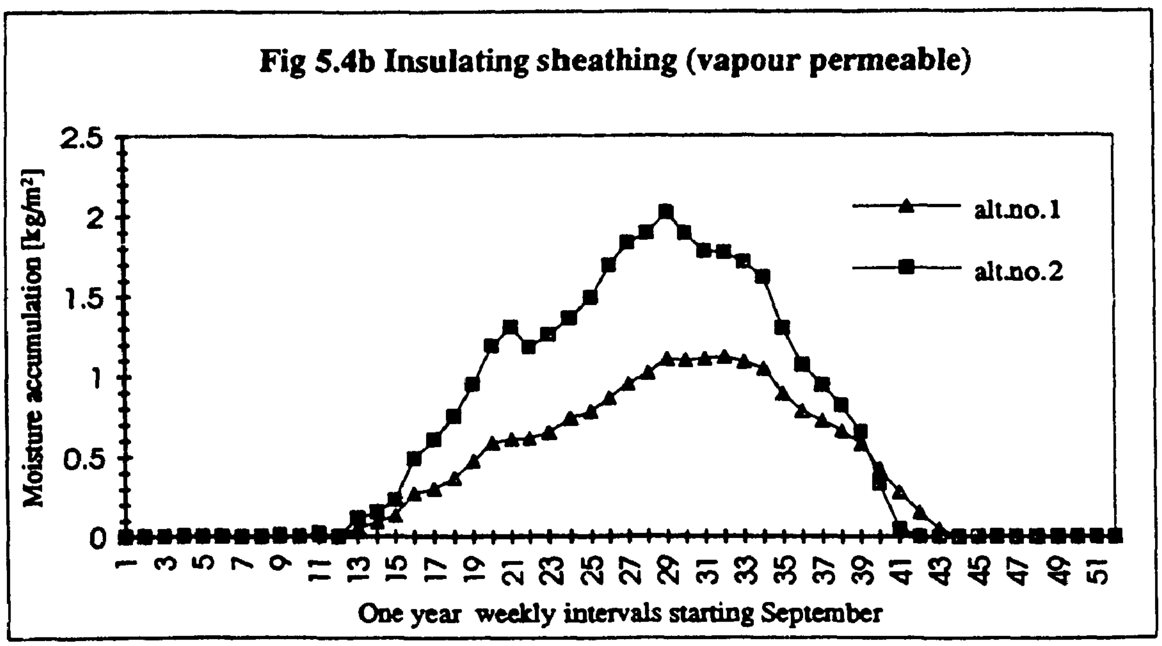

IN
IN
(I) WALL WITH
INSULATING SHEATHING
(II) WALL WITH
NON-INSULATING SHEATHING

Fig. 5.3

Impact of sheathing materials properties on accumulation



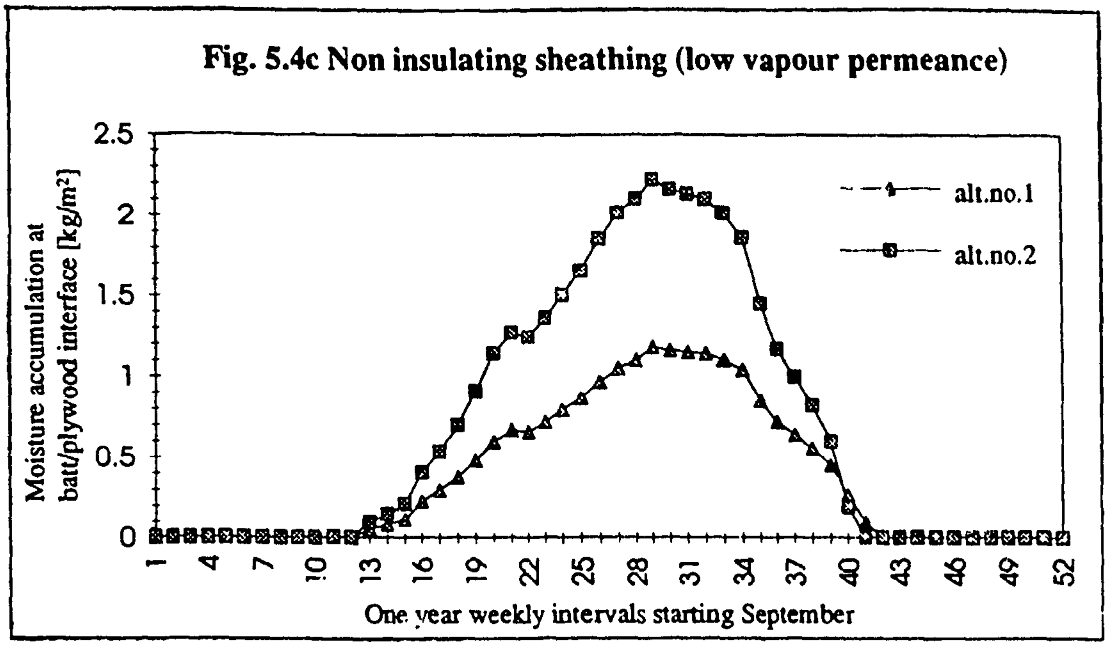


Fig. 5.4c Non insulating sheathing (low vapour permeance)
Moisture accumulation at batt/plywood interface [kg/m²]
One year weekly intervals starting September
alt.no.1
alt.no.2
2.5
2
1.5
1
0.5
0
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46 49 52

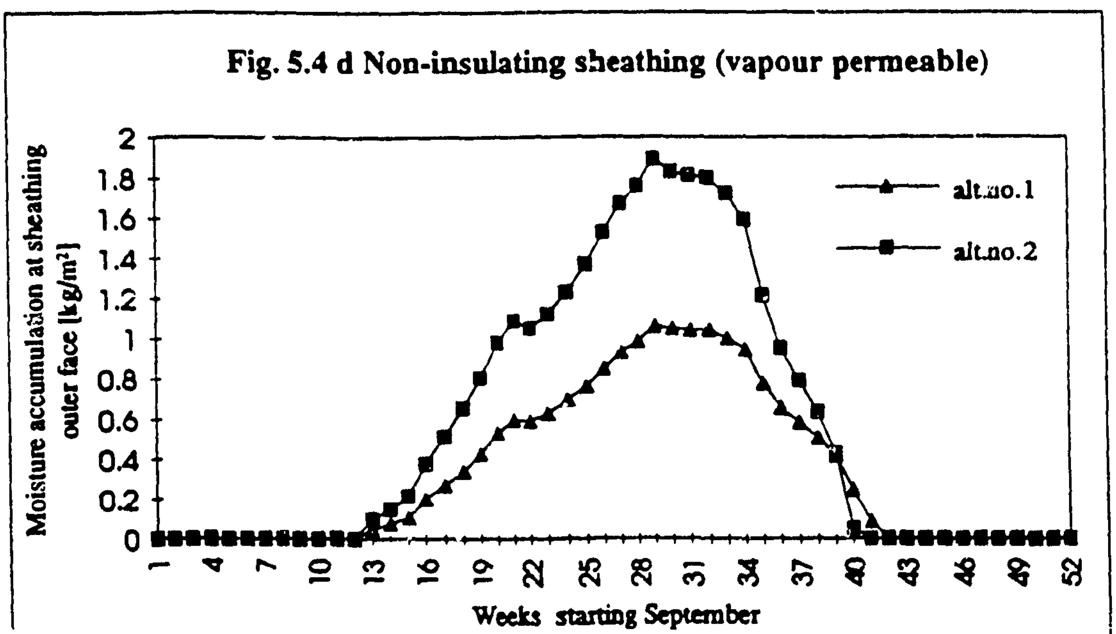


Fig. 5.4 d Non-insulating sheathing (vapour permeable)
Moisture accumulation at sheathing outer face [kg/m²]
Weeks starting September
alt.no.1
alt.no.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46 49 52

## 5.4 ANALYSIS OF THE 1990 NATIONAL BUILDING CODE ARTICLE 9.25.5.2

Article no 9.25.5.2 in 1990 N.B.C. specifies that if the material chosen to act as the air barrier also has the characteristics of a vapou. barrier, the temperature at such an air/vapour barrier should be checked when the outdoor temperature is at a fairly low value. The temperature used for the check being 10°C above the January ?.5 percent value. If the temperature at the location of the air/vapour barrier is below the dew point of the interior air, then the design is not acceptable.

To verify the requirements of the above article, four alternatives of the wall section described in 5.3.1 were analyzed. These alternatives have the same air permeability which yields an air flow rate of 0.21 L/s.m$^2$ at 75 Pa.

Description of the alternatives:

Each alternative has a different combination of batt and polystyrene thicknesses as detailed below:

Alt.no.1: batt = 89mm, polyst.= 25mm, thermal resist. = 3.55, diff.resist.=0.079

Alt.no.2: batt = 89mm, polyst.= 50mm, thermal resist. = 4.43, diff.resist.= 0.099

Alt.no.3: batt = 89mm, polyst.=100mm, thermal resist. = 6.17, diff.resist.=0.140.

Alt.no.4: batt =140mm, polyst.= 50mm, thermal resist. = 5.62, diff.resist.= 0.0995

Results:

- In all the analyzed cases, the major amount of the accumulation occurs at the cavity/siding interface. Fig 5.5 shows the time varying cumulative condensation values. They are almost the same for all alternatives except for alt.no.2 where the maximum reached is 1.04 kg/m², whereas for the other alternatives the maximum is around 0.94 kg/m².

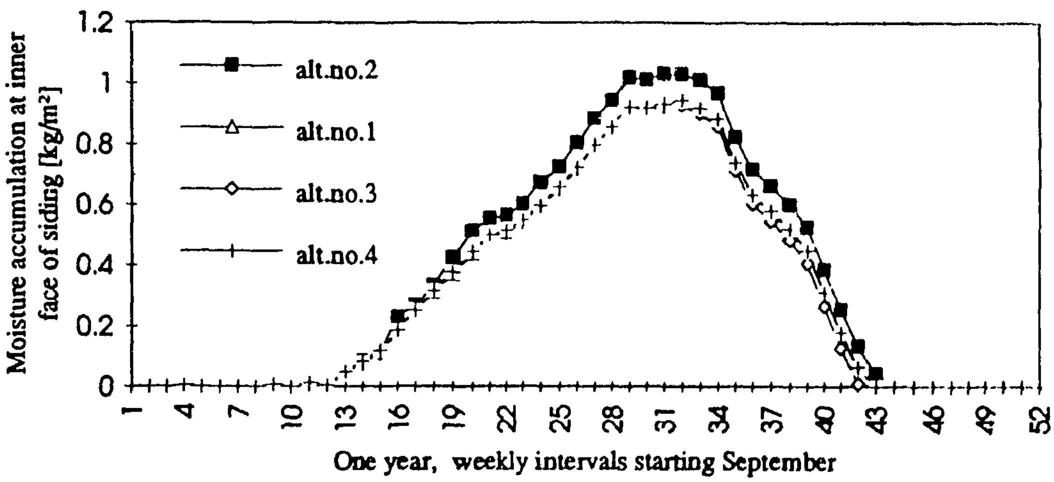
- By considering the accumulations at the critical location which is the batt/polyst. interface, we find that alt.no.1 with the thinnest polyst. and consequently the lowest temperature at the batt/polyst. interface shows the highest amount of condensation which reaches a maximum value of 0.077kg/m² followed by 0.035kg/m² for alternative no.4, 0.005kg/m² for alternative no.2, and no condensation for alternative no.3. which has the warmest batt/polyst. interface. Consequently, the amount of condensation at this location depends mainly on its temperature. A thinner polystyrene and/or a thicker batt lead to a colder surface.

Discussion:

The example given in N.B.C. article was followed to carry out the check on the wall section in question. For Montreal where the 2.5 percent temperature is -23° C, the temperature at the batt/extruded polystyrene interface for an interior dry bulb of 20° C is: -1.01°C for alt.no.1, +3.1°C for alt.no.2, +7.8° C for alt.no.3 and -0.26°C for alt.no.4. Knowing that the dew point of the interior air is 4°C, only alt.no.2 and alt.no.3 are acceptable. Our analysis which was run for an exfiltrative air flow case (where the amount of condensation is expected to be higher than in a case of pure diffusion) shows that the performance of a wall with an 89mm batt and 25mm thick polyst. could be acceptable. This is true if we consider the amount condensed at the batt/polyst. interface negligible. In fact, the maximum accumulated moisture at this interface doesn't exceed 0.077 Kg/m$^2$. This maximum value is reached in January and by the end of February, wetting gives place to drying.

Hence, requirements for low moisture diffusion air barriers should be related to an assessment of the rate of moisture accumulation and evaporation over a period of time covering the wetting and drying seasons. Therefore, simulation of dynamic boundary conditions is essential to reach an understanding of moisture related behaviour of wall sections.

**Fig. 5.5 Impact of thermal and diffusion resistance on accumulation**



## 5.5 IMPACT OF THE VAPOUR RETARDER LOCATION

According to the 1990 building code article no 9.25.6.2, a vapour retarder should be installed on the warm side of the insulation. Practitioners follow a rule that limits the location of the vapour barrier within the first third of the total R-value of the wall insulation. To investigate the effect of the vapour barrier location on condensation two types of wall configurations with non-insulating sheathing were analyzed for different locations of the vapour barrier (a polyethylene membrane). In the first wall the sheathing is a vapour barrier type II and in the second wall the sheathing is vapour permeable. A constant value of -0.8 is assigned to the wind pressure coefficient.

### 5.5.1 Wall with Vapour Barrier Type II Sheathing

Description of the wall:

- Gypsum board 13 mm thick with type II vapour barrier paint.
- Batt 38mm thick (strapping) and 38x140 mm studs with batt insulation. Or double stud wall; two 38x89 mm studs with batt insulation. Refer to Fig 5.6 for illustration.
- Plywood sheathing 8mm thick.
- Air cavity 40mm.
- Brick veneer 100mm.

In addition to a 6 mil polyethylene membrane fulfilling the double function of air / vapour barrier.

Analysis:

Three different locations are considered for the polyethylene membrane:

Alt.no.1: Between the 38mm and the 140mm batts, thus obeying the rule.

Alt.no.2: The combination of batts is 89mm and 89mm instead of 38 and 140mm and the poly. is in the middle thus not following the 1/3 to 2/3 rule.

Alt.no.3: The polyethylene is at the cold side of the assembly, just before the sheathing.

All these wall configurations have the same air permeability, yielding an air flow rate of 0.23 $L/m^2$ at 75 Pa.

Results:

- Moisture accumulation takes place at two locations: the outer surface of batt insulation and the air cavity/brick interface. Accumulation at the first location being much more important.
- The location of the polyethylene doesn't seem to affect the amount of condensate which is nearly the same for all cases. The maximum accumulation at the batt surface reached in alt.no.3 with the polyethylene next to the plywood is only about 8% higher than the maximum reached in the other alternatives. Refer to Fig 5.7a

From the above results, we notice that the location of the polyethylene doesn't have a relevant impact on the hygric behaviour of the wall assembly. The problem of condensation at the batt outer surface exists in all the analyzed cases, as could have been expected from the analysis of case 5.3.3 (wall with non-insulating / vapour barrier sheathing).

### 5.5.2 Wall with Vapour Permeable Sheathing

Description of the wall section:

The plywood sheathing in the previously analyzed section (5.5.1) was replaced by an 11mm thick fibreboard panel covered with Tyvek acting as a weather barrier. A 6 mil polyethylene membrane acts as an air/vapour barrier.

Analysis:

Similar to the previous case, three alternatives concerning the location of the polyethylene membrane were considered. The air permeability is the same for all alternatives and yields an air flow rate of 0.235 L/$m^2$ at 75 Pa.

Results:

- The major amount of condensation for the first two alternatives occurs at the cavity/brick interface, minor condensation occurs at the fibre/Tyvek interface. The weekly accumulation values are nearly the same for these two alternatives. Refer to Fig 5.7b and 5.7c. At the poly/batt interface condensation is either non-existent or not significant.
- For alternative no.3 accumulation at the batt/polyethylene interface is important and reaches a maximum of 1.1 Kg/$m^2$ by the end of March. Refer to Fig 5.7d.

From the analysis of the two cases of non-insulating sheathing, we can observe that the location of the vapour barrier (a polyethylene membrane) does not dramatically change the hygric behaviour of the wall section considered unless it is placed next to the sheathing. In that case, the behaviour of the wall is similar to the behaviour of a wall with a non-insulating, high diffusion resistant sheathing and therefore a high potential for accumulation exists.

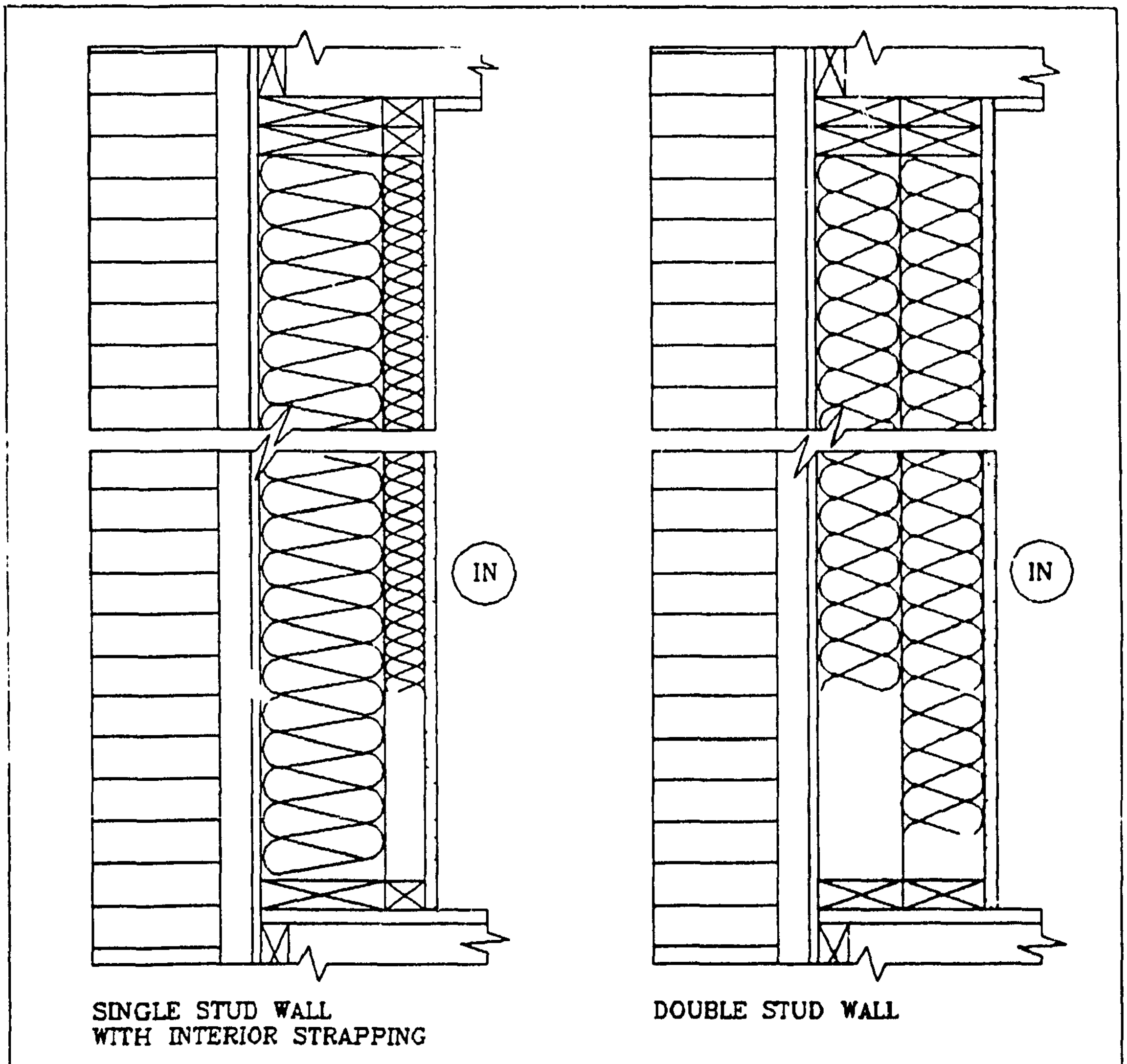
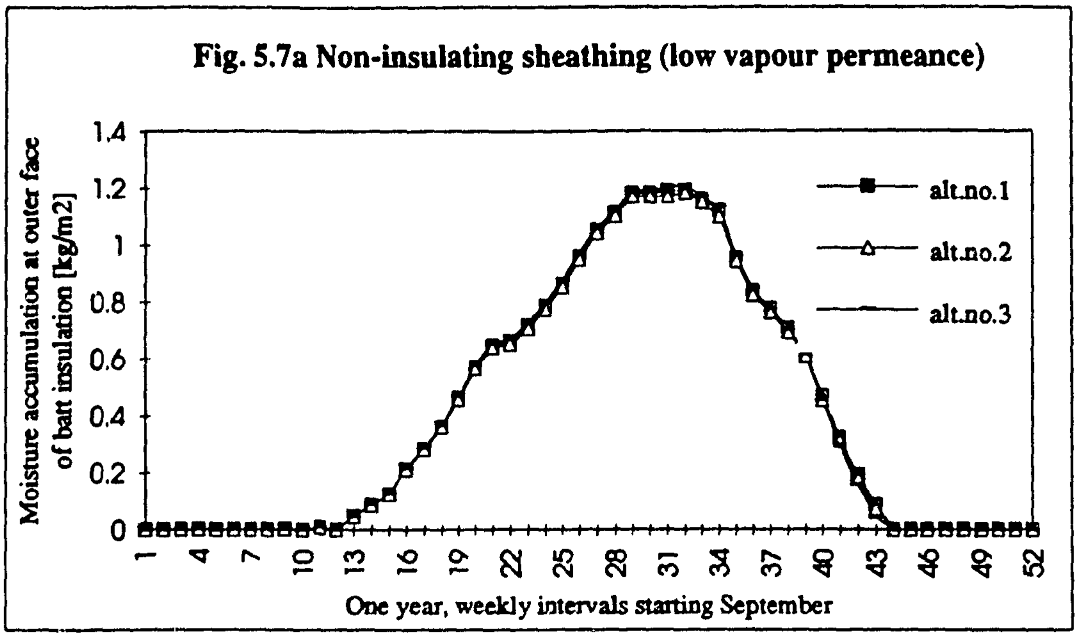
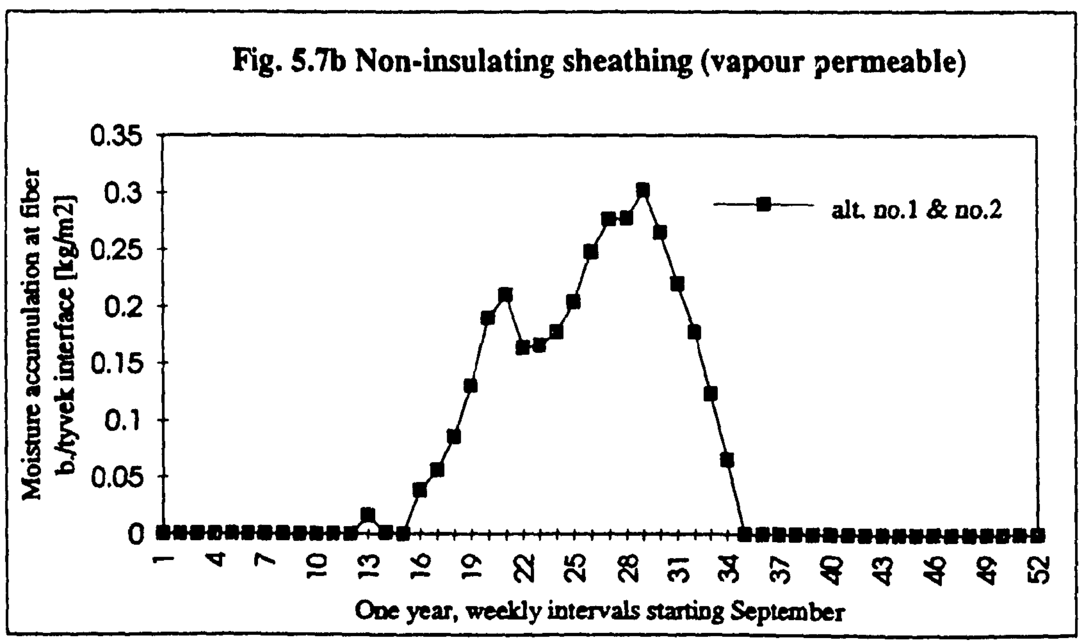



Fig. 5.6

Impact of vapour retarder location on moisture accumulation



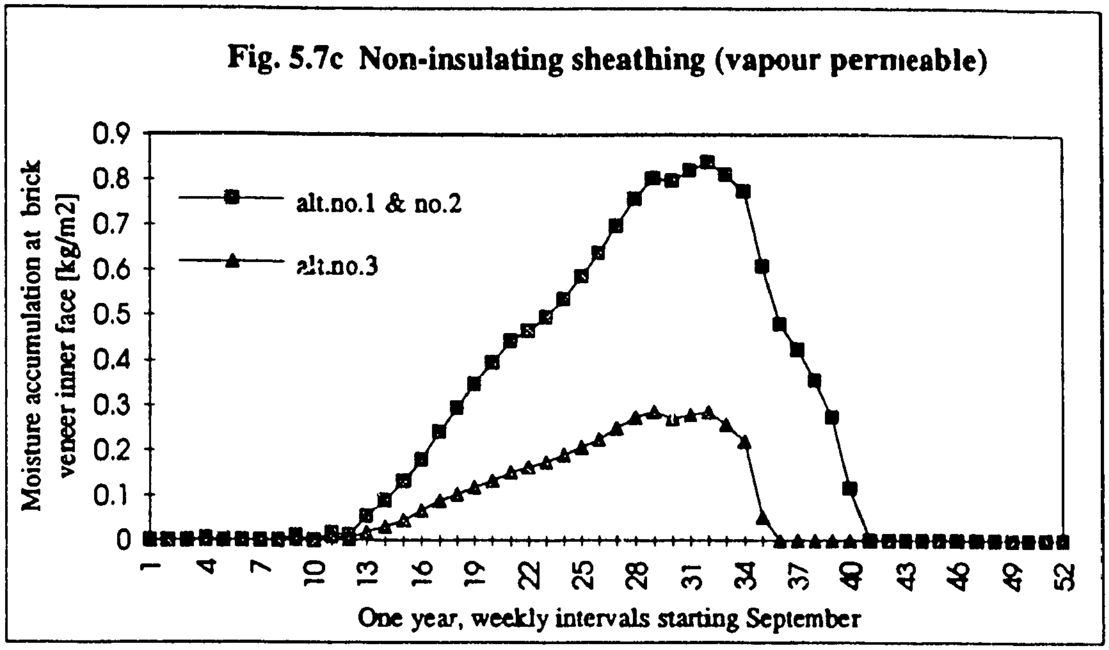


Fig. 5.7c Non-insulating sheathing (vapour permeable)
Moisture accumulation at brick veneer inner face [kg/m2]
alt.no.1 & no.2
alt.no.3
One year, weekly intervals starting September

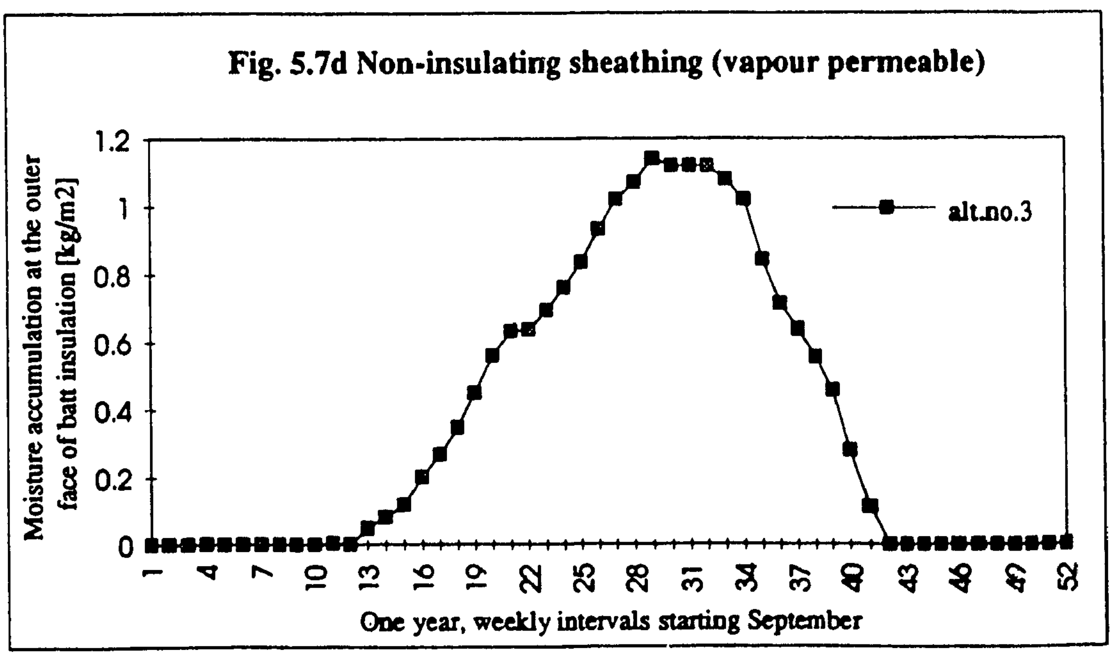


Fig. 5.7d Non-insulating sheathing (vapour permeable)
Moisture accumulation at the outer face of batt insulation [kg/m2]
alt.no.3
One year, weekly intervals starting September

## 5.6 IMPACT OF WALL SECTION VAPOUR PERMEABILITY

The effect of diffusion resistance on vapour condensation has been explored through the analysis of a wall section, by varying the permeance of the interior gypsum board of the wall.

Description of the wall section:

- Gypsum board 13 mm thick with paint.
- Batt 140 mm.
- Fibreboard 11 mm.
- Tyvek (air barrier/weather barrier).
- Painted wood siding (tongue and groove), 15 mm thick.

  Total thermal resistance: 3.882

  Permeability to air yields a flow rate of 0.44 L/s.$m^2$ at 75 Pa.

Analysis:

Alt.no.1: Permeance = 1587 ng/s.$m^2$.Pa (one coat of Latex).

Alt.no.2: Permeance = 145 (two coats of acrylic).

Alt.no.3: Permeance = 60 (paint/vapour barrier type II, one coat of latex and one of acrylic).

Alt.no.4: Permeance = 2.85. In this case, the gypsum board is backed by an Aluminium foil (vapour barrier type I).

Results:

The different alternatives were first analyzed for a pure diffusion case.

- Condensation occurs mainly at two places, the fibre bd./tyvek and the tyvek/siding interfaces. For the first alternative, condensation also occurs at the batt/fibre bd. interface, and in the fourth alternative practically all condensation disappears. See Fig. 5.8a.

The alternatives were also analyzed for the case of exfiltrative airflow. The results are the following:

- At the tyvek/siding interface, accumulation amounts for all the considered alternatives are quite close.
- Heavy condensation takes place at fibre bd./tyvek interface. Alternatives no. 2, 3 and 4 gave close results concerning the accumulations at this location, but alt.no.1 shows an appreciably higher rate. See fig. 5.8b.
- In alternative no. 1, condensation also occurs at the critical location of batt/fibre bd. interface where accumulation reaches a maximum of 0.4 kg/m$^2$. For all other alternatives, condensation at this location is either negligible or non-existent.

The considerable moisture accumulation on either side of the sheathing in alt.no.1 makes this wall design not recommendable for the boundary conditions considered. The other alternatives considered don't show significant condensation on the insulation face, but the condensation occurring at the outer face of sheathing is debatable. In alt.no.3 (permeance

= 60) the accumulation reaches a value of 0.85 kg/m² by mid of May. This is equivalent to about 29% of the fibreboard mass. For alt.no.4 (permeance = 2.85), the accumulation is 0.68 kg/m² at that time, corresponding to 23% of the mass. This shows that a 95% reduction in vapour permeance did not insure more than a 20% reduction in the maximum accumulation at this particular location and therefore the cost increase is not justified. This leads us to conclude that a vapour retarder type I may not be necessary for a similar section and for the considered boundary conditions, as a vapour barrier paint type II may function equally well.

Impact of the section vapour permeability on moisture accumulation

**Fig. 5.8a Case study with no air flow**

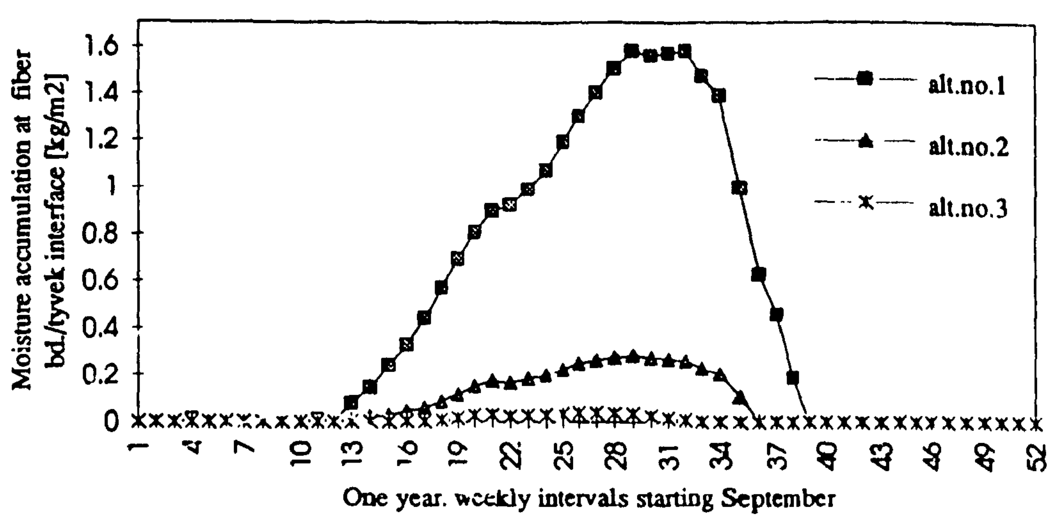
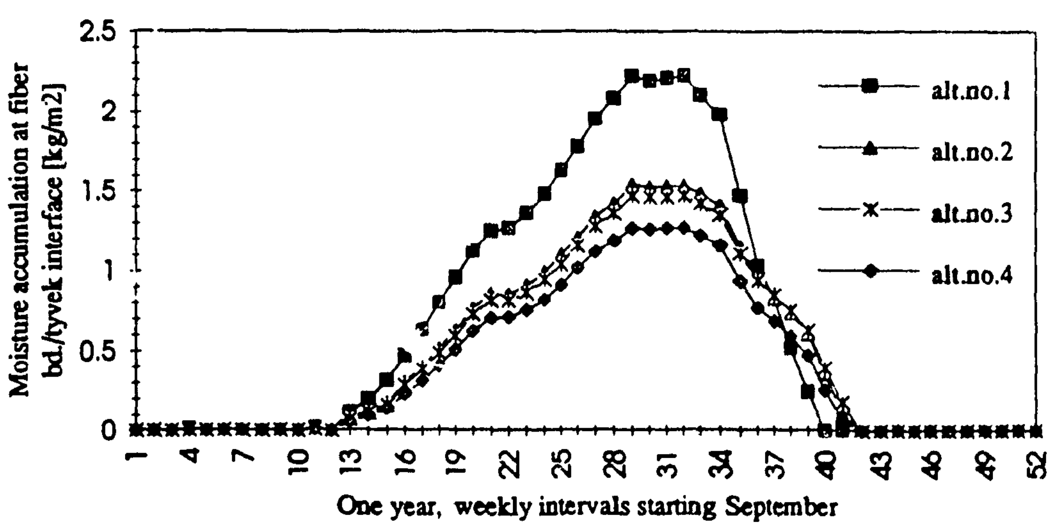



**Fig. 5.8b Case study with air flow**



## 5.7 IMPACT OF INTERNAL RELATIVE HUMIDITY AND AIR VELOCITY

Two types of analysis have been carried out using the same section configuration as in 5.6 with a vapour barrier type II paint. The first analysis explores the impact of the interior air relative humidity and the second one investigates the impact of air velocity on moisture accumulation.

Analysis:

For the same wall air permeability equal to 0.433 L/s.m$^2$ at 75 Pa, the interior air relative humidity was varied from 30% to 35% to 40% for a constant air temperature of 22°C. A total differential pressure value of 15 Pa was maintained for the whole duration of each of the simulations.

In the second analysis the total differential pressure acting across the wall was assigned alternatively the values of 5, 10 and 15 Pa, which yielded exfiltrative air velocity values of 0.5E-4, 0.87E-4 and 0.12E-3 m/s respectively. The interior air temperature was maintained at 22°C and the relative humidity at 40%.

Results:

- Accumulations at both sides of the tyvek membrane are affected by the interior air relative humidity. Fig 5.9a shows that an increase of 16.6% in R.H. (from 30% to 35%) causes an increase of 37% in the maximum accumulation value at the fibre/tyvek interface.

- Fig 5.9b shows the impact of air velocity on moisture accumulation. We notice that an increment of 73% in air velocity (from 0.5E-4 to 0.87E-4) causes an increment of 49% in the maximum cumulative condensation reached at the fibre/tyvek interface.
- If we compare the peak values of the six graphs plotted in figures 5.9a and 5.9b, we notice that at a constant pressure of 15 Pa, a variation of about 14-16% in the relative humidity produces almost the same effect as a variation of 33-50% in differential pressure for a constant relative humidity of 40%. This shows that moisture accumulation can be more sensitive to changes in indoor vapour pressure than to changes in exfiltrative air velocity or pressure.
- Another observation is that the drying rate slope is not affected by higher humidity values (fig. 5.9a), whereas it becomes steeper with higher air velocity values (fig. 5.9b).

## Impact of relative humidity and air velocity on moisture accumulation

**Fig 5.9a Effect of interior air relative humidity**

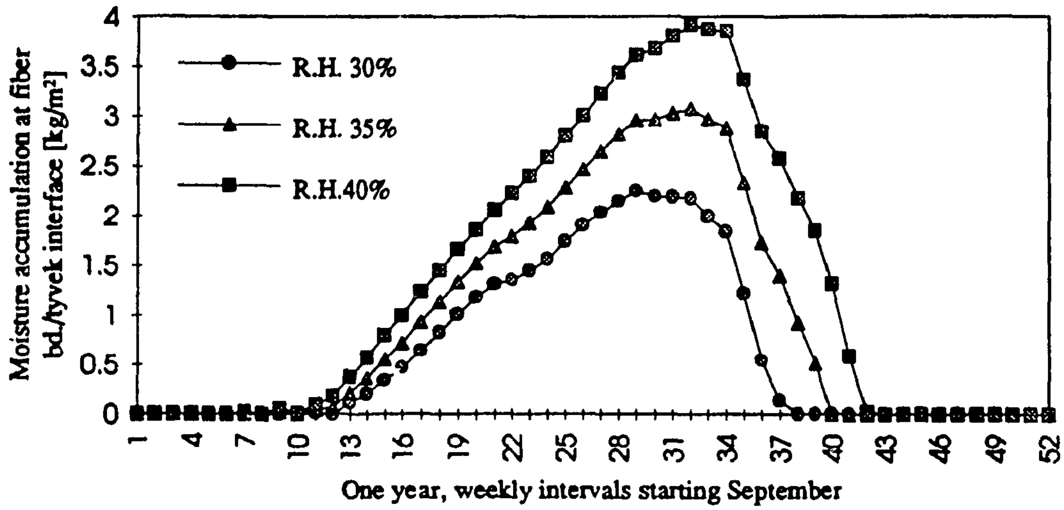
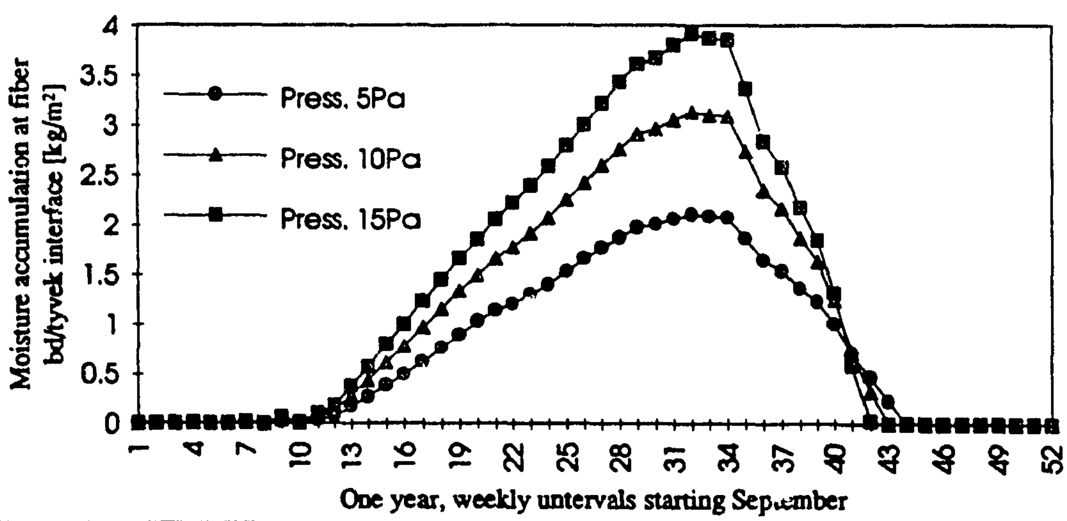



**Fig. 5.9b Effect of air velocity**



## 5.8 SUMMARY

The numerically analyzed cases presented show the potentials for moisture condensation in wood frame residential walls subjected to exfiltration of warm moist air. The results lead to some observations:

- With respect to moisture behaviour, walls with insulating sheathing seem to perform better than walls with non-insulating sheathing.
- Walls with low permeance non-insulating sheathing have the potential to accumulate moisture that could stay trapped.
- Special care should be given to the choice of the building paper used in walls with non-insulating sheathing regarding its moisture diffusion permeability.
- Condensation rates at different locations within a wall might be affected differently by changes in airflow rates.
- Building code requirements regarding location of low permeance air barriers should be based on a combination of field tests and computer simulations rather than on simple predictive calculations.
- Some widely used rules in the building community (like the ones regarding the vapour barrier location and the ratio of the permeance of materials on the cold side to permeance of materials on the warm side of a wall) need to be reexamined.
- The air flow modelled by the program is assumed to be uniformly distributed over the analyzed sections. But in practice, an air flow path can be very concentrated through joints and in that case, the materials thermal and diffusion properties become less

significant factors in moisture condensation. Condensation will likely be governed by air flow rates, outdoor temperature and interior air relative humidity.

The analyzed cases were all simulated under the weather conditions of Montreal, therefore these wall configurations might be evaluated differently under different climate conditions.

# CHAPTER VI

# CONCLUSION

## 6.1 SUMMARY AND CONCLUSIONS

Understanding and predicting moisture movement within and through building envelopes is of fundamental importance to the design of durable constructions. The present work deals with the implementation of air transfer in a simplified model, in an attempt to answer an existing need. The present research has resulted in the development of a computer model capable of calculating airflow rates in multi-layered walls and quantifying moisture accumulation due to the combined effects of diffusion and convection within a wall. Some features of the developed model can be formulated as follows:

i) The proposed methodology to calculate airflow rates transforms the envelope into a network of resistances, where the airflow resistances of the layers work in series, whereas the resistances of the components making up each layer work in parallel.

ii) This methodology is characterized by its flexibility. It allows the user to simulate airflow through a variety of wall section designs as well as through specific areas of the same wall section.

This model was used to analyze a number of common wall sections and investigate the impact of some parameters on moisture accumulation like air velocity, relative humidity and the thermal and diffusion properties of sheathing. The National Building Code requirements, 9.25.5.2 and 9.25.6.2 regarding the location of low permeance air barriers, and the installation of vapour barriers were examined, along with some of the adopted norms in the building community. The following findings can be drawn from the results:

i) Exfiltrative airflow in cold climates can highly influence the hygric performance of a wall by inducing new condensation planes and increasing the accumulation rates at some locations to the detriment of others.

ii) The presence of airflow can tremendously increase the impact of interior relative humidity on moisture deposition.

iii) Walls with non-insulating sheathing materials present a higher risk for moisture accumulation at critical locations within the wall if the sheathing has low diffusion permeance.

vi) Safe design principles like providing a type I vapour barrier and locating it within the first third of the insulation value of the wall might not be true or necessary for the wall sections analyzed and for Montreal weather conditions.

The analyzed cases were all simulated under the weather conditions of Montreal and for defined interior boundary conditions, therefore these wall configurations might be evaluated differently under different climatic and interior conditions. By ignoring the heat and moisture storage capacity of materials, the capability of the model in assessing moisture drying is significantly restricted. Nevertheless, this limitation is inherent to all steady-state models. Exact criteria and acceptable limits for the analyzed parameters cannot be given by simulation results only, because moisture behaviour in real cases differs from a one-dimensional approximation.

## 6.2 CONTRIBUTIONS

The research has offered several contributions:

i) The development of a method to calculate air flow rates through composite walls.

ii) The development of a model which incorporates the air barrier characteristics of building envelopes in the evaluation of their moisture performance.

iii) The development of a simple and practical design metodology to assist designers in evaluating the performance of exterior walls.

iv) The evaluation of the moisture performance of a number of commonly used wall designs in the context of the 1990 NBC requirements.

## 6.3 RECOMMENDATIONS FOR FUTURE WORK

This work can be used as a basis for further developments:

i) Extend the program's materials database to include a greater variety of components and also values for roof components and window details.

ii) Test a prototype model with different leaky components in the laboratory, and compare recorded air flow rates to the values calculated by the model.

iii) Conduct experimental work to define the air permeability properties of commonly used construction components; more specifically the ones with comparatively high air permeability like joints.

iv) Incorporate an algorithm in the program to model convective looping of air in cavities.

v) Conduct experimental work to determine the moisture diffusivity of building materials under variable airflow rates.

vi) Conduct full scale tests in C.B.S. environmental chamber to determine the effect of airflow on moisture accumulation.

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# APPENDIX "A"

# MATERIAL PROPERTIES DATABASE

| Materials | Diffusion permeability [ng/m.s.Pa] | thermal conductivity [W/m.°C] | Qtest [$m^3/m^2.s$] | Δp (test) [Pa] | expon. | thickness (test) [m] |
|---|---|---|---|---|---|---|
| **INTERNAL FINISHES (PANELS)** | | | | | | |
| Gyp/1 coat latex permeance=1587 | 20.634 | 0.1604 | 0.0196 E-3 | 75 | 1 | 0.013 |
| Gyp/2 coat acrylic permeance=145 | 1.884 | 0.1604 | 0.0196 E-3 | 75 | 1 | 0.013 |
| Gyp/1 coat latex + 1 coat acrylic permeance=60 | 0.78 | 0.1604 | 0.0196 E-3 | 75 | 1 | 0.013 |
| Gyp/2 coat enamel permeance=40.81 | 0.5306 | 0.16 | 0.0196 E-3 | 75 | 1 | 0.013 |
| Gyp/al.foil back permeance=2.85 | 0.0457 | 0.16 | 0 | 75 | 1 | 0.013 |

| Materials | Diffusion permeability [ng/m.s.Pa] | thermal conductivity [W/m.°C] | Qtest [$m^3/m^2.s$] | Δp (test) [Pa] | expon. | thickness (test) [m] |
|---|---|---|---|---|---|---|
| **MEMBRANES; ( AIR, VAPOUR & WEATHER BARRIERS)** | | | | | | |
| Polyethylene (vapour retarder/ air barrier) | 0.00045 | 1000 | 0 | 75 | 1 | 0.0001 |
| Polyethylene | 0.00051 | 1000 | 0 | 75 | 1 | 0.00015 |
| Spunbonded Olefin Tyvek (weather barrier/air barrier) | 0.5 | 0.00555 | 0.4 E-3 | 75 | 1 | 0.0001 |
| Reinf. polyolefin (weather/air barrier) | 0.5 | 0.00555 | 0.0195 E-3 | 75 | 1 | 0.0001 |
| Alum. foil (vapour retarder/air barrier) | 0.0003 | 1000 | 0.0 | 75 | 1 | 0.0001 |
| Air-bloc 07 BAKOR trowel applied (weather/air barrier) | 0.729 | 1000 | 0.054E-3 | 75 | 1 | 0.003 |

| Material | Diffusion permeability [ng/m.s.Pa] | thermal conductivity [W/m.°C] | Qtest [$m^3/m^2.s$] | Δp (test) [Pa] | expon. | thickness (test) [m] |
|---|---|---|---|---|---|---|
| **INSULATION MATERIALS** | | | | | | |
| Batt glasswool glassfiber | 169.45 | 0.0427 | 36.7327 E-3 | 75 | 0.949 | 0.152 |
| Rigid glassfiber /1side tyvek | 73.42 | 0.0327 | 0.488 E-3 | 75 | 0.987 | 0.0254 |
| Semi-rigid glassfiber (GLASCLAD) | 169.45 | 0.0331 | 4.65 E-3 | 75 | ~0.9 | 0.05 |
| Expanded polystyr. type 1 | 6.256 | 0.0384 | 12.2372 E-3 | 75 | 0.9 | 0.0254 |
| Expanded polysty. type 2 | 4.163 | 0.0357 | 0.1187 E-3 | 75 | 0.993 | 0.0254 |
| Extruded polysty. | 1.233 | 0.0285 | 0.0 | 75 | 1.0 | 0.038 |
| Cellulose fiber spray-on | 1.727 | 0.04 | 86.9457 E-3 | 75 | 0.97 | 0.038 |
| Vermiculite loose-fill | 3.846 | 0.0625 | 70.4926 E-3 | 75 | 0.979 | 0.075 |

| Material | Diffusion permeability [ng/m.s.Pa] | thermal conductivity [W/m.°C] | Qtest [$m^3/m^2.s$] | Δp (test) [Pa] | expon. | thickness (test) [m] |
|---|---|---|---|---|---|---|
| **SHEATHING MATERIALS** | | | | | | |
| Plywood | 0.2571 | 0.1304 | 0.0067 E-3 | 75 | 0.944 | 0.008 |
| Plywood | 0.2708 | 0.1304 | 0.0 | 75 | 1.0 | 0.0095 |
| Plain fiberboard | 50.0 | 0.0526 | 0.8223 E-3 | 75 | 0.99 | 0.011 |
| Particle board | 2.0 | 0.1351 | 0.0155 E-3 | 75 | 0.996 | 0.0127 |
| Particle board | 2.0 | 0.0783 | 0.026 E-3 | 75 | 0.949 | 0.0159 |
| Flake wood board | 2.0 | 0.1038 | 0.0108 E-3 | 75 | 0.998 | 0.011 |
| Flake wood board (wafferboard) | 2.0408 | 0.1038 | 0.0069 E-3 | 75 | 0.979 | 0.016 |
| Tempered hardboard | 0.928 | 0.144 | 0.0274 E-3 | 75 | 0.979 | 0.0032 |
| Gyp. exterior grade | 43.3333 | 0.1025 | 0.0091 E-3 | 75 | 1 | 0.0127 |
| Pine wood rim joist | 0.263157 | 0.1123 | 0.0 | 75 | 1.0 | 0.038 |
| Tyvek between 2 (12 mm fiberboards) | 39.4736 | 0.0506 | 0.20 E-3 | 75 | 1.0 | 0.024 |

| Material | Diffusion permeability [ng/m.s.Pa] | thermal conductivity [W/m.°C] | Qtest [$m^3/m^2.s$] | $\Delta p$ (test) [Pa] | expon. | thickness (test) [m] |
|---|---|---|---|---|---|---|
| **SIDING MATERIALS WITH AIR CAVITY** | | | | | | |
| Brick good masonry work | 0.6545416 | 1.4145605 | | | | |
| Brick poor masonry | 0.654541646 | 1.4145605 | | | | |
| Alum. cladding | 0.0028 | 0.0090 | | | | |
| Alum. cladding | 0.0588 | 0.0090 | | | | |
| Parging cement/ 1 coat acrylic | 0.2708 | 0.5909 | | | | |
| Wood siding/ 2 coats of paint | 0.5 | 0.0856 | | | | |
| **SIDING WITH NO AIR CAVITY** | | | | | | |
| Wood siding(tongue & groove)/2 coats of paint | 0.5 | 0.0856 | 2.3 E-3 | 75 | 0.564 | 0.015 |
| **AIR CAVITY** | | | | | | |
| Air cavity | 100 | 0.1117 | | | | |

| Material description | Qtest [$m^3$/unit.s] | Δp (test) [Pa] | expon. |
|---|---|---|---|
| **UNITS ELEMENTS** | | | |
| Electrical outlet poly approach; standard box with rubber insert, poly sealed to box w. tape & caulking | 0.35 E-3 | 75 | 0.6 |
| Electrical outlet ADA approach; air tight box with flange & gasket. G.B. sealed to flange, wires sealed to box w. caulking | 0.2 E-3 | 75 | 0.6 |
| Electrical outlet poly approach; using polypan; a heavy gauge poly memb. fitted thru a plywood backing support | 0.02 E-3 | 75 | 0.6 |
| Electrical outlet ADA approach; traditional box w. a closed cell face gasket placed between the drywall & the cover plate | 0.38 E-3 | 75 | 0.6 |
| Cut in polyetylene 4 cm | 0.016 E-3 | 10 | 0.73 |
| Cut in polyethylene 8 cm | 0.137 E-3 | 10 | 0.478 |
| Cut in polyethylene 16 cm | 0.273888 E-3 | 10 | 0.672 |
| Cut in polyethylene 32 cm | 0.96111 E-3 | 10 | 0.68 |
| Penetration for plumbing PVC pipe, d=75mm, thru poly, 2 crossing cuts 85mm long | 0.76 E-3 | 10 | 0.605 |

| Material description | Qtest [$m^3/m.s$] | Δp (test) [Pa] | expon. |
|---|---|---|---|
| **JOINTS ELEMENTS** | | | |
| Unattended joints between (gypsum) boards, with no nailing strip behind | 1.989 E-3 | 75 | 0.744 |
| Unattented joints between (gypsum) panels, with nailing strip behind | 0.901E-3 | 75 | 0.666 |
| Ethafoam gasket, well compressed (ADA) | 0.022E-3 | 75 | 0.7 |
| Glazing tape (3*12 mm) (ADA) | 0.151E-3 | 75 | 0.7 |
| Acoustic sealant (poly/tyvek) or (poly/poly) | 0.12 E-3 | 75 | 0.7 |
| Acoustic sealant (poly/tyvek) or (poly/poly) | 0.0731E-3 | 75 | 0.7 |
| EPDM gap gasket (sill plate) | 0.0177E-3 | 75 | 0.7 |
| Ethafoam gasket, 1" (sill plate) | 0.03E-3 | 75 | 0.7 |
| 0.3 mm gap (in concrete) | 0.0181E-3 | 75 | 0.7 |
| 0.5 mm gap (in concrete) | 0.1127E-3 | 75 | 0.7 |
| 0.7 mm gap (in concrete) | 0.351E-3 | 75 | 0.7 |