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Life Cycle Analysis of the Residential HVAC Systems in Montréal

Lijun Yang

A Thesis

in

The Department

of

Building, Civil, and Environmental Engineering

Presented in Partial Fulfillment of the Requirements
for the Degree of Master of Applied Science (Building Engineering) at
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ABSTRACT

Life cycle analysis of the residential HVAC systems in Montréal

Lijun Yang

Residential buildings use a substantial amount of energy not only during the construction but also for the operation of their heating, ventilation, and air-conditioning (HVAC) systems. The life cycle assessment methodology allows evaluating the overall environmental and economic impacts of heating systems. This study, therefore, presents the life cycle analysis of two residential heating systems, the hot water heating system with ventilation and the forced air heating system. The analysis is performed with respect to the life cycle energy consumption, life cycle greenhouse gas emissions, life cycle exergy destruction, and the life cycle costs.

The total amount of material used for piping and ducting systems is estimated based on the complete design of the systems. However, there is a high level of uncertainty in the evaluation of the environmental impact of some HVAC equipment due to the absence of detailed manufacturers' data. The present study hence applies a decision model under uncertainty to analyze this situation. Using a payoff matrix model coupled with various decision criteria, the range of embodied energy and greenhouse gas emissions of such equipment is estimated.

The annual energy use for heating and the exergy destruction are estimated with the help of mathematical models developed during this study in the Engineering Equation Solver (EES) environment.

The exergy analysis allows to the evaluation of the depletion of natural resources and indicates the location of major inefficiencies in the system. The energy and exergy analyses are both implemented to evaluate the performance of the HVAC systems over the house life cycle.

A house built in Montreal was used as the base case of the life cycle analysis. In the pre-operating phase, the heating systems cause marginal impacts compared with the entire house. In the operating phase, the heating systems cause significant environmental impact. Based on the life cycle analysis, the electric hot water heating system causes the lowest greenhouse gas emissions, the gas hot water heating system causes the lowest energy use and exergy destruction, and the electric forced air heating system has the lowest life costs.

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NOMENCLATURE

A	Area (m^2)
a	Effective interest rate
a_i	Design alternative i^{th}
C	Annual energy cost in the first year (CAN$)
cp	Specific heat (kJ/kg·K)
CO_2	Equivalent CO_2 emissions (kg·CO_2)
$CO_2(MC_n)$	Unit equivalent CO_2 emissions due to the manufacturing of material n, (kg·CO_2/kg·material)
COP	Coefficient of performance
D	Depth (m)
e	The rate at which energy cost are expected to increase
EE	Embodied energy (MJ)
$ee(MC_n)$	Unit embodied energy of material n (MJ)
$\dot{E}$	Energy flow rate (kW)
E_{gas}	The natural gas consumed at the house level (kWh)
$\dot{FP}$	Electric power of fans of the heat recovery unit (kW)
$FRAC$	Fraction of the hour the boiler is on
GWP	The global warming potentials
H	Height (m)
HIR	Nominal heating input ratio
IB	IB=0, for electric boiler/furnace; IB=1, for gas-fired boiler/furnace
i	Discount rate of the cost of money (including inflation)
M	Mass (kg)
MC	Material in the component of boiler
$\dot{m}$	Mass flow rate (kg/s)
n	Lifetime (years)
P	Pressure or pressure loss (kPa)
$P(C_i)$	Mass percentage of the material in component i (%)
$P(\theta_j)$	Assigned equal probability for each state θ_j

PLR	Part load ratio
PW	The present worth value of energy costs (CAN$)
$\dot{Q}$	Heat flow rate (kW)
$\dot{Q}_{Load}$	Heating load of the house (kW)
$RPLR$	PLR or RMIN whichever is larger
$RMIN$	Minimum part load ratio
s	Specific entropy (kJ/kg·K)
$\dot{S}$	Rate of entropy (kW/K)
T	Temperature (°C)
TK	Temperature (K)
Th	Thickness (m)
v	Air velocity (m/s)
$\dot{V}$	Volumetric flow rate (m^3/s)
W	Width (m)
W_0	Total mass of equipment (kg)
$\dot{W}$	Rate of work (kW)
$\dot{X}$	Rate of exergy (kW)

Greek letters

α	Optimistic factor
α_{CO2}	Pollutant coefficient in terms of CO_2
α_{NOx}	Pollutant coefficient in terms of NO_x
α_{CH4}	Pollutant coefficient in terms of CH_4
α_{fuel}	Contribution of different energy sources to the off-site electricity generation
a_i (i=1-5)	Equivalent CO_2 emissions for hydro, natural gas, heavy oil, coal, and nuclear power, respectively in the power plants, (kt ·CO_2/TWh)
ρ	Density (kg/m^3)
θ	States of nature
η_{mech}	mechanical efficiency

η_{comp}	Compression efficiency of fluid
η_{HR}	Heat recovery unit efficiency
η_{pp}	Energy efficiency of power plant
η_{trans}	Efficiency of electricity transmission
η_1	Energy efficiency of the system
η_2	Exergy efficiency of the system

Subscripts

A	Air
avg.	Average
C	Casing
cap	Capacity
de	(Exergy) Destruction
des	Design conditions
diffu.	Diffusers
eboiler	Electric boiler
efurnace	Electric furnace
exhaust	Exhaust air
reheater	Electric air reheater
fresh	Fresh air
FP	Fans of the heat recovery unit
fuel	Fuel type
g	Gas-fired
gen	(Entropy) Generation
HR	Air-to-air heat recovery unit
i	Inside of the house
in	Air or water flowing in
mech.	Mechanical
mix	Mixing box
o	Outside of the house

out	Air or water flowing out
pp	Power plant
preheater	Electric air preheater
rad	Radiator
sys	System
trans	Electricity transmission losses
useful	Utilized heat energy (kW)
w	Water

CHAPTER 1

Introduction

1.1 General background

It is now widely recognized that the global climate is changing. One of the most critical reasons is the increasing of greenhouse gas (GHG) emissions mainly caused by human activities. In December 1997, Canada and more than 160 other countries met in Kyoto, Japan, and agreed to target to reduce GHG emissions. Canada's target is to reduce its GHG emissions to 6 percent below 1990 levels by the first commitment period of 2008 to 2012 (Government of Canada, 2000).

Most GHG emissions come from the production and consumption of energy. Energy consumption in today's society is steadily increasing as a result of population growth and increasing standard of living. This trend is producing an increasing demand on our dwindling resources and on the environment. The high energy consumption has become a worldwide concern not only because of the eventual exhaustion of the non-renewable sources of energy, but also due to the increasing emission of pollutants in the environment. Buildings contribute directly to the GHG emissions by burning fossil fuels to generate heat. In addition, the buildings sector contributes indirectly to GHG emissions through electricity consumption, such as lighting and power for work places (Government of Canada, 2000). Natural Resources Canada (NRC, 2003) also reports that the residential sector accounted for 17% of secondary energy use, which comprises energy consumed for residential, agricultural, commercial/institutional, industrial and transportation purposes, in Canada and 16% of the related greenhouse gas (GHG) emissions in 2002. To reduce the energy consumption and GHG emissions, actions in these areas will result in substantial benefits including greater home comfort, buildings and homes that are healthier for our families, and dollar savings (Government of Canada, 2000).

The increasing demand on natural resources is putting a greater burden on the global eco-system. However, the world has finite resources and a limited ecological carrying capacity. Because of this awareness, we must become less wasteful in our use of natural resources and take the appropriate steps necessary to maintain the world in a healthy environment, today, and for the future.

In recent years, increasing interest has led to a significant progress in environmental research. Various techniques and methodologies for the assessment of environmental performance have been developed to reduce the environmental impacts of a variety of products and services, e.g. life cycle assessment (LCA). LCA is an assessment of all direct and indirect impacts of a product, a service, or a system during its entire life cycle.

1.2 Problem statement

Residential houses use up a substantial amount of energy not only while under construction, but also for the operation of their heating equipment, cooling systems, lighting and other application. Space and water heating make up 80.2% of residential energy use over the life cycle (NRC, 2003). However, in the literature, most papers found applying LCA on the environmental impacts of buildings focused on the building envelope; very few focused on the HVAC system. Nevertheless, the study of the environmental impact of the residential heating system is essential, since it is one of the activities that account for most of the energy consumption in houses. The overall picture of the environmental impacts of the residential HVAC systems could help and guide designers and architects to understand how energy is consumed over their life cycles, eventually achieving more sustainable building designs.

1.3 Methodology

When evaluating a product or a service, all phases of the life cycle should be taken into account to gain a true understanding of the potential environmental impacts of a product or a service. The evaluation of environmental impacts of HVAC systems is therefore carried out appropriately by using the life cycle assessment methodology. The life cycle analysis of the residential HVAC systems includes among other items the life cycle energy consumption, the life cycle GHG emissions, the life cycle exergy destruction, and the life cycle cost. The life cycle energy consumption in this study is defined as the total amount of embodied energy, operating energy, maintenance energy, re-use energy, recycle energy, and demolishing energy.

Two heating systems are the objects of the present study: (1) a hot water heating system, and (2) a forced air heating system. The life cycle assessment of the entire system relies on detailed quantitative data derived from particular manufacturers' documents. In the absence of reliable data, however, the evaluation of environmental impact is extremely difficult because of the high uncertainty that exists in HVAC equipment such as boilers, furnaces, etc. Since equipment such as a boiler or furnace is made of multiple materials with different quantities, this detailed information is often not available from either manufacturers' documents or existing literatures. The present study therefore introduces decision models under uncertainty, in which a payoff matrix is employed to analyze all design alternatives under a variety of proportional combinations of the materials used in an equipment, to deal with the life cycle energy consumption associated with GHG emissions caused by the manufacturing of HVAC equipment. The design alternatives are represented by the combinations of the components made of different materials. The life cycle environmental impacts due to the piping system for hot water heating system or the duct system for forced air heating system including fittings and accessories such as valves, strainer, and grilles etc. are also more straightforward to evaluate.

1.4 Objectives of this thesis

The objectives of the present study are to evaluate the life cycle energy consumption, the life cycle GHG emissions, the life cycle exergy destruction associated with entropy generation, and the life cycle costs of two residential HVAC systems. In detail, the study intends to:

- Compile the life cycle inventory for the selected heating systems, in terms of mass and energy input/output flows;
- Locate the ranges of embodied energy and GHG emissions values rather than individual values for the equipment by applying decision models to some equipment with uncertain information;

- Calculate the environmental impacts of the selected HVAC systems in the operating phase by the simulation of hourly heating operation; and
- Identify the best performing HVAC system for a house in Montreal, which minimizes the life cycle energy consumption, the life cycle GHG emissions, the life cycle exergy destruction associated with entropy generation, and the life cycle costs.

1.5 Organization of the thesis

The organization of the thesis is described by a flow chart (Figure 1-1) to illustrate the methodology used in the following chapters. This thesis is organized as follows:

- Chapter 2 provides a literature review of researches and projects about life cycle analysis and life cycle analysis tools and databases. The topics of life cycle exergy analysis and decision-making under uncertainty models are also presented.
- The system designs of the two selected heating systems are presented in Chapter 3. This is the starting point of the life cycle analysis of the residential heating systems.
- However, due to the lack of detailed and reliable manufacturers' data, quantitative data of some HVAC components such as boilers and furnaces cannot be compiled for the life cycle inventory. So this thesis adopts decision models under uncertainty to deal with this situation and the results are presented in Chapter 4.
- The impact indices in terms of embodied energy, greenhouse gas emissions, exergy destruction, and initial cost are evaluated for the pre-operating phase of the systems in Chapter 5.

- In Chapter 6, the mathematical models for the simulation of the hot water heating system and the forced air heating system are developed in the program EES (Engineering Equation Solver). The same impact indices are also examined in the operating phase considering the different energy sources: hydro electricity and natural gas.
- The overall impacts of the residential heating systems compared with the envelope are presented in Chapter 7.
- Chapter 8 provides conclusions and recommendations for future work based on the findings of this study.

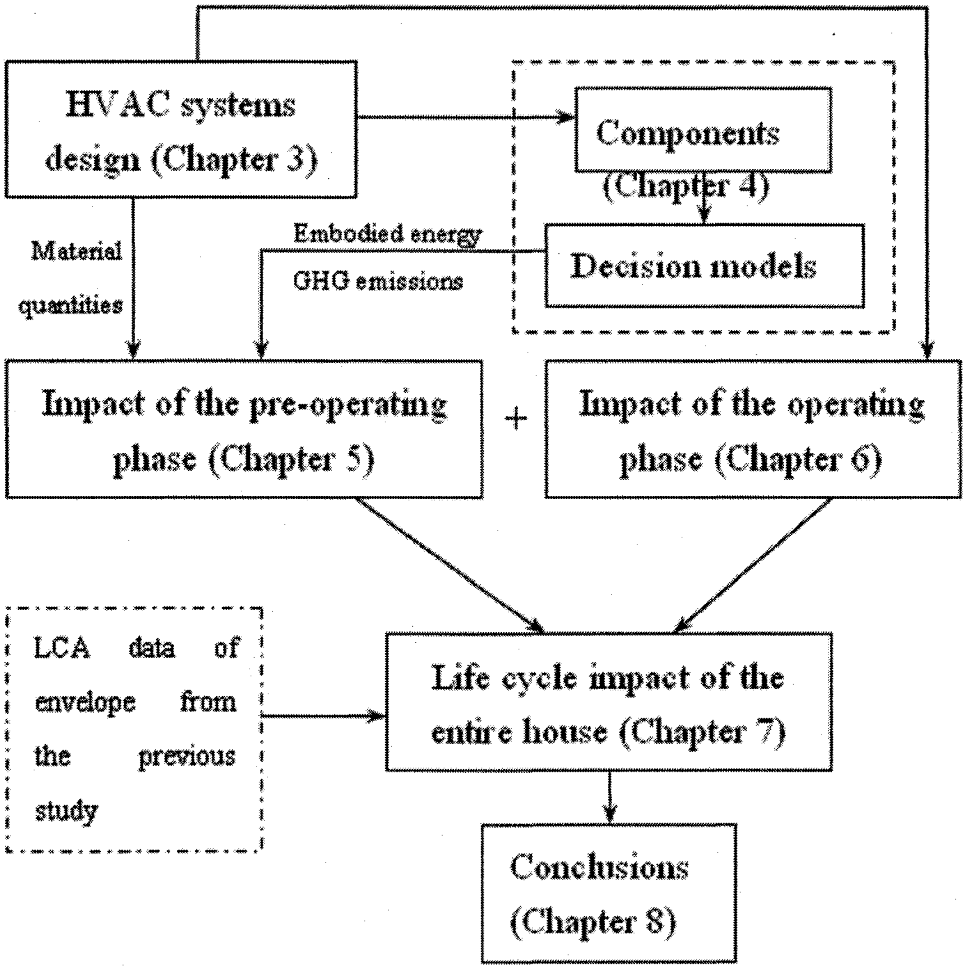


Figure 1-1 The flowchart of the research and the structure of this thesis

CHAPTER 2

Literature review

The literature review presents similar researches and projects about life cycle energy, life cycle greenhouse gases emissions, life cycle cost, and life cycle exergy destruction for HVAC systems and relevant equipments. It also introduces the methodology of life cycle assessment and decision-making under uncertainty.

2.1 Life cycle analysis (LCA) methodology and LCA tools

2.1.1 Introduction to LCA

The life cycle assessment (LCA) methodology was initially developed by the Society of Environmental Toxicology and Chemistry (SETAC) and was later optimized by ISO (Ayres, 1995). The life cycle assessment is a tool that can be used for assessing the environmental impacts of a product, process or activity throughout its life cycle and for identifying opportunities for reducing the impacts attributable to relevant wastes, emissions and resource consumption (Pennington et al., 2004). In this study, the LCA methodology is adopted to assess the environmental impacts and cost of the selected heating systems throughout their life cycle. The LCA has become one of the most widely-used approaches for the study and analysis of strategies to meet environmental challenges during design and decision making processes. Figure 2-1 illustrates the methodology of LCA. According to the standard of ISO 14040 (1997), the LCA methodology generally consists of the following four steps:

- The goal and scope definition step spells out the purpose of the study and its breadth and depth.
- The inventory analysis step identifies and quantifies the environmental inputs and outputs associated with a product over its entire life cycle. The environmental inputs include water, energy, land, and other resources; outputs include releases to air, land, and water. However, it is not these inputs and outputs, or inventory flows that are of primary interest. The aim of inventory analysis should be settled on their consequences, or impacts on the environment.
- The impact assessment step characterizes these inventory flows in relation to a set of environmental impacts. For example, the impact assessment step might relate greenhouse gas emissions, a flow, to climate change, an impact by using generic characterization factors. These factors come from basically the output of characterization models, in the form of databases and LCA support tools (Pennington et al., 2004). Several impact assessment methods are found in the literature: direct use of inventories, critical volumes (Habersatter, 1991), environmental priorities system (EPS) (Steen, 1999), Eco-Indicator 99 (Goedkoop and Spriensma, 2000), and environmental problems (SETAC, 1992).
- Finally, the interpretation step combines the environmental impacts in accordance with the goals defined in the LCA study. The results that are reported in the most informative way possible and the need and opportunities to reduce the impact of the product(s) or service(s) on the environment are systematically evaluated.

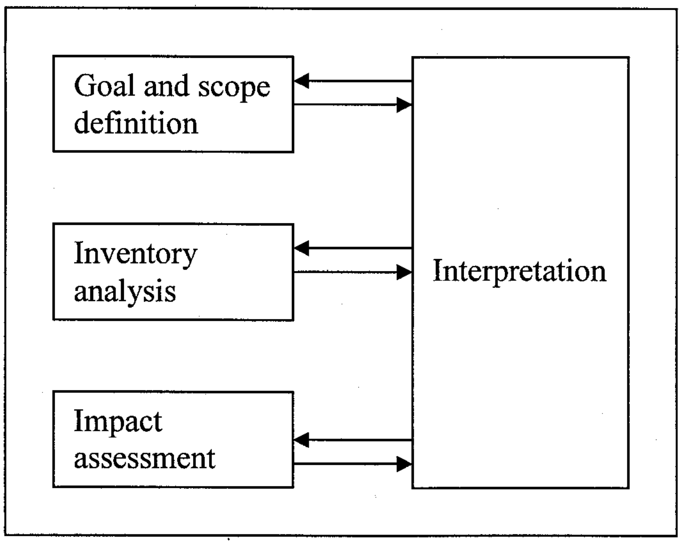


Figure 2-1 The LCA flowchart (source: ISO 14040)

2.1.2 Functional unit

The ISO 14040 (1997) defines functional unit as a quantified performance of a product system. A functional unit provides a reference to which the input and output data are related. It is used to normalize the data. The amount of product, necessary for fulfilling the function, must be quantifiable and is thereby the basis for the analysis. The flows related to the functional unit are then used to calculate the inputs and outputs of the system. Comparisons between systems are made on the basis of the same function, and quantified by the same functional unit. The bottom line of this definition is that it is the quantified performance/service of a product, which has to be comparable to the service/performance of another product, not the product itself. When comparing different products, the different product systems must be comparable (Paulsen, 2001).

In the present study, the function of the systems studied is to heat a house to reach the desired indoor temperature during the whole year. The functional unit of this study is defined as a heating system with related components, for instance, a 12.2 kW gas-fired boiler with a circulating pump, radiators, an expansion tank, and pipes/fittings. The functional unit provides a certain indoor environmental quality (21°C) for an area of 310 m^2 of residential habitation in Montreal, Canada. The design heating load is 11.09 kW for this house.

2.1.3 Inventory analysis

Life Cycle Inventory (LCI) is a tool that uses an engineering approach to quantitatively assess environmental impacts of products and processes. This tool analyzes a product's life cycle, which begins at raw material extraction and ends at the product's disposition. To have reliable LCA results, it is important that LCI are based on quality data that quantifies all of the material and energy inputs and outputs over the life cycle (Vehar, 2001). On the basis of inventory analysis, the LCA assessment could be clearly addressed. This process of collecting the data is called Life Cycle Inventory.

A number of approaches (EPA, 1993) may be used to compile the inventory data for the life cycle inventory (LCI) analysis. They are described as follows:

- Unit process and facility specific: collect data from a particular process within a given facility that is not combined in any way. Using this method, one can obtain direct material flow rate and energy flow rate from the producing process. Manufacturer- specific product data are primarily collected using the unit process and facility specific approach.

- Composite: collect data from the same producing process in different locations and combine into an average data. This method has the data compared with that from other locations.
- Aggregated: collect data combining more than one process. This method gets data of product or service created by different processes.
- Industry-average: collect data derived from a representative sample of locations believed to statistically describe the typical process across technologies.
- Descriptive: collect data whose representatives may be unknown but which are qualitatively descriptive of a process.

2.1.4 Databases

Databases are the capstone of LCA tools because of a LCA study that relies on the appropriate databases that are capable of compiling the life cycle inventory for a service or a product at first. Most databases are usually maintained and updated by one or several organizations periodically. However, most of the data found in the literature is often out of date because the producing processes, which are cited in the old literature, have changed significantly due to the development of science and technology. Databases are often meant for a region. A literature survey of the existing databases (IEA, Annex 31, 2002) has found a number of databases from around of world: 16 European databases, in which 12 of them have an English version; and 9 databases from Non-European countries, 2 of them use Japanese. These are listed in Appendix-1. These databases include data about energy (fuels and electricity), transport and waste treatment. With the aid of these databases, the assessment of the energy related environmental impacts of buildings can be carried out in their respective regions. Three such databases are presented below, which are: SIMAPRO, OPTIMSE, and DEAM™ databases.

a. SIMAPRO Database

The Australian LCA inventory data are currently available in the SIMAPRO database prepared by the Centre for Design at RMIT University (Graham, 2003). SIMAPRO compiles the embodied energy values from a comprehensive hybrid input-output embodied energy model for Australian construction. This database contains a number of impact assessment methods, namely, characterization, damage assessment, normalization, and weighting, which are used to calculate impact assessment results. The indicator evaluation technique produces a single figure for environmental impacts. SIMAPRO can add together all the different environmental effects from the evaluation stage to give a total impact for each material and process in the assembly. The value mode in SIMAPRO displays the effect scores in tabular form. This option allows four interpretations of the effect scores to be displayed (Gouda, et al., 2001).

The database includes input and output data concerning material production and processing, energy generation, transport, waste treatments and waste scenarios (Jönbrink and Erixon, 2000). The database uses the primary energy factor to characterize primary energy value from industry data. Most of the data contained in SIMAPRO according to a review of databases done by Forintek Canada Corp. (1999) are grouped into 14 classes: Aluminum, Cement, Copper, Concrete, Decking, Membrane, Reflective foil, Steel, Stainless steel, Laminate, Clear float glass, Plastic, Timber, and Vinyl. It is also possible to add new data in projects or to the database.

b. OPTIMISE database

OPTIMISE is a Canadian Mortgage and Housing Corporation (CMHC) database, developed by Sheltair Scientific Limited (1995). It is used to determine the life-cycle environmental impact of single dwellings. The primary data of the program focuses on the embodied energy of materials used in the construction of wood-frame low-rise housing. OPTIMIZE incorporates a number of useful features (e.g., life cycle costing, operating energy costs and indoor air quality measures) and has good breadth of coverage in its material commodity data. The model does not comply with ISO standards for life cycle assessment procedures and is not really an LCA model, For example, its reliance on I/O data means that the air emissions of GHG emissions are not included and therefore underestimated (Forintek Canada Corp., 1999).

The embodied energy is determined not only from the process method but also from input-output tables from Statistics Canada for the Canadian economy. The volume of product and gross energy data used in each of 58 commodity sectors are used to derive embodied energy data. In this database, eight energy sources and 58 products, representing those that might be used in building construction, have been identified. Data regarding embodied energy in this database takes into account the energy attributable to transportation to site, construction, maintenance and replacement, demolition and disposal (Forintek Canada Corp., 1999). A further limitation results from the fact that the

I/O data is inferior in terms of accuracy and does not allow sufficient distinction among products.

c. DEAM^{TM} database

DEAM^{TM} stands for "Data for Environmental Analysis and Management". This database (RMIT, 2001) contains some 500 data sheets concerning energy, transportation, materials and production, and end of life channels of more than 30 industrial sectors. The current database has both European and American versions. The different versions of data reflect different regional conditions (e.g. Europe, North America). Some studies (Blanchard and Reppe, 1998; Landfield and Karra, 2000; Scheuer et al, 2003) have adopted the data from DEAM^{TM} database. The database is coupled with the TEAM^{TM} software. The Tool for Environmental Analysis and Management (TEAM) is developed by Ecobilan Inc.(2004). In order to compile the life cycle inventory data, the TEAM^{TM} software is at first used to model the production or manufacturing processes and activities and then report the environmental performance of the study (Landfield and Karra, 2000). The TEAM^{TM} software consists of the following modules:

1. Bibliographic data (e.g. US EPA AP-42, APME)
2. Real site data (e.g., from site questionnaires)
3. Calculated data (generated from the results of site data, e.g. electricity production).

Basically, energy is usually a big driver in LCA studies. Applying geographically relevant data sets, this database considers the production of electricity from different energy sources for different countries and regions (Ecobilan Inc, 2004).

2.2 Embodied energy and life cycle energy consumption in HVAC systems

This section presents the concept of embodied energy and life cycle energy consumption as well as the calculation methods for embodied energy. Moreover, the embodied energy values and the values of equivalent CO_2 emissions for a number of materials used in the manufacturing of HVAC systems and equipment are compiled from existing studies.

2.2.1 Embodied Energy

Embodied energy (Treloar et al., 2001) is the energy consumed directly and indirectly by all processes associated with the production of a product or a service, from the acquisition of natural resources to product installation. This includes the mining and manufacturing of materials and equipment, the transport of the materials and the administrative function. Some studies use the concepts of initial embodied energy and recurring embodied energy, in fact, the summary of the two parts equals to the embodied energy of material during its life cycle. Initial embodied energy refers to the energy required to extract the raw materials, produce materials, and manufacture products, as well as transportation and installation. Occurring embodied energy expands to analyze the embodied energy occurring in the phrases of maintenance, replacement and demolition (Cole and Kernan, 1996; Treloar et al., 2001). According to Lawson (1996), embodied energy could serve as a general indicator of environmental impact; it may also provide an indication of the degree of depletion of natural resources and greenhouse gas emissions.

There are four calculation methods (Alcorn and Baird, 1996) to compute the embodied energy in a product or a service. They are:

- Process analysis, gathers direct energy inputs to a process from manufacturers and the raw material inputs to the process.
- Input-output analysis, examines the dollar flows to and from the energy producing sectors of a national economy, and comparing these with the known amount of energy produced by each sector.
- Statistical analysis uses published statistics to determine energy use by particular industries.
- Hybrid analysis, combines useful features of these above methods, especially the input-output analysis and process analysis.

In order to clarify embodied energy data from different sources based on different calculation method, the International Federation of Institutes of Advanced Study (IFIAS) has defined a classification of amount of embodied energy in product or services (Baird et al., 1997):

- Level 1—typically less than 50% of the direct energy involved in the process only;
- Level 2—frequently around 40% of the energy involved in extracting materials;

- Level 3—rarely greater than 10% of the energy needed to make capital equipment;
- Level 4—usually very low energy used to make the machines that make the capital equipment.

The literature survey conducted within the framework of the present study has reviewed a large number of embodied energy values for building materials. In order to calculate the embodied energy for the selected HVAC systems, reliable embodied energy data are essential. However, the embodied energy data of materials used in HVAC systems are limited to relatively few numbers in the published literature. A presentation below gives more attention to the materials frequently used in mechanical systems. A comprehensive summary is presented in Appendix-2.

1. Steel

Baird and Chan (Baird et al., 1997) used the input-output method based figures from the United States and applied them to New Zealand input-output data. This failed to take into account the technology related to the New Zealand steel industry where wire rod and structural sections are produced from recycled steel only, whereas virgin steel is used for making coiled sheet, plate and tube steel only. The environmental impact of the production of steel mainly lies in the extraction of coal (coke) and the production of steel from iron (Anink et al., 1996). Compared with other metals, the embodied energy of steel is relatively low. The average of the energy embodied in steel products (Treloar et al., 2001) is from 80 to 115 MJ/kg. Steel reinforcement with 100 percent recycled content has an embodied energy value of 20-50 MJ/kg. However, the lowest value embodied energy for steel is produced by electrical furnace with only 3 MJ/kg, according to Harvard (2004).

2. Copper

The copper is a material used in many components of HVAC systems. An advantage of copper is that it can be recycled. Pipes and other copper products are recycled on a large scale because it is economically attractive (Anink et al., 1996). The study by Ardente et al. (2005) has shown a great variability of the energy and environmental data for copper products that is attributed to the use of heat for melting and electricity in the electrolysis and to the ratio of recycled copper scraps. The energy embodied in copper ranges from 46 to 96 MJ/kg (Appendix-2).

3. Aluminum

The most important environmental impacts of aluminum occur during extraction and during conversion of the raw material, bauxite, into a semi-manufactured product. Aluminum is produced with electricity, demanding a large quantity of energy (Anink et al., 1996). Virgin aluminum has an embodied energy value of 130-230 MJ/kg. Secondary aluminum, which means that the product comprises recycled aluminum, has an embodied energy value of 8-198 MJ/kg. A great variability of the embodied energy of aluminum exists depending on the fraction of recycled aluminum in its production (Ardente et al., 2005).

4. Zinc

Zinc is used in the hot-dip galvanizing process to protect steel from corrosion. According to the zinc industry, zinc is the 27th most abundant element in the earth's crust and is fully recyclable (NJHEPS, 2005). Extraction of zinc involves emission of cadmium, which is damaging to the environment (Anink et al., 1996). The embodied energy of zinc is about 51 MJ/kg as reported by Baird et al. (1997).

It is worthy mentioning that the quantification of embodied energy for any particular material is an inexact science (Mumma, 1995). All the calculation methods of embodied energy have certain degrees of inaccuracy. Errors for process analysis data are ±10 percent. For input-output analysis, errors are approximately ±50 percent. Errors for hybrid method depend on the degree of its mixture (Treloar et al., 2001). Furthermore, embodied energy can vary because of many factors such as the geographic origin and date of publication. Some researchers (Mumma, 1995; Lawson, 1996; Treloar et al., 2001) point out that figures quoted for embodied energy are only broad guidelines and should not be taken as 'correct'. What is important is to consider the relative relationships and try to use materials that contain low embodied energy. The guidelines are that the more producing processes a product goes through, the higher its embodied energy will be; and recycling processes could save a large part of the embodied energy that would otherwise be wasted. Therefore, for the purposes of a life cycle energy analysis it is only important to recognize the potential differences in relative embodied energy to make wise material and system choices.

2.2.2 Operating Energy

The energy used to heat, cool, ventilate, and light buildings, called operating energy, represents 20% of the Canadian national energy use (Cole and Kernan, 1996). Operating energy consumption depends in a large part on the occupants. Embodied energy is not occupant dependent—the energy is built into the materials. Operating energy is accumulated over the lifetime and can be influenced throughout the life of a building. Several case studies in the literature that compare the embodied energy and operating energy use are presented below.

A estimate by Cole and presented by Malin (1993) also compares the embodied energy and operating energy of a 3,750 ft^2 (348 m^2) ranch-style house in Canada built in either the conventional or the energy efficient style. Cole's figures reveal that for both versions of the house, the embodied energy equivalently ranges from seven to eighteen years of the annual operating energy use (Mumma, 1995).

A study by Adalberth (1997b) displayed the life cycle energy uses of three single-unit dwellings built in Sweden. The amounts of embodied energy used in manufacturing the construction materials in the houses range from 730 kWh/m^2 to 900 kWh/m^2 and account for 10% of the total energy use for a life of 50 years. The operating energy use ranges from 6,400 to 7,400 kWh/m^2 and account for 85% of the total life cycle energy use. The total embodied energy corresponds to about seven years of occupation (space heating, hot water and electricity). However, the operating energy could be reduced when the house is built by using higher quality materials and products, but the embodied energy would be increased.

A study carried out by Mithraratne and Vale (2004) analyzed that the embodied energy and the operating energy consumption for space heating of a 94 m^2 typical residential house built with the softwood frame structure, located in Auckland, New Zealand. The life cycle embodied energy is 4425 MJ/m^2 over a 100-year lifespan. The space heating energy requirement for the house is 2149 kWh/annum. The embodied energy could be estimated at 54 times the annual heating energy consumption.

The large difference among these studies reveals that the ratio of embodied energy to the operating energy consumption depends on the building design, fuel type, operating efficiency, lifespan, local climate, and the method of energy analysis (Treloar et al., 2001). On the other hand, these studies indicate that the more energy efficient the house is, the larger the embodied energy percentage will be of the total life-cycle energy.

2.3 Life cycle greenhouse gas (GHG) emissions

The Earth's atmosphere is a mixture of many gases that absorb the sun's heat and radiate it back to the Earth's surface, trapping it like a greenhouse. More and more of these gases are being created and trapped in our atmosphere due to increased energy consumption by the world population, leading to increased global temperatures. The life cycle GHG emissions in this study refer to the embodied emissions and the emissions due to the operating energy consumption that causes the greenhouse effect on the earth's atmosphere. The embodied GHG emissions due to the manufacturing of HVAC products is the same concept of embodied energy to examine the GHG emissions accompanying the producing process of the product studied from “cradle to grave”. They are expressed in kg of emission of each greenhouse gas per ton of the produced material. Data about GHG emissions of some other materials are compiled in Appendix-3.

2.3.1 Global warming potential (GWP)

The global warming potential (GWP) is a quantified measure of the globally averaged relative radiative-forcing impacts of a particular greenhouse gas. It is defined as the cumulative radiative-forcing of both direct and indirect effects integrated over a period of time from the emission of a unit mass of gas relative to some reference gas (IPCC 1996). Carbon dioxide (CO_2) was chosen as this reference gas. GWP is a weighting factor that enables comparison to be made between the global warming impact of 1 kg of any greenhouse gas and 1 kg of CO_2. It is dimensionless and includes a time horizon during which the impact will be felt. For instance, the 100-year GWP for methane (CH_4) is 21, which means that 1 kg of CH_4 emitted today will have the same effect on global warming over the next 100 years as 21 kg of CO_2 emitted today.

Global Warming Potential (GWP) coefficients were introduced by the Intergovernmental Panel on Climate Change (IPCC, 1996). The GWP values for the greenhouse gases considered in the calculations of CO_2, SO_2, NO_x, CO, CH_4, and Particulate Matter for time horizons of 20, 100, and 500 years were provided. Examples of GWP coefficients are presented in Table 2-1 for CO_2, CH_4, and NO_x. It is worth mentioning that the uncertainty associated with the calculation of these coefficients is about ±35% (IPCC 1996).

Table 2-1 Global warming potentials in different time horizons (Masters, 1998)

Time period (yr)	Gases	GWP
20	CO_2	1
	CH_4	56
	N_2O	280
100	CO_2	1
	CH_4	21
	N_2O	310
500	CO_2	1
	CH_4	6.5
	N_2O	170

2.3.2 Emissions due to the operating energy use

Operating emissions are the emissions caused by burning fossil fuels due to the operating energy use for heating, cooling, cooking, and other household energy uses. In the present study, only the energy use for heating is considered. The emissions vary depending in a large part on fuel sources. Table 2-2 provides the off-site electricity mix per energy source at the provincial level in Canada.

Table 2-2 Provincial mix of the electricity generation as percentage (Nyboer et al., 2003)

Province/Country	Coal	Oil	Natural Gas	Nuclear	Hydro.	Other
British Columbia	2	2	2	0	94	0
Alberta	84	8	8	0	0	0
Ontario	4.33	4.33	4.33	54	26	0
Quebec	0	1.1	1.1	1.1	96.7	0
Canada	19	3.5	3.5	12	62	0

Similarly to the manufacturing phase, the amounts of GHG emissions resulting from the operation phase are expressed as tons of emissions for the different greenhouse gases, and are also converted to equivalent CO_2 emissions by using the Global Warming Potential (GWP) coefficients for a selected time horizon.

2.4 Life cycle analysis of residential HVAC systems

According to NRC (2003), over 80% of the residential energy is used for space and water heating. Residential HVAC system is considered an important area for improving efficiency because equipment has a shorter life span than residential buildings. Therefore, the researches relevant to the LCA assessment for residential houses and HVAC systems and the impacts of HVAC systems on the houses are reviewed and briefly presented chronologically in this section.

Adalberth (1997a) presented a method for calculating the life cycle energy use in a building. The life cycle of a building is divided into seven stages, namely, product manufacturing, transportation, erection, occupation, renovation, demolition, and removal. The embodied energy use in every one of these phases is calculated by cumulating the energy consumed in each manufacturing, transportation, or construction process per material. The energy use during the occupation (space heating, hot water and electricity) is calculated with the aid of the Swedish computer program Enorm.

Blanchard and Reppe (1998) undertook the life cycle analysis of a residential house. A 228 m^2 (2,450 ft^2) house was built in Ann Arbor, Michigan, using standard construction materials and techniques. The analysis was divided into the following eight systems: walls, roof/ceilings, floors, doors/windows, foundation, appliances/electrical, sanitary/HVAC, and cabinets. The total life cycle energy consumption is 15,455 GJ. Its raw material extraction/production and construction (pre-use phase) energy use is 942 GJ or 6.1% of total life cycle energy use, while its operating energy use is 14,482 GJ (93.7%), and it's end-of-life phase energy use accounts for 31 MJ (0.2%). The mass inventory of the house revealed a total amount of steel of 3,719 kg. The total mass of various materials used is 306 tons for all construction maintenance and improvement over a 50-year life cycle. The estimate in terms of embodied energy and greenhouse gas emissions for steel is 120,974 MJ and 8,700 kg, respectively. According to the data provided by the authors, it can be estimated that the steel is mainly distributed in the duct system, appliances, and the assorted fasteners, and accounts for 13% (49.4 MJ/ft^2 or 531 MJ/m^2) of the initial embodied energy of the house. The research mainly used the DEAM^{TM} database, and primary data about equipment/appliances were collected from suppliers and manufacturers.

Legarth et al. (2000) carried out an inventory analysis for the ABB EU2000 air-conditioning unit. The unit in study comprises an air heater, an air cooler, a rotary heat exchanger, filters, silencers, fans with large size motors and the hulls. The detailed quantitative data of the product materials and the energy input/output of the producing processes can be collected at the production stage, and then an inventory analysis was carried out by using the Danish EDIP environmental impacts method, EDIP software, and database. They analyzed the environmental impacts of the air-conditioning units in nine impact categories (such as global warming and ozone depletion), four waste categories, and nine natural resource categories. Based on the results of the study, the authors pointed out that more attention should be paid to: energy efficiency, substitution of CFC chemicals and avoidance of galvanization surface treatment in order to reduce the environmental impacts of manufacturing the air-conditioning units. However, a limitation of this study is that they evaluated the specific product only with data obtained from manufacturers. Although these results are considered to be relatively precise, the method cannot completely deal with the environmental impacts of the other products, such as boilers or furnaces, due to the lack of quantitative information from manufacturers.

A study reported by the Canadian Mortgage and Housing Corporation (CMHC, 2001) focused on a new multi-unit residential building located in Ottawa, Ontario, with 84 units, 4 stories, a concrete structure with steel stud/brick exterior walls. The embodied energy of the mechanical systems accounts for 13% of both initial embodied energy and life cycle embodied energy. Unfortunately, there are no more detailed data reported in this study such as quantities for the mechanical system.

A study by Treloar et al. (2001) evaluated the environmental impacts of an energy efficient two-story residential house of 115 m^2. All building elements were analyzed, including substructure, services such as space heaters, solar hot water service, and external elements such as paving and pergolas. The initial embodied energy was found to be 1,277 GJ, of this, 101 GJ was used for the construction process. The life cycle embodied energy was estimated at 2,760 GJ in a 100-year life span. The paper did not provide the percentage of embodied energy for the mechanical system, even though the HVAC system was included.

A previous study by Kassab (2002) presented a life cycle analysis of the energy performance of a 310 m^2 residential house in Montreal, Canada. The embodied energy and the GHG emissions were evaluated by the following building subsystems: envelope, structure, and interior partitions. The total embodied energy of the house is 707,863 MJ or 635 kW/m^2. The operating energy was simulated by the Energy Plus software at 10,470 kWh or 34 kW/m^2. The life cycle GHG emissions are 69.41 tons of equivalent CO_2 emissions and the life cycle costs for the house are 217,266 dollars or 702 $\$/m^2$. However, this life cycle analysis did not evaluate the impact of the HVAC system in the house.

Prek (2004) studied the environmental impact of three residential heating systems for the production phase, namely, a radiator heating system using steel or copper pipes, a floor heating system using polyethylene or polybuten pipes, and a fan coil convector heating system. The total heat demand was 11.8 kW. The functional unit was defined as heating the house at temperature 21°C by operating the whole heating system. The comparison among the three different heating systems was made by using the Eco-indicator 95 method, which is used to aggregate various environmental impacts to one single indicator. The results obtained by the author show that for the radiator heating system, the copper pipes contribute three times higher environmental impact than steel pipes despite their small dimensions. The floor heating system has the lowest Eco-indicator value if no extra building construction is considered. The fan coil unit heating system is in the middle point among the three different systems. In this study, the heat conversion equipment and the detail fittings of the systems were not taken into account.

Heikkilä (2004) assessed the sustainability of two air conditioning systems for commercial buildings using the life cycle assessment method as well as the weighting method. System A consists of an all-air air-handling unit with a cooling coil and a vapor compression chiller (its materials and their amounts were excluded from the calculation). System B is an all-air desiccant cooling air handling unit. The quantitative information of materials of the air handling unit (AHU) and the refrigeration machine was determined by approximations based on another study (Legarth et al., 2000) and personal communication with manufacturers. The total internal loads for the offices are 33 W/m^2. The functional unit of this study is an AHU, which distributes a constant airflow volume of 4.8 m^3/s and works 24 hours a day for 15 years. The required temperature of the supply air is constant of 16°C and the room temperature varies between 20-25°C. This study reveals that system A causes greater environmental impacts than system B in the production stages due to more material used. On the other hand, in the operating stage, system A has less impact than system B because of less electricity use. Furthermore, the comparison shows that the energy use during the operating stage has the larger environmental impact for the two systems.

Ardente et al. (2005) carried out a life cycle assessment of a solar thermal collector. The main materials of the solar collector are broken down as: galvanized steel 112.6 kg, thermal fluid 37.5 kg, stainless steel 29.1 kg, copper 13.6 kg, glass 10.5 kg, rigid polyurethane (PUR) 9.0 kg, aluminum 4.0 kg, and cardboard 3.0 kg. They investigated six life cycle phases from the production and delivery of energy and raw materials to the disposal phase. On the basis of the detailed material composition of the solar collector, the study assessed the quality of input data of the dominant raw materials in terms of embodied energy and CO_2 emissions. They found that the global energy consumption could vary by about ±20% from its reference value of 11.0 GJ; equivalent CO_2 emissions can vary about ±17% from the reference value of 700 kgCO_2. Consequently, a strong dependence of the environmental impacts to the input materials was found in their study. In other words, the uncertainty existing in the input values significantly influence the environmental impacts determined for the solar collector.

2.5 Decision-making under uncertainty

In the life cycle analysis of the HVAC systems, life cycle inventory has to be compiled in order to fulfill the life cycle analysis. However, due to the lack of detailed and reliable manufacturers' data, the quantitative data about some HVAC components such as boilers and furnaces cannot be compiled in the life cycle inventory. Since the equipment such as a boiler or furnace is made of multiple materials with different quantities, this detailed information is often not available in either manufacturers' documents or existing literatures. This situation results in decision-making uncertainty. "A decision situation where several states are possible and sufficient information is not available to assign probability values to their occurrence is termed a decision under uncertainty (Szonyi et al., 1982)". The present study therefore introduces the decision models under uncertainty, in which a payoff matrix is employed to analyze all design alternatives under a variety of proportional combinations of the materials used in an equipment, to deal with the life cycle energy consumption associated with GHG emissions caused by the manufacturing of HVAC equipment. The design alternatives are represented by the combinations of the components made of different materials. The payoff matrix model has been widely applied to problems relating to economics, social sciences and engineering. This section presents three similar studies, in which decision models under uncertainty were used.

Zmeureanu and Fazio (1987) used decision models under uncertainty to analyze the performance of a solarium. A payoff matrix model composed of design alternatives and states of future was established to handle uncertainty in the design alternatives of the building thermal characteristics under possible futures, which are defined as 17 individually random days' weather conditions in Montreal. The Hurwicz criterion, which brings a compromise between the most optimistic design alternative and the most pessimistic design alternative, was mainly applied in the paper. The expected heating loads of design alternatives were presented under consideration of the different levels of the decision-maker's confidence. The best design solution is the one that is the least sensitive to the random weather condition, therefore to any states of futures.

Belyaev (1990) illustrated the payoff matrix technique with an example of decision-making for choosing the installed capacity of a hydropower plant (HPP) in Siberia. In this case, the problem was reduced to choose a rational number of generators for the given capacity. The decision variants are discrete corresponding to the different number of units. The range is between 13 to 18 units with 375 MW per unit. Five states of nature were considered by combining these factors: capacity, load density, cost of substituting thermal power plant etc. The analysis of payoff matrix revealed that the problem might be simplified after excluding non-dominant variants, and then different criteria might recommend different optimal variants since none of the criteria inspires complete confidence. Therefore, the final decision should be made by the decision-maker himself based on his experience and intuition.

Pasqualetto and Zmeureanu (1995) applied the decision model under uncertainty to select energy conservation measures in buildings. They developed a payoff matrix using the combination of energy conservation measures under possible states defined as the different accurate level measures. The accurate levels of measure introduce the variations or errors apart from the data of the base case in the input files, such as the variants of the glazing ratio, the lighting power density, or those set points of thermal design temperature etc. Five decision criteria were used to analyze energy cost savings.

Nevertheless, the cases of using the payoff matrix model in HVAC field are rarely found in the literature. This approach is actively applyed in the other fields. Three such examples are found in the literature. Hoag et al. (2002) presented a study of using payoff matrix in determining the environmental indicators. Huang H. (2002) carried out a study of the application of payoff matrix model to the autonomous behaviors in automated manufacturing systems (AMS). In addition, Raju K. et al. (2000) used a payoff matrix to conduct the evaluation of an irrigation system.

2.6 Life cycle exergy analysis of HVAC systems

Exergy is "the amount of work obtainable when some matter is brought to the state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes, involving interaction only with the above-mentioned components of nature" (Szargut et al. 1988). Recently, the concept of exergy associated with entropy for the evaluation of the building environmental impact has been given more attention by a number of studies (Shukuya and Hammache, 2002; Ren et al., 2002; Schmidt, 2003; Rosen and Scott, 2003). Exergy has been used as an environmental impact indicator to link with the depletion of natural resources (Wall, 1977 and 1990; Szargut et al. 1988; Finnveden and Östlund, 1997; Rosen and Scott, 2003). In the literature, exergy destruction is commonly referred to as *availability destruction, irreversibility, and lost work.* Compared with energy, exergy has the advantage of being able to evaluate the quality of different energy sources. For example, the quality index of electricity is 100% and of district heating is 30%, respectively (Wall 1977).

Wall (1977) suggested that the exergy content of the energy resources may be given by their energy content multiplied by a quality factor that applies to the "energy form" in question. Tables 2-3 and 2-4 present the quality factors for energy sources and non-fuel materials.

Table 2-3 The qualities of different forms of energy (Source: Wall, 1977)

	Forms of energy	Quality index (% of exergy)	Examples
Extra superior	Potential energy[1] Kinetic energy[2] Electrical energy	100 100 100	1. highly situated water resources 2. waterfalls
Superior	Nuclear energy[3] Sunlight Chemical energy[4] Hot steam District heating	almost 100 95 95 60 30	3. the energy in nuclear fuel 4. oil, coal, gas or peat
Inferior	Waste heat	5	
Valueless	Heat radiation from the earth	0	

Table 2-4 The qualities of different materials (Source: Wall, 1977)

Form of matter	Quality index (% of exergy)	Examples
Matter in an ordered form[1]	100	1. carbon in the form of diamond
Matter as commercial goods[2]	almost 100	2. iron, gold or lead
Mixtures of elements[3]	approximately 90	3. steel, alloys or plastics
Rich mineral deposits[4]	50-80	4. bog iron (limonite) or sea nodules
Ore approximately	50	
Poor mineral deposits[5]	20-50	5. bauxite
Mineral dissolved in seawater or soil	approximately 0	

Exergy efficiency is defined as the exergy output divided by the exergy input, and is also called second law efficiency or rational efficiency (Gong and Wall, 1997). Compared with energy efficiency, exergy efficiency is more useful to pinpoint where the losses occur and the inefficiencies in the HVAC system. Energy and exergy losses can be directly translated to an increase in primary fuel consumption. Many researchers propose that the thermodynamic performance of a process is best evaluated with exergy efficiency (Ren et al., 2002; Çomaklı et al., 2004).

From the point of view of thermodynamics, exergy is consumed or destroyed in any real process due to irreversibility as entropy is generated. Exergy efficiencies are useful in comparing the performance of energy systems and may also be used as a tool to evaluate the effectiveness of improvements performed or to be performed on existing energy systems (Finnveden and Östlund, 1997). In order to reduce the quality as well as the quantity of energy that is wasted which cause the environmental impact, the second law efficiency has become one of the important measurements for environmental impact.

Zhang and Reistad (1998) introduced a method for calculating material exergy that can be divided into two parts: exergy content of material and production exergy of material. The exergy content is the portion of exergy that could be used by the energy conversion system to transform to the desired energy forms such as heat, mechanical work etc. The production exergy of the material is the exergy used to mine, refine and shape the material to the final equipment parts of the thermal system. The exergy content of non-fuel material usually accounts for the relative small portion of the total material exergy, while the production exergy accounts for a dominant portion. However, it is not true for the fuel material, in which the exergy content takes the bigger share.

In the production processes of metals and fuels, exergy consumption is associated with the energy requirement for the processes. The concept of cumulative exergy consumption introduced by Szargut et al. (1988) is expressed as the sum of the exergy of all natural resources consumed in all steps of the production processes. Unlike cumulative energy consumption or embodied energy, cumulative exergy consumption takes into account the exergy consumption of not only energy sources but also the non-fuel resources extracted from the environment. Therefore, the cumulative exergy consumption can be estimated based on the embodied energy (Szargut et al. 1988).

Cornelissen (1997) analyzed a heat exchanger, which is made of copper tubes, steel tubes, and polyurethane (PUR) foam, using the life cycle exergy analysis approach. The estimation of the irreversibilities or exergy destruction associated with the use of the material is discussed. The production of copper tube and steel tube includes three processes, namely, mining process, refining process, and manufacturing process. The exergy destruction is the exergy input reduced by the exergy increase due to the change of product during the processing. The exergy input is assumed to be equal to energy consumption. In the primary process, most inputs are raw materials and fossil fuels, because exergy and energy are then equal. In the secondary process, the efficiency of the electricity production is considered as 0.5. In the manufacturing process, the exergy destruction is assumed to be equal to the energy consumption, because the exergy of the material is hardly changed. Therefore, two points could be drawn from this study: first, the cumulative exergy destruction is derived from the cumulative energy consumption or embodied energy; second, the cumulative exergy destruction takes into account all steps of the production processes of the material in question. However, only three types of materials were discussed in this study.

Franconi and Brandemuehl (1999) carried exergy analyses of the performances of a constant air volume (CAV) distribution system and a variable air volume (VAV) distribution system. They found that the depleted useful work across the fans was greater than the total fan power supplied during the operation. This was explained by the fact that the air temperature increased across the fan as well as the pressure. The increase in pressure increased the flow stream exergy while the increase in temperature caused the supplied air temperature close to ambient temperature, as a result, reducing the flow stream exergy. The total fan power supplied is 7,122 W and the efficiencies of the fan and motor are 0.54 and 0.85, respectively. Of the power supplied, 3,853 W are depleted by fan/motor inefficiencies, and the remaining 3,269 W of shaft power is imparted on the flow stream to overcome pressure drop in the duct system.

Taniguchi et al. (2005) studied the energy conversion processes that the exergy and energy balances in thermodynamic processes supported by the evaluation of temperature level with some examples for the power generation, heat pump, boiler and combustion processes were discussed. The great difference between exergy and energy values is influenced by their temperature levels. For example, a high temperature energy of 1500°C and above in power generation cycle has a higher conversion efficiency than that of 500-600°C in steam cycle.

2.7 Conclusions from the literature review

The literature review presented the relevant studies and the knowledge for the application of life cycle analysis, decision-making models, and exergy analysis in the assessment of HVAC systems. The following conclusions can be drawn:

- Life cycle analysis with respects to life cycle energy consumption, life cycle greenhouse gas emissions and life cycle costs of building products is mostly limited to building envelope materials in the literature. So far, the life cycle analysis of residential HVAC systems has not been studied enough. The literature review has revealed that, with a few exceptions, the life cycle energy use for HVAC systems is based only on the operating energy consumption.
- The current researches applying the approach of decision-making under uncertainty have not been applied to the study of environmental impacts of HVAC systems or equipment. Quantitative data for complex equipment are difficult to be obtained from published manufacturers' documents. This uncertainty has not been studied yet with the appropriate decision model.
- Life cycle exergy analysis should be used in the evaluation of the environmental impacts of a residential building or its building subsystems. Exergy efficiency combines the first and second thermodynamics laws and is able to pinpoint where the loss occurs in a system and indicates to what extent that natural resources are depleted. For the study of non-fuel material exergy, several studies (Szargut et al., 1988; Cornelissen, 1997; Zhang and Reistad, 1998) demonstrated that the exergy input during the production dominates the total material exergy. Therefore, based on the embodied energy the exergy destruction can be evaluated.

CHAPTER 3

DESIGN OF THE SELECTED HVAC SYSTEMS

The hot water heating system and the forced air heating system are two commonly used approaches for residential space heating (ASHRAE, 2003). These two heating systems are selected to compare their life cycle impacts for residential house heating. The present study focuses on the life cycle analysis of these two heating systems. In the following sections, the design of the systems is conducted based on the characteristics of an example house, followed by the inventory of the materials used in the heating systems, which is the basis of the evaluation of life cycle impacts.

3.1 System descriptions

The brief descriptions of the heating systems are given first.

3.1.1 Hot water heating (HWH) system

In a closed hot water-loop heating system, illustrated in Figure 3-1, the components are: a boiler, a circulating pump, radiators, a strainer, an expansion tank, and a piping system. The hot water is heated in the boiler, where energy is transferred from the combustion of natural gas or from an electric coil to the circulating water. The pump circulates the hot water throughout the piping system between the boiler and radiators. The radiators emit a required amount of heat to the rooms. The strainer is used in pipes to protect pump and valves by eliminating unwanted solids from water. The expansion tank is used to accommodate the expansion of water and to maintain a stable pressure for the piping system.

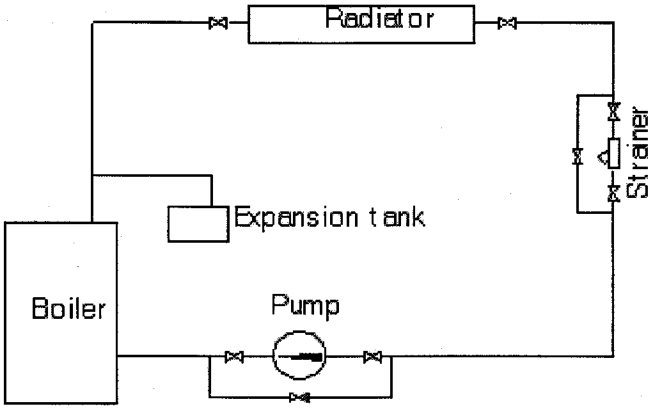


Figure 3-1 Hot water heating system

3.1.2 Forced air heating system

In a forced air heating system, illustrated in Figure 3-2, a furnace uses energy from the combustion of natural gas or from electric coil to heat air distributed to rooms, in order to maintain the design indoor air temperature. The air is circulated through the ducts by a blower, which is built within the furnace. The other components include ducts, a plenum, and diffusers and registers. The diffusers and registers are the terminal devices, which are used to supply or collect air to or from the heating spaces. The plenum, a box, is used to connect the supply ducts and the furnace.

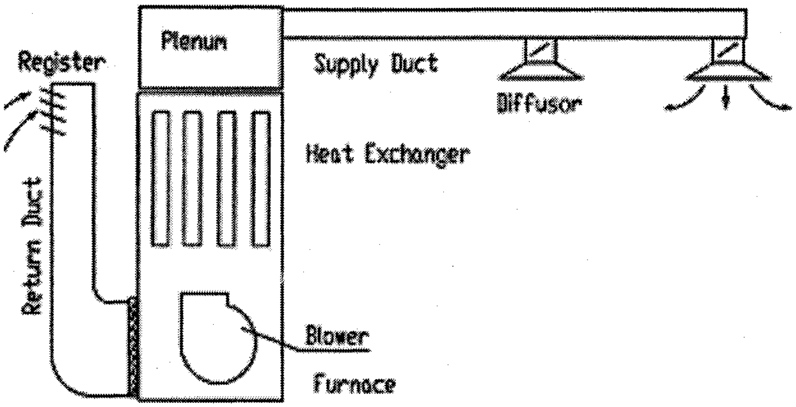


Figure 3-2 Forced air heating system

3.2 Characteristics of the house

The house under study is a two-story dwelling located in Longueuil, on the south shore of Montreal, Canada. The house was designed and built with the goal of being energy-efficient. The house consists of the basement, the ground floor and the first floor. The total floor area is about 310 m^2. The house is built in wood-frame structure and brick veneer. Figures 3-3 to 3-6 present the plans of floors and elevations of the house. The heating load of the house calculated is 11.09 kW at –23°C outdoor temperature and 21°C indoor design temperature. This house has been studied for energy performance by Kassab (2002).

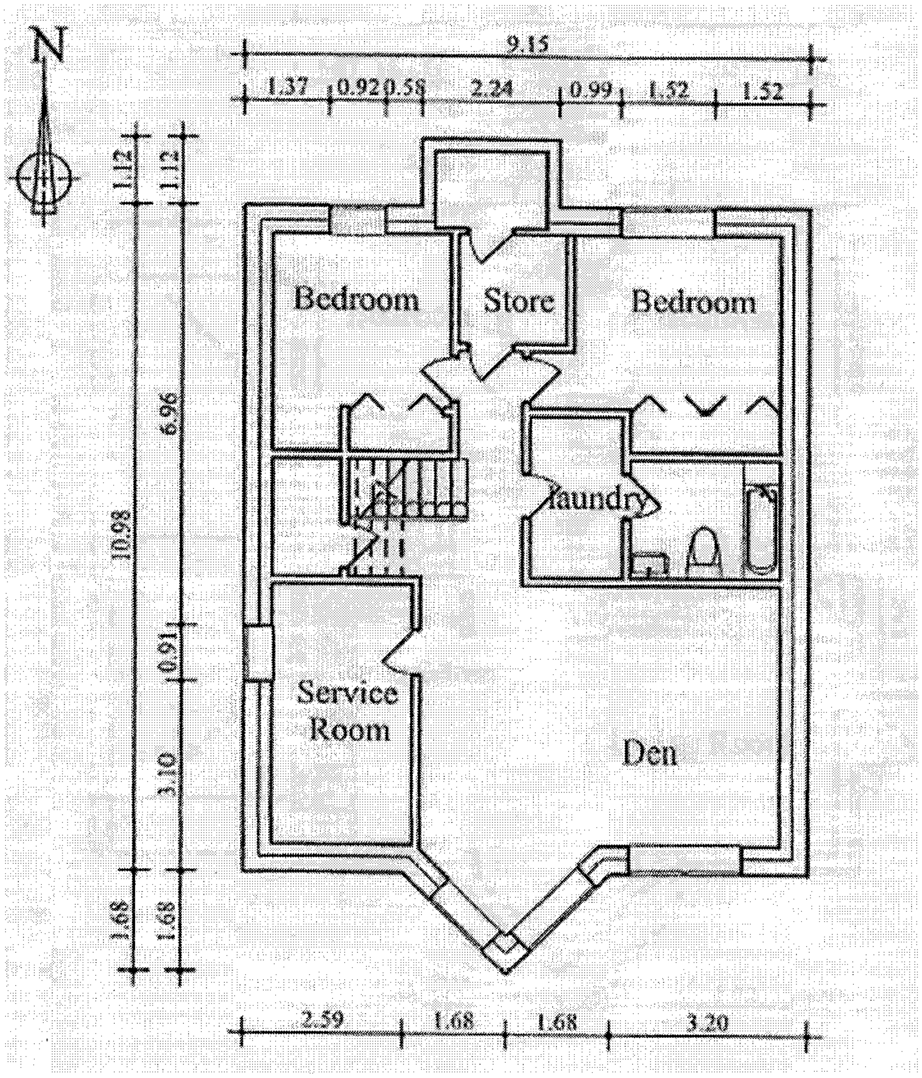


Figure 3-3 The basement plan (Kassab, 2002)

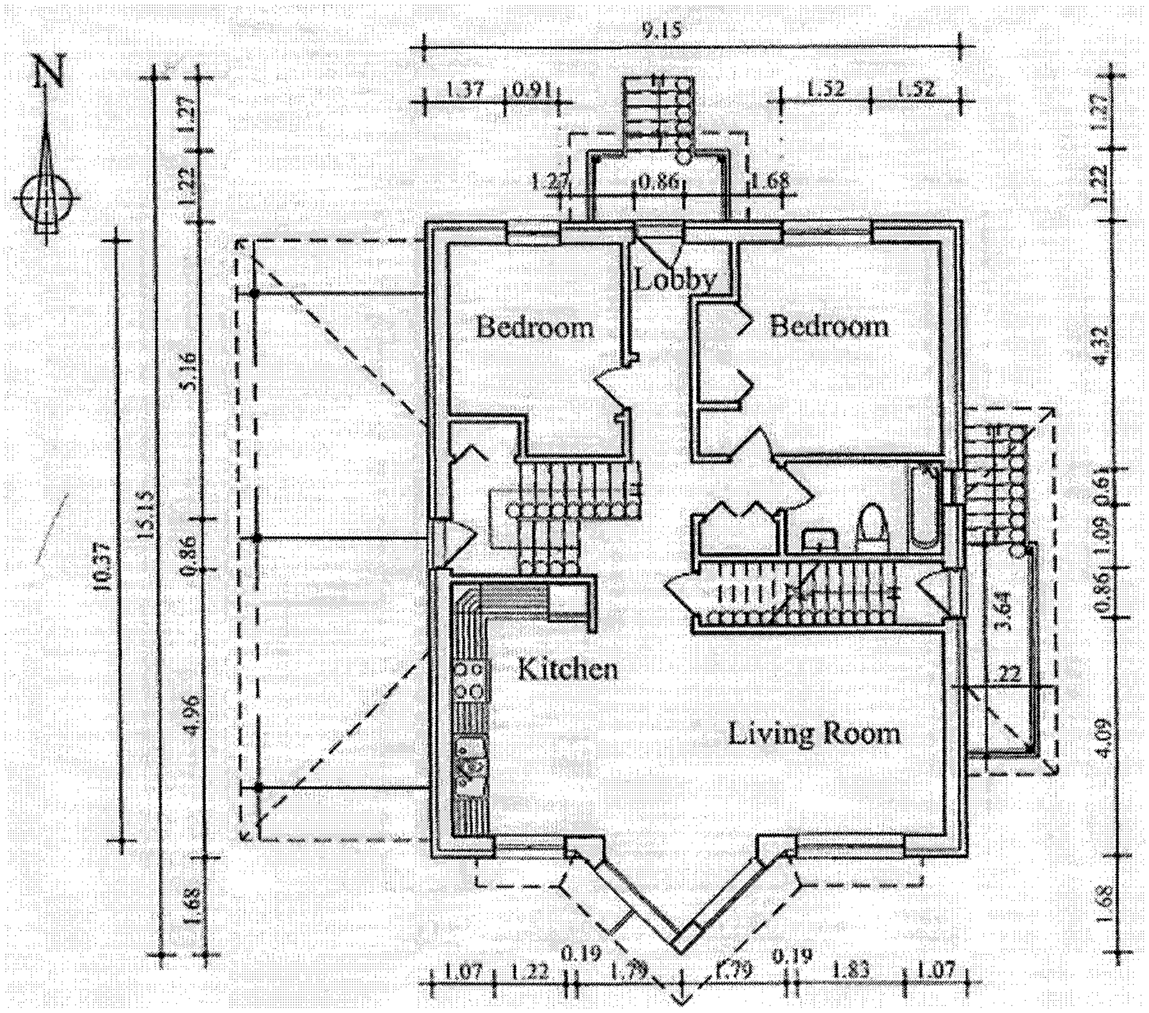


Figure 3-4 The ground floor plan (Kassab, 2002)

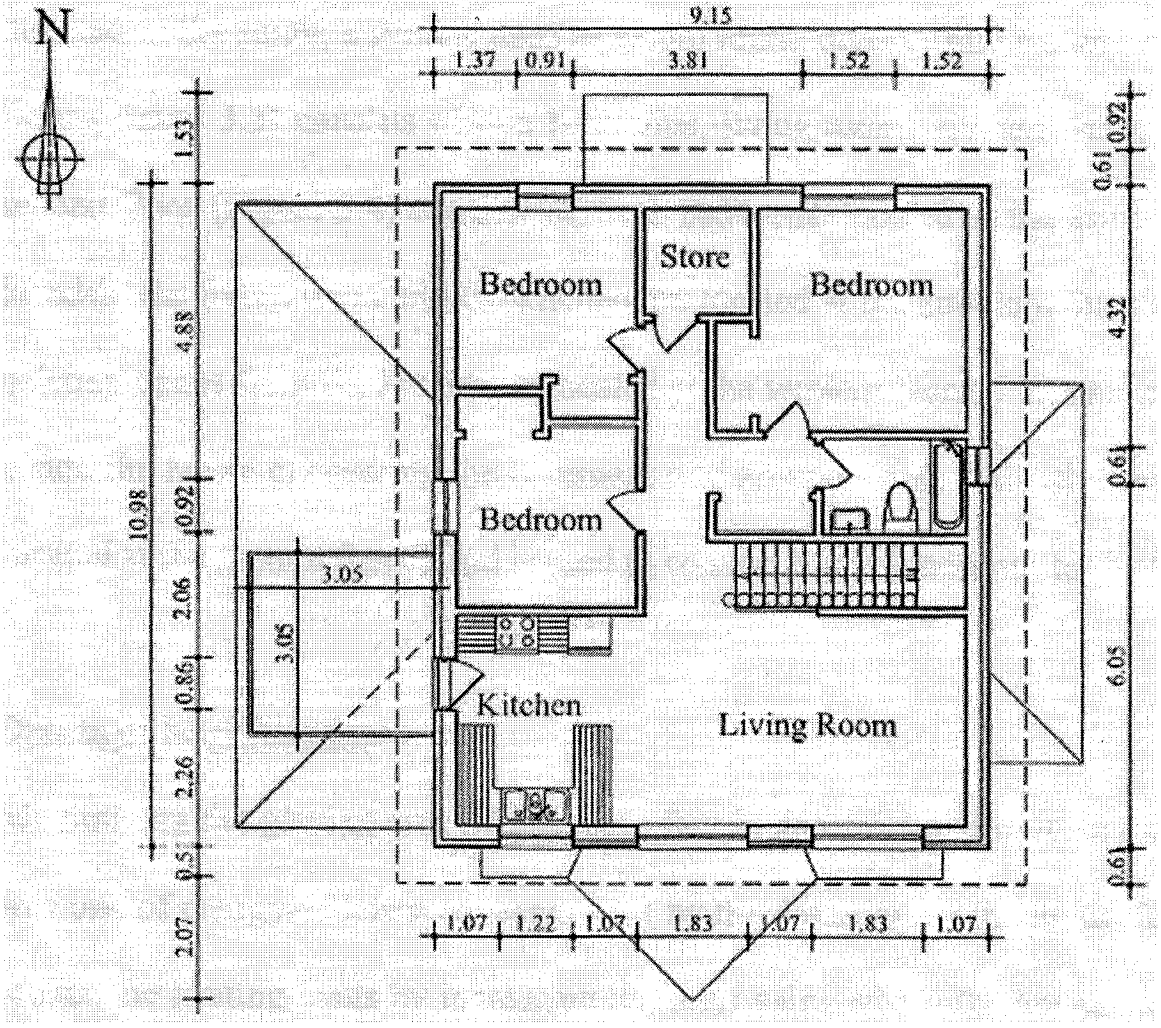
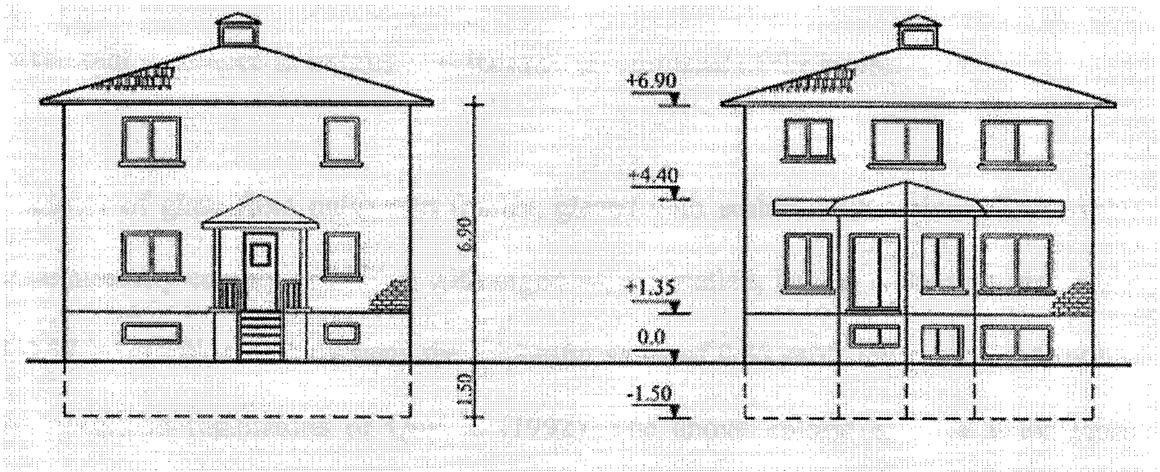
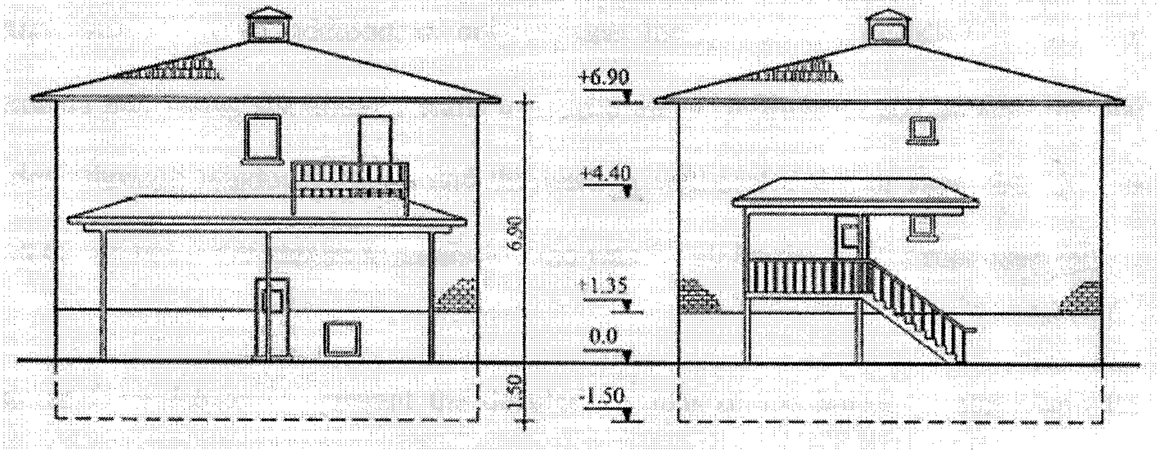


Figure 3-5 The first floor plan (Kassab, 2002)



Northern Facade

Southern Facade



Western Facade

Eastern Facade

Figure 3-6 The house facades (Kassab, 2002)

3.3 Design of the hot water heating (HWH) system with mechanical ventilation

For hot water heating, a two-pipe system is selected, which consists of copper pipes, a pump, radiators, an expansion tank and a boiler. By considering an oversize factor 1.1, the capacity of the boiler is selected at 12.2 kW, which is the closest value offered by manufacturers to satisfy the heating load. The design temperature of water leaving and entering the boiler is 90°C and 70°C according to ASHRAE (2000). The ventilating system, which consists of an air-to-air heat recovery unit and the electric pre-/re-heaters, is used to meet the indoor air quality requirement. The ventilating air exchange rate is assumed as 0.08 kg/s (0.066 m^3/s), which corresponds to 0.35 ach (ASHRAE-62, 2001). The ventilator (Model: SHR 2004) is selected from the manufacturer's catalogue (Fantech, 2005) with the following parameters: the net airflow 0.076 m^3/s at 0°C, the electrical power of 150 W, and the sensible efficiency of 62%.

In order to size the piping system, the water mass flow rate required by radiators must be first determined by using the following formula:

$$\dot{m}_w = \dot{Q}_{load}/(cp_w \cdot \Delta T) \tag{3-1}$$

where, $\dot{m}_w$ is the required mass flow rate of water, in kg/s;

$\dot{Q}_{load}$ is the heating load, in kW;

cp_w is the specific heat of water, in kJ/kg·°C;

ΔT is the temperature drop, in °C.

Because the specific heat of water is a constant at 4.2 kJ/kg·°C, the mass flow rate is

$\dot{m}_w = 11.09/(4.2 \times (90-70)) = 0.132$ kg/s.

The sizing of the piping system is based on a common sizing method—the equivalent length method, which satisfies that the flow resistance in a fitting or a valve is stated in terms of the pressure loss in the equivalent straight pipe (ASHRAE Handbook of fundamentals, 2001, Chapter 35). The sizing tables for the flow resistance in pipes and fittings provided by Curry (2001) are used for this propose in this system design.

There are 16 radiator assemblies, of which three assemblies are used for heating the bathrooms and the others are used for heating the various rooms (Figure 3-7). The tabular calculations are presented in Appendix-5. The piping design scheme of the system is illustrated in Figure 3-7, in which the actual measured lengths of the labeled straight pipes are indicated; and the equivalent lengths of the fittings and valves are given in the tabular calculation (Appendix-5).

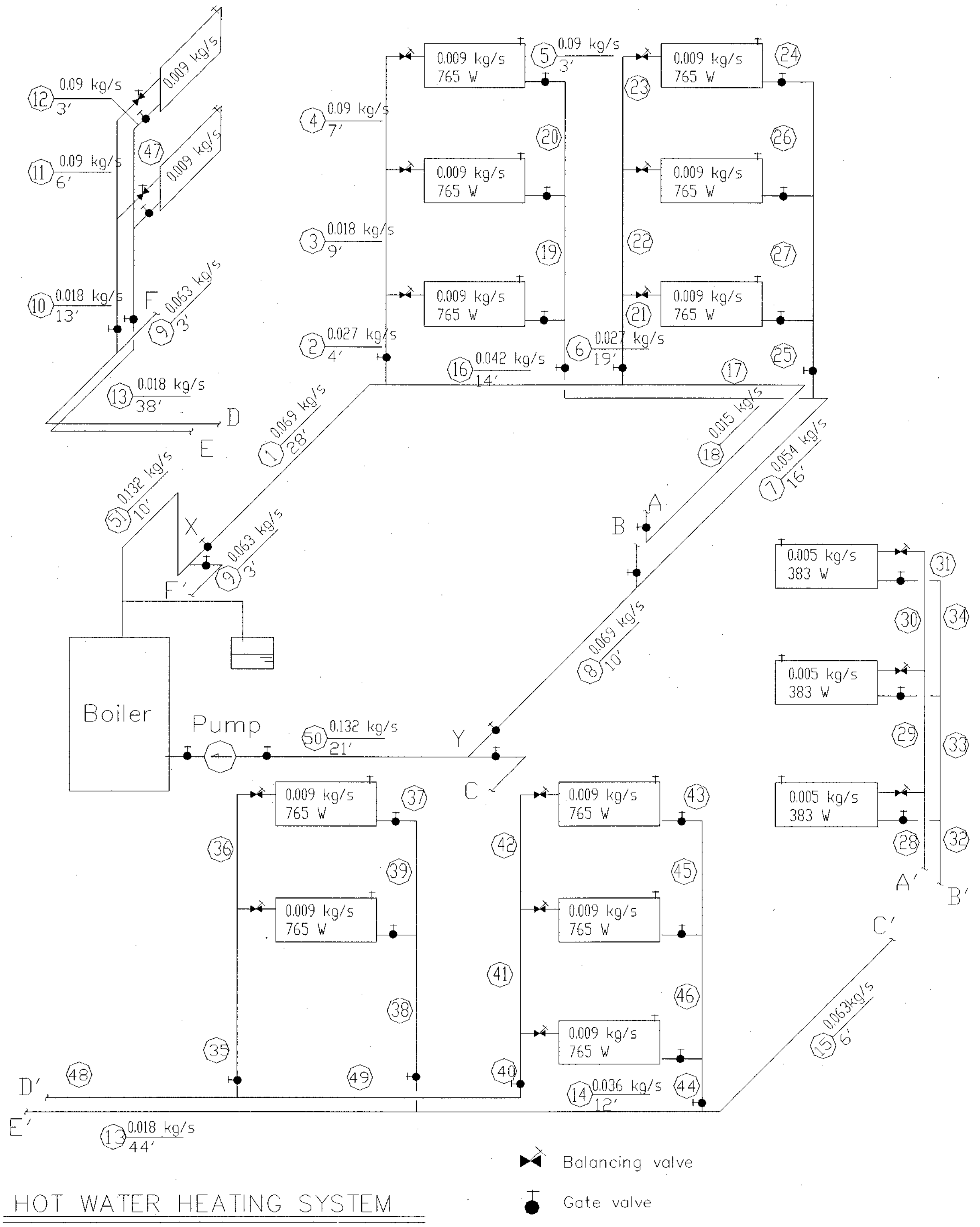


Figure 3-7 The hot water heating system design

The pressure loss in each pipe section is calculated as the product of the flow resistance per meter with the straight pipe measured length and the equivalent length of the fittings and valves. The total pressure loss is 1.87 m water column (18.5 kPa), which needs to be overcome by the pump to ensure the appropriate water circulation within the piping system. The detailed tabular calculation is shown in Appendix-5. So the shaft power of the pump is determined by using the following formula:

$$\dot{W}_{pump} = \dot{V}_{pump} \cdot \dot{P}_{loss} / (\eta_{pump}) \tag{3-2}$$

where, $\dot{W}_{pump}$ is the shaft power of the pump, in kW;

$\dot{P}_{loss}$ represents the total pressure loss in the piping system, boiler, and radiators, in kPa;

$\dot{V}_{pump} = \dot{m}_w / \rho_w$ is the volumetric flow rate of water circulated by the pump, in m^3/s;

ρ_W is the density of water, in kg/m^3 (ρ=971.8 kg/m^3 at 80°C and 101 kPa);

η_{pump} is the efficiency of the pump, (e.g., η_{pump}=0.5).

The shaft power of the pump is hence calculated at $\dot{W}_{pump}$ = (0.132/971.8) × 18.5/0.5 = 0.005 kW. The three computed parameters: the water flow rate (0.132 kg/s) through the pump, the pressure loss (18.5 kPa), and the shaft power (5 W) are used to select a pump from manufacturers' catalogues (Energy supermarket, 2005).

The amount of radiator sections calculated is 112 sections of 4-column cast iron radiator based on the manufactures' information (Colonialsupply, 2004). In addition, the expansion tank is selected with a size of 54 liters (Porges, 1982, pp.130) corresponding to the capacity of the heating system. The quantities of pipes and fittings are estimated based on the measured lengths or quantities from the design drawings and the information from available sources (see Appendix-4). Table 3-1 shows the resulting quantities of pipes and fittings as well as the ventilating system.

Table 3-1 The quantities of pipes and fittings

<table>
<tr><th colspan="2" rowspan="2">Component</th><th colspan="3">Nominal size (in.)</th><th rowspan="2">Mass (kg)</th></tr>
<tr><th>3/8</th><th>1/2</th><th>3/4</th></tr>
<tr><td>Pipe
(Copper)</td><td>Length (m)</td><td>107</td><td>13</td><td>26</td><td>69.4</td></tr>
<tr><td>Tee
(Copper)</td><td>Pieces</td><td>38</td><td>19</td><td>4</td><td>0.88</td></tr>
<tr><td>90° Elbow
(Copper)</td><td>Pieces</td><td>49</td><td>3</td><td>5</td><td>0.9</td></tr>
<tr><td>Strainer
(Cast Iron)</td><td>Pieces</td><td></td><td></td><td>1</td><td>1.35</td></tr>
<tr><td>Gate valve
(Bronze)</td><td>Pieces</td><td>24</td><td>2</td><td>2</td><td>7.9</td></tr>
<tr><td>Radiator
(Cast Iron)</td><td>Sections</td><td colspan="3">112</td><td>745</td></tr>
<tr><td>Pump
(Cast Iron)</td><td>Mass (kg)</td><td colspan="4">1.2</td></tr>
<tr><td>Expansion tank
(Steel)</td><td>Mass (kg)</td><td colspan="4">5.4</td></tr>
<tr><td>Ventilator
(Steel)</td><td>Mass (kg)</td><td colspan="4">27.5</td></tr>
<tr><td>Ducts Φ150
(Steel)</td><td>Length (m)</td><td colspan="3">6</td><td>29.3</td></tr>
<tr><td>Total mass (kg)</td><td></td><td colspan="3"></td><td>888.83</td></tr>
</table>

3.4 Design of the forced air heating (FAH) system

The forced-air heating system is another heating approach considered for this house. This system includes the following components: a furnace, the blower built within the furnace, ducts, and diffusers.

The following design parameters are considered: (1) the supplied air temperature is $T_{a,supplied} = 43^{\circ}C$; (2) the room air temperature is $T_{room} = 21^{\circ}C$; (3) the outdoor temperature at design conditions is $T_{out} = -23^{\circ}C$; (4) the ventilation air change rate is $\dot{m}_{a,fresh} = 0.08$ kg/s, which corresponds to 0.35 ach (ASHRAE-62, 2001) for the volume of the house of 868 m^3. By considering an oversize factor 1.1, the furnace capacity is selected as 16 kW to satisfy the design heating loads of 11.09 kW and ventilation load of 3.5 kW.

In order to size the ducts, the air mass flow rate required for the house must be determined by using the following formula:

$$\dot{m}_a = \dot{Q}_{load}/(cp_a \cdot \Delta T) \tag{3-3}$$

where, $\dot{m}_a$ is the required mass flow rate of air, in kg/s;

$\dot{Q}_{load}$ is the heating load of the house, in kW;

cp_a is the specific heat of air, in kJ/kg·°C;

ΔT is the temperature drop between the supplied air and room air, in °C.

Because the specific heat of air at standard indoor conditions of 20°C and 101.3 kPa is 1.006 kJ/kg·°C, the total mass flow rate is $\dot{m}_a = (11.09+3.5)/\ [1.006\times(43-21)] = 0.66$ kg/s. The volumetric air flow rate $\dot{V}_{blower}$ is also calculated at 0.55 m^3/s, corresponding to the density of the air $\rho_a = 1.204$ kg/m^3.

The system layouts in the basement and the ground floor are shown in Figures 3-8 and 3-9. In Figure 3-10, the system scheme shows the measured length and the air flow rate for each duct section. The equal friction method (ASHRAE, 2000) is used for sizing the ductwork system. The detailed calculations are presented in Appendix-5.

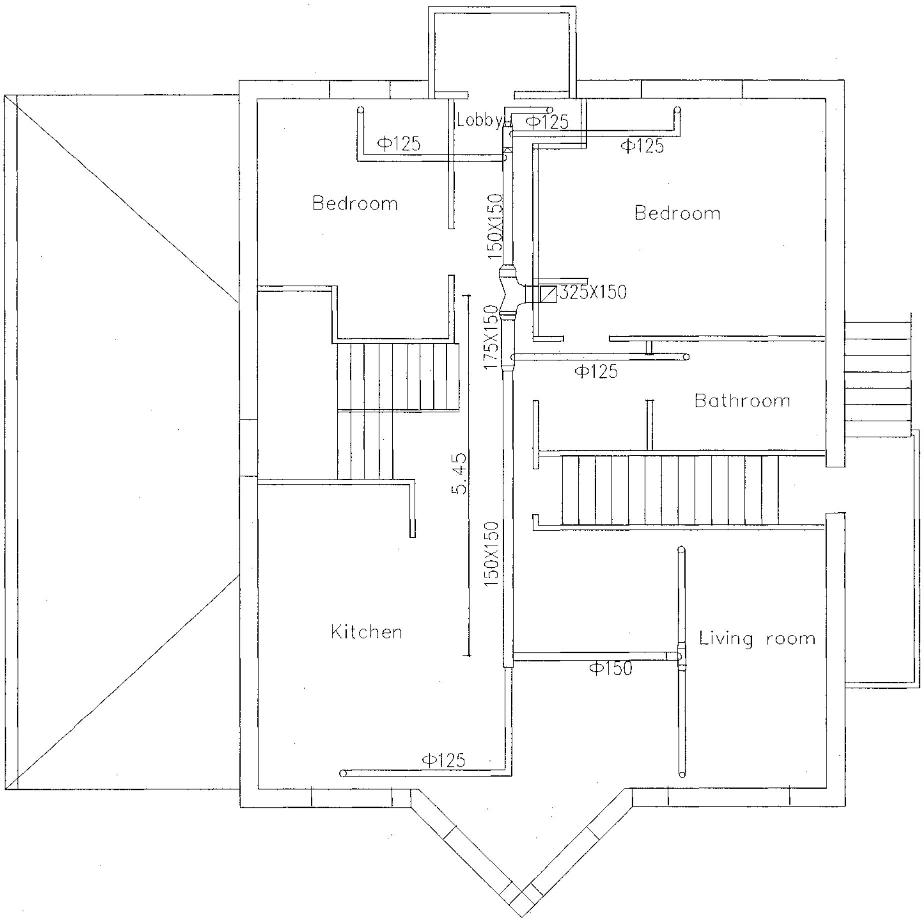


Figure 3-8 Ground floor plan ductwork layout

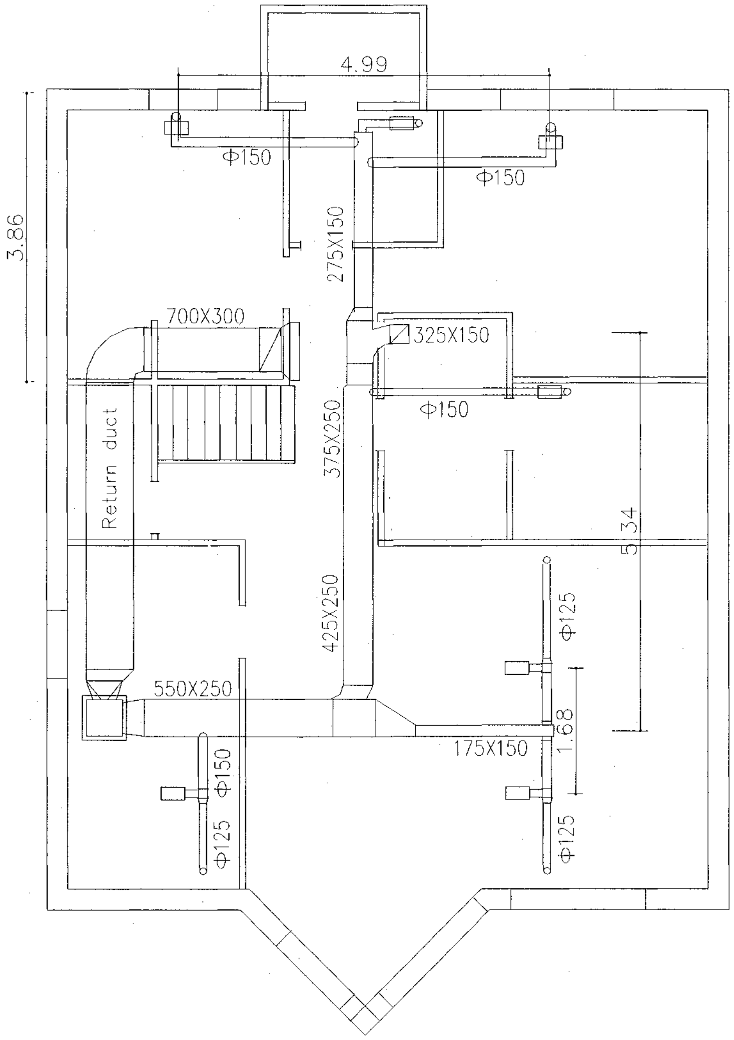


Figure 3-9 Basement plan ductwork layout

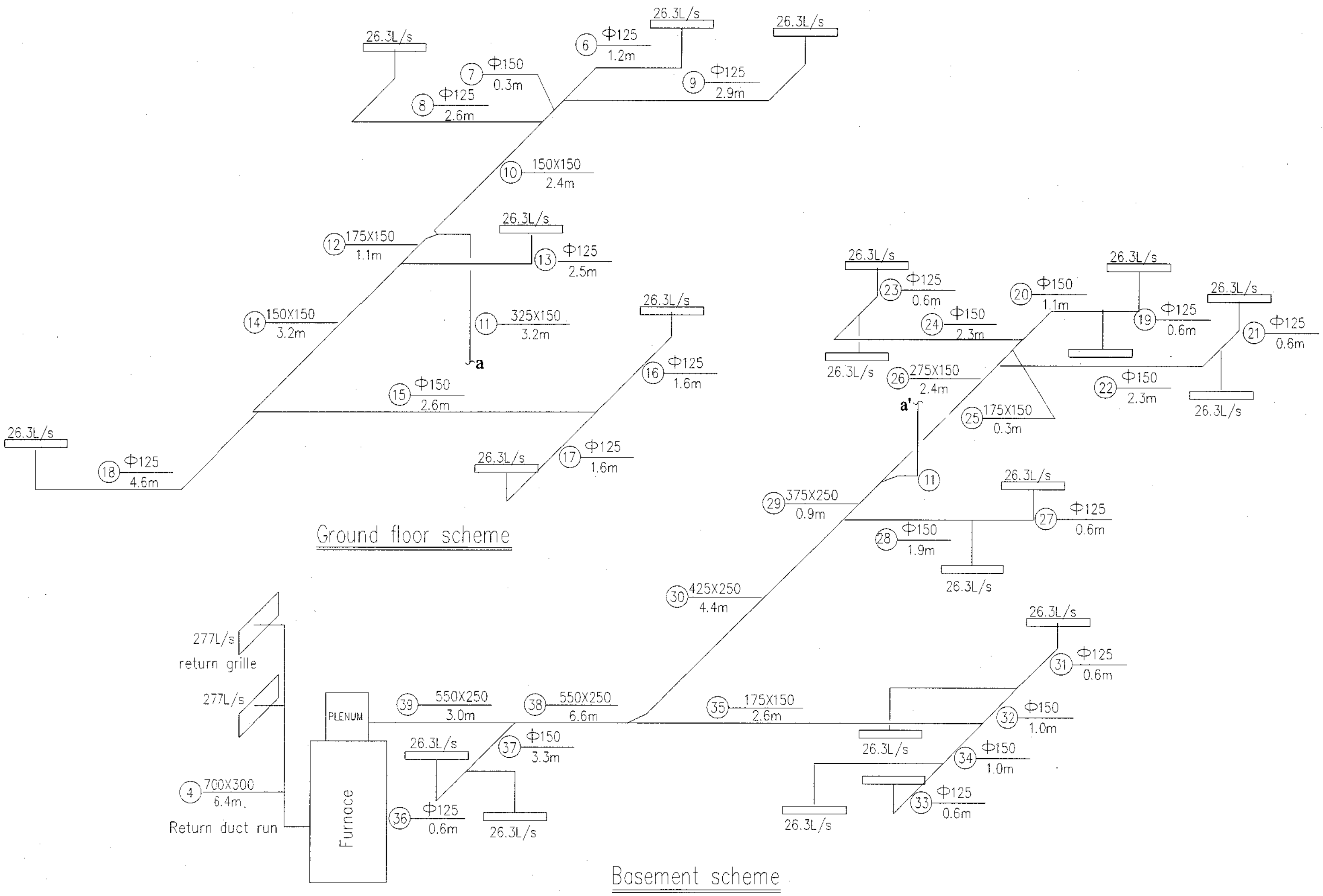


Figure 3-10 Ductwork schematic design

The total pressure loss in the critical path, which refers to the path of the numbered ducts 14, 18, 12, 11, 29, 30, 38, and 39 indicated in Figure 3-6, is calculated at 109 Pa; while the pressure loss in the return ducts is 7.5 Pa. Assuming that the pressure losses in the supply and return registers are 7.5 Pa and in the box plenum is 13 Pa (ASHRAE, 2000), the total pressure loss is thus 137 Pa. The system volumetric air flow rate $\dot{V}_{blower}$ is 0.55 m^3/s.

Based on these results, the blower power can be determined. The dimension of the blower outlet is selected at 250×200 mm (10×8 inch) based on a manufacturer's data (York gas furnace, Appendix-4). The outlet velocity and the velocity pressure loss can be then determined by using the following formulas:

$$\dot{v} = \dot{V}_{blower} / A \tag{3-4}$$

$$P_V = \frac{\rho_a}{2} \cdot \dot{v}^2 \tag{3-5}$$

where,

$\dot{v}$ is the outlet velocity, in m/s;

$\dot{V}_{blower}$ is the volumetric air flow rate in m^3/s;

A is the outlet area of the blower, in m^2;

P_V is velocity pressure, in Pa.

The blower outlet velocity $\dot{v}$ obtained is 11 m/s, and the velocity pressure P_V is equal to 72.8 Pa. The static pressure loss $\dot{P}_{loss}$ equals to 137 – 72.8 = 64.2 Pa. The shaft power of the fan is calculated by using the following formula:

$$\dot{W}_{blower} = \dot{V}_{blower} \cdot \dot{P}_{loss} / \eta_{blower} \qquad (3\text{-}7)$$

where,

$\dot{W}_{blower}$ is the shaft power of the blower, in W;

$\dot{P}_{loss}$ is the static pressure loss, in Pa;

η_{blower} is the blower efficiency assumed to be 50%.

The shaft power of the fan is found to be 71 W.

3.4.1 The mass estimation of the FAH system

The quantities of the materials used in the forced air heating system are estimated based on the system design. The masses of the ducts, the fittings, the dampers, the hangers, and the ventilator are estimated in this chapter (Table 3-2). The mass of the ventilator is obtained from the manufacturer's data (Fantech, 2005). The masses of materials for the furnace with the built-in blower are evaluated in Chapter 5.

The mass of the ducts is estimated based on the measured length, the thickness of the steel sheet, and the density of the material. The total mass of the ducts is 310 kg. The detailed calculations are presented in Appendix-5.

The mass of the fittings are obtained in two ways. In the first way, the mass per fitting is obtained from the manufacturer's catalogue (Frapol, 2004). In the second way, the mass per fitting is calculated with the product of the calculated surface area A_s of the fitting, the thickness of the steel sheet, and the density of the material. The calculating formulas of the surface areas of the fittings, which the manufacturer's data are not available, are given in Appendix-5. The total mass of fittings is 90 kg. The detailed calculations are presented in Appendix-5.

The total mass of the balancing dampers, which are placed at the point before each branch duct is connected to the main ducts, is 12.4 kg. The detailed data are presented in Appendix-5.

The hangers for rectangular ducts are designed in accordance to the HVAC duct construction standards (SMACNA, 1985). The hangers are installed at each joint of the main ducts. Each terminal also needs a hanger. The hangers are made of hot-rolled steel straps (1" × 22 gages; 25.4 mm × 0.759 mm) for rectangular ducts; while the hangers are made of the steel wires (12 gages, diameter 2.657 mm) for round ducts, respectively. The total mass of hangers is 3.0 kg. The detailed calculations are presented in Appendix-5.

Table 3-2 summarizes the data for the masses of the materials used in the forced air heating system. The mass of the ventilator is also included. The masses of the furnace and the blower will be discussed in Chapter 4.

Table 3-2 The mass of the materials used in the forced air heating system

Component		Material	Mass (kg)
Ducting system	Duct	Galvanized steel	309.8
	Fittings (including elbows, tees, transitions, diffusers, dampers)	Galvanized steel	102.6
	Hangers	Hot-rolled steel	3
Ventilator	Model: SHR 2004	Galvanized steel	27.7
Total			443

CHAPTER 4

EVALUATION OF EMBODIED ENERGY AND GHG EMISSIONS IN BOILERS AND FURNACES

Due to the lack of detailed information about the composition (type of materials and quantities) of the heating heavy equipment (i.e. the boilers and furnaces), a model of decision under uncertainty is used in order to estimate their embodied energy and greenhouse gas emissions related to the manufacturing of boilers and furnaces.

4.1 Decision models under uncertainty

A decision model is a systematic framework that considers all aspects of a decision problem. In the present study, a payoff matrix model is used to deal with uncertain information. A set of decision alternatives for material composition is established under possible combinations. A set of alternatives are compared by using an evaluation method and those with the minimum/maximum consequences under any possible states of nature are selected.

"A payoff matrix model, in general, describes a set of alternatives available where a single alternative is to be selected at the present time. It is implied that the outcomes possible for a given alternative do not necessitate decisions at future time" (Szonyi et al., 1982). It has the following basic elements: feasible alternatives, states of nature, probabilities of states of nature, and outcomes of alternatives against each state of nature. The decision alternatives should represent the total set of alternatives that the decision maker may wish to consider. In a payoff matrix model shown in Table 4-1, the mutually exclusive feasible alternatives are the combinations of various metals, which can be used in the manufacturing of equipment. This information is generated by compiling data from technical literature (e.g. manufacturers' catalogues, textbooks). The states of nature are defined as a finite set of combinations of the mass of different components in the total mass of equipment. The outcomes of alternatives against each state of nature are the embodied energy and embodied emissions values due to the manufacturing of the equipment. For example, the alternative 1 means that the equipment under study is composed of n components (n=1, 2... n), which are made of the different materials (MC_1, MC_2 ...MC_n). State of nature j indicates the contribution of each material to the total mass of equipment. For instance, the material C_1 accounts for P (C_1) [%] of the total mass, the material C_2 accounts for percentage P (C_2) [%] and so on. The following condition applies $\Sigma P(C_i) = 100\%$.

Table 4-1 The payoff matrix model

Design alternatives	**States of nature**			
	1	2	……	j
	$P(C_1)$ $P(C_2)$ … $P(C_n)$	$P(C_1)$ $P(C_2)$ … $P(C_n)$		$P(C_1)$ $P(C_2)$ … $P(C_n)$
	$\Sigma = 1$	$\Sigma = 1$	……	$\Sigma = 1$
Alternative1 (MC_1, MC_2, …, MC_n)	$EE_{1,1}$ $(CO_2)_{1,1}$		……	
Alternative2				
Alternative3				
…				
Alternative i				$EE_{i,j}$ $(CO_2)_{i,j}$

The first outcome, the embodied energy in the equipment is expressed as:

$$EE_{i,j} = W_0 \cdot \Sigma[P(C_n) \cdot ee(MC_n)] \tag{4-1}$$

The second outcome, the CO_2 emissions due to the manufacturing of equipment, is expressed as:

$$(CO_2)_{i,j} = W_0 \cdot \Sigma [P(C_n) \cdot CO_2(MC_n)] \tag{4-2}$$

where,

$EE_{i,j}$ is the embodied energy of the design alternative i under state of nature j, in MJ;

$(CO_2)_{i,j}$ is the equivalent CO_2 emissions for the design alternative i under state of nature j, in $kgCO_2$;

W_0 is the total mass of equipment, in kg;

$ee(MC_n)$ is the unit embodied energy of material n, in MJ/kg;

$CO_2(MC_n)$ is the unit equivalent CO_2 emissions due to the manufacturing of material n, in $kg \cdot CO_2/kg \cdot$material.

4.2 Criteria for the decision making under uncertainty

The decision-making criteria used in the study are the maxi-max criterion, maxi-min criterion, mini-max criterion, mini-min criterion, Laplace criterion, and Hurwicz criterion in order to illustrate the range of the payoffs with different criteria. A brief description of these criteria (Szonyi et al., 1982) is given here:

a. Maxi-max—the decision maker selects the decision that will result in the maximum of the maximum payoffs.

b. Mini-min—the decision maker selects the decision that will result in the minimum of the minimum outcomes.

c. Maxi-min—the decision maker selects the decision that will result in the maximum of the minimum outcomes.

d. Mini-max—the decision maker selects the decision that will result in the minimum of the maximum payoffs.

e. Laplace principle—each state is assigned equally likelihood. The alternative is selected based on the arithmetic average. According to the Laplace principle, if the probability of occurrence of each state of nature is unknown, the states should be considered as equally probable. Then, the expected values for each alternative under all the equally likely states are calculated as the following formula:

$$E\left[U\left(a_i\right)\right] = \sum_j EE_{ij} P\left(\theta_j\right) \tag{4-3}$$

where,

$E\left[U\left(a_i\right)\right]$ is the expected value of outcome of each alternative a_i, under all possible states of nature θ_j,

EE_{ij} is the outcome of each alternative a_i under state θ_j,

$P(\theta_j)$ is the assigned equal probability for each state θ_j,

i is the index of design alternatives,

j is the index of the possible states.

Based on the results obtained from formula (4-3), the decision can be further considered as under risk.

f. Hurwicz principle brings a compromise between the maximum and minimum criteria. Payoff values are weighted using a coefficient of optimism α, which measures the decision maker's optimism regarding the outcomes of the alternatives. Under different optimistic factors α (0< α <1), the Hurwicz criterion is applied here to estimate the ranges of outcomes between the most optimistic view (α =1) and the most pessimistic view (α =0). The mathematical expressions are:

$$\min_i \left\{ (1-\alpha) \max_j EE_{ij} + \alpha \min_j EE_{ij} \right\} \tag{4-4}$$

$$\max_i \left\{ (1-\alpha) \max_j EE_{ij} + \alpha \min_j EE_{ij} \right\} \tag{4-5}$$

4.3 Boilers

There is a high level of uncertainty in evaluating the life cycle environmental impact of residential heating boilers due to the lack of detailed manufacturers' data. Hence, the present study adopts the payoff matrix model to estimate the embodied energy and associated equivalent CO_2 emissions for a boiler in the absence of complete information. The type of boiler selected is the natural gas-fired hot water non-condensing boiler. The boiler's capacity is 12.2 kW as estimated in Chapter 3.

4.3.1 Materials

The definition of a boiler according to the ASHRAE handbook (ASHRAE, 2000) is a cast-iron, steel, aluminum, or copper pressure vessel heat exchanger designed to (1) burn fossil fuels (or use electric current) and (2) transfer the released heat to water (in water boilers) or to water and steam (in steam boilers). Boilers are divided into seven major components (Grimm and Rosaler, 1990): (1) fuel burner, (2) mechanical draft system (forced or induced), (3) external insulation (usually with casing or jacket), (4) refractory, (5) trim (gauges, safety or relief value, and water-column), (6) panel-mounted controls and (7) interconnecting piping and complete wiring.

The basic structure (Brumbaugh, 1976) of a residential heating boiler fired by fossil fuels consists of an insulated steel jacket enclosing a lower chamber in which the combustion process takes place and an upper chamber containing cast iron sections or steel tubes in which the water is heated or converted to steam for the circulation of water through the pipes of the heating system. "Most non-condensing boilers are assembled of cast iron sections or steel parts. Some small boilers are made of copper or copper-clad steel (ASHRAE, 2000). For a gas-fired boiler, the gas burners are most frequently made of cold-rolled steel coated with high temperature paint or with a corrosion resistant material such as stainless or aluminized steel in order to meet the corrosion protection requirements. The burners sometimes are also made of cast iron (Brumbaugh, 1976). The heat exchangers of a residential heating boiler are commonly designed in cast iron sections and steel tubes. Parallel finned copper tube coils with headers, and serpentine copper tube units are most common in the copper boiler, which are usually some variation of the water-tube boiler.

4.3.2 Assumptions

Usually the dimensions and shipping weight are easily obtained from manufacturers' documents. However, this is not sufficient for the calculation of embodied energy and GHG emissions. Therefore, based on the descriptions in the literature above, the following four components of the boiler need to be considered: the heat exchangers, the burners, the draft blower, and the casing (body jackets with insulation layers). The following assumptions are made:

1. Electrical and control systems as well as accessories, which are difficult to break up into different materials, are not considered in this study. Their contributions are assumed to be 10% of the total mass.
2. The casing jacket is made commonly of heavy gauge steel (Beaty, 1987) with various finishes in most boilers. The quantities of materials for the jacket can be roughly calculated by using the boiler's dimension and the material densities. The jackets are commonly made with a plate thickness of 2.0 mm (Beaty, 1987) which has a density of 7850 kg/m^3 for steel and 7900 kg/m^3 for stainless steel.
3. Insulation layer of 25.4 mm (1") thick fiberglass (Beaty, 1987) is commonly used in most boilers (density of fiberglass 32 kg/m^3). The mineral wool of the same thickness is assumed as an alternative.
4. The most important part of a boiler is the heat exchanger which can possibly be made of cast iron, steel, copper or copper alloy and aluminum (ASHRAE, 2000).
5. The burner is usually made of cast iron, steel (Brumbaugh, 1976, ASHRAE, 2000), or stainless steel (Beaty, 1987; Brumbaugh, 1976).

4.3.3 Design alternatives

The design alternatives in the payoff matrix are defined by the combinations of the components made of different materials. The heat exchangers are possibly made of the five kinds of metals mentioned in the literature: cast iron, steel, stainless steel, copper, or aluminum. The burners are possibly made of three types of metals: stainless steel, steel, or cast iron. The draft blower can be made of stainless steel or steel. The casing or body jackets can be made of steel or stainless steel. Two types of insulation materials, fiberglass or mineral wool can be used. All of these materials used in the components are combined to define a set of design alternatives. The total number of alternatives is 5*3*2*2*2=120. The feasibility of each alternative is not established due to the lack of manufacturing information. The selected design alternatives cover a wide range of possible combinations. A code is used to clearly identify each alternative. Each material for each component is defined as shown in Table 4-2. For instance, an alternative is coded as 1232a, it indicates that the boiler that has a cast iron heat exchanger (code 1), steel burners (code 2), a stainless steel draft blower (code 3), and steel jackets (code 2) with fiberglass insulation (code a).

Table 4-2 Codes of materials of component

HEX		Burner		D-blower		Casing		Insulation	
1	Cast iron	1	Cast iron					**a**	Fiberglass
2	Steel	2	Steel	2	Steel	2	Steel	**b**	MineralW.
3	StlS	3	StlS	3	StlS	3	StlS		
4	Copper								
5	Aluminum								

Note: "HEX" refers to heat exchanger, "D-blower" refers to draft blower; "StlS" refers to stainless steel; "MineralW." refers to mineral wool.

4.3.4 States of nature

The states of nature are defined as the combinations of various percentages representing the participations of different components to the total mass of the equipment. The estimates of mass percentage are based on the calculation of nine boilers (see Appendix-6) produced by four manufacturers (Viessmann, Burham, Olsen, and HydroTherm).

The casing mass can be calculated first using the boiler dimensions and data (density of 7850 kg/m^3 for steel and 7900 kg/m^3 for stainless steel, with a thickness of 2 mm). The Formula (4-5) below is used to estimate the casing mass.

$$M_C = 2\times\left[H\cdot(W+D)+W\cdot D\right]\cdot Th\cdot\rho \tag{4-6}$$

where,

M_C is the casing mass, in kg;

H is the height of the boiler, in m;

W is the width of the boiler, in m;

D is the depth of the boiler, in m;

Th is the thickness of the boiler casing, in m; and

ρ is the density of material, in kg/m^3.

Since some parts (such as control or electric parts) of the boiler are excluded from the calculation, the estimated weight of the components should be slightly less than the actual total mass of the boiler. On the other hand, since the openings or holes in the jackets are not considered in the calculation, the actual volume of the jacket is less than the estimated volume. The results are presented in Table 4-3.

Table 4-3 The estimated masses of different boiler casings

	*Boiler 1	Boiler 2	Boiler 3	Boiler 4	Boiler 5	Boiler 6	Boiler 7	Boiler 8	Boiler 9
Manufacturer	Hydro Therm	Viessmann	Viessmann	Oslen	Oslen	Oslen	Burnham	Burnham	Burnham
Output (kW)	15.2	15	16	13	12.3	13	15.2	15.2	15
Actual total mass (kg)	121	101	106	100	92	142	123	120	158
Height (m)	0.628	0.663	1.003	1.002	0.781	0.781	0.790	0.914	1.016
Width (m)	0.333	0.500	0.340	0.711	0.286	0.380	0.628	0.368	0.368
Depth (m)	0.826	0.780	0.502	0.502	0.686	0.686	0.304	0.628	0.635
Estimated jacket volume (m^3)* 10^{-3}	4.012	4.955	4.061	6.289	3.821	4.373	3.709	4.566	5.011
Estimated jacket mass (kg)	28.3	38.9	31.9	49.4	30.0	34.3	29.1	35.8	39.3

Note: *the casing of boiler1 is made of stainless steel casing finish; other boilers' casings are made of steel.

Data for the draft blower could not be found in the corresponding boilers' manufacturer catalogue, so substituted equipment is used. The mass of the draft blower (model DJ-3) from TJERNLUND is 3.3 kg (Grainger, 2004) for boilers of capacity varying from 20 kW to 29 kW. This draft blower seems bigger than what is required, but this is the smallest one available in its category from this manufacturer.

The mass of the burner is calculated by using the data for the 15 kW gas-fired boiler (Boiler8) produced by Burham, a boiler's manufacturer. There are two 25.4 mm (1") main burner tubes and two 40 mm burner tubes. The lengths of them are estimated to be 600 mm by considering some clearance according to the 628 mm depth of the boiler, and the wall thickness is assumed to be 3 mm. The material of the burners is stainless steel, and the density is 7900 kg/m^3. So the mass of these burners is approximately 7.2 kg.

Since the insulation material (see section 4.2 Assumption 4) is usually integrated with the boiler jacket, the same calculation procedure is used for the insulation material as for the jackets. Based on these data, the contribution of each major component to the boiler is estimated as shown in Table 4-4.

Table 4-4 The estimated masses of major components of the boiler

Components	Mass (kg)	%
Heat exchanger	51.7-96.6	45-65
Burners	7.2	5-7
Draft blower	3.3	2-4
Casing (jackets)	28.3-49.4	25-42
Insulation	0-1.5	0-2
Total	92-158	100

Note: the boiler's capacity is 12.2 kW.

The selection of a representative set of states of nature is in fact the discretization of the problem with regard to usually continuous input data. In the domain of states it is necessary to choose a finite number of points that characterize sufficiently well the set as a whole. This operation requires great attention as the completeness and reliability of subsequent analysis depends on how properly this choice is made (Belyaev, 1990). However, the specific percentage corresponding to each component is unknown. The distribution of the percentages is assigned as the scale interval of 5% corresponding to the mass percentage range of the heat exchanger out of the total mass. Considering the possible errors in the input values, a broadened range (45%-75%) is used instead of the range indicated in Table 4-4 for heat exchanger. Another condition extracted from Table 4-4 is that the contribution of mass of the heat exchanger should be greater than that of the casing component in the total mass of the boiler. Several states of natures are then assumed as shown in Table 4-5.

Table 4-5 State of nature (Distribution of mass contribution)

	State of nature						
Heat exchanger	0.45	0.5	0.55	0.6	0.65	0.7	0.75
Burners	0.07	0.05	0.07	0.06	0.05	0.06	0.05
Draft blower	0.04	0.03	0.04	0.02	0.02	0.03	0.02
Casing (jackets)	0.42	0.4	0.34	0.31	0.27	0.21	0.17
Insulation	0.02	0.02	0	0.01	0.01	0	0.01
	Σ=1	Σ=1	Σ=1	Σ=1	Σ=1	Σ=1	Σ=1

The calculation of the payoff matrix is programmed by using the EXCEL worksheets presented in Appendix-7 for embodied energy and Appendix-8 for equivalent CO_2 emissions. The input data, outcomes, and criteria applied to the payoff matrix are the followings:

- Input data: The total mass of boiler (according to Section 4.2 Assumption 1), mass percentages of each component.
- Outcomes: embodied energy, equivalent CO_2 emissions.
- Criterion: Laplace principle, Mini-min principle, Maxi-min principle, Mini-max principle, Maxi-min principle, and Hurwicz principle.

4.3.5 Results and Discussion

Based on the developed payoff matrix model, the variations of the embodied energy and the GHG emissions due to the manufacturing processes of the gas-fired heating boilers in their production stages affected by the types of metal used and the corresponding quantity are presented. The calculations in this case (see Appendices 7 and 8) show that the heat exchanger made of aluminum or copper contains much higher embodied energy than those of cast iron, stainless steel, or steel because of the higher embodied energies in aluminum and copper. Hence, the stainless steel components have less embodied energy because of the lower embodied energy value. The specific embodied energy and equivalent CO_2 emissions values for the calculation are estimated in Table 4-6, in which these data are extracted from Appendices 2 and 3.

Table 4-6 Specific embodied energy & equivalent CO_2 emissions values

Material	Embodied energy		Equiv. CO_2 emissions	
	(MJ/kg)	Reference	(kg·CO_2/kg)	Reference
Cast iron	32.8	12	*2.4	N/A
Steel	28.8	11	2.1	12
Steel, *recycled*	14.1	11	N/A	N/A
Stainless steel	16.3	11	1.2	12
Copper	48.7	11	6.1	12
Copper, *recycled*	40-50	3	N/A	N/A
Aluminum	207	11	10	12
Aluminum, *recycled*	8.1	1	N/A	N/A
Brass	62	1	*4.5	N/A
Fiberglass	24.5	12	1.5	22
MineralW	15.6	12	*1.0	N/A
PVC	70	1	3	9

Note: 1. values* are calculated, e.g. equiv. CO_2 emission value of cast iron is assumed proportional to that of steel. 2. Reference numbers indicated in Appendices 2 and 3

If primary materials are used, among the 120 design alternatives, the range of embodied energy varies from the lowest value of 2,440 MJ for the design alternative 3333b, which represents the boiler made of stainless steel (heat exchanger, burner, draft blower, and body jacket) and mineral wool as insulation material, up to the highest value of 24,400 MJ for the design alternative 5122a, which represents the boiler made of aluminum (heat exchanger, cast iron burner, steel draft blower, and steel body jacket) and glass fiber as insulation material; the range of equivalent CO_2 emissions varies from the lowest value of 179 kg equivalent CO_2 for the design alternative 3333b up to the highest value of 1,205 kg equivalent CO for the design alternative 5122a.

If recycled materials are used, the modeling results will vary significantly. For example, the embodied energy value of recycled aluminum is 8.1 MJ/kg compared with 207 MJ/kg for virgin aluminum (Baird et al., 1997). Only the embodied energy values for the recycled steel (14.1 MJ/kg), copper (45 MJ/kg), and aluminum (8.1 MJ/kg) are found in the literature (see Table 4-6). The range of embodied energy in this situation is between 1,440 MJ for the design alternative 5222b, which represents a boiler made of aluminum (heat exchanger, steel burner, steel draft blower, and steel body jacket) and of mineral wool as insulation material, and 5,800 MJ for the design alternative 4123a, which represents the boiler made of copper (heat exchanger, cast iron burner, steel draft blower, and stainless steel body jacket) and of glass fiber as insulation material. However, due to the lack of detailed data for all recycled materials, this scenario is not considered at this moment.

In the payoff matrix, the design alternative 3333b yields the minimum outcome, and the design alternative 5122a yields the maximum outcome. Those alternatives with outcomes between 125% of the design alternative 3333b and -125% of the design alternative 5122a are selected for further analysis. There are twenty-four selected design alternatives in this range (see Table 4-7) where present the minimization and maximization problems. Tables

4-8 and 4-9 present the values of the embodied energy and CO_2 emissions evaluated under the maximin, maximax, minimax, and minimin criteria. Each subset of design alternatives is grouped in terms of material used for the corresponding heat exchanger. Since the analysis is dealing with a high uncertainty, the outcomes of the payoff matrix are reasonably rounded to three digits.

Table 4-7 The selected design alternatives

Minimization					vs.	Maximization				
3	1	2	3	a		5	1	2	2	a
3	1	2	3	b		5	1	2	2	b
3	1	3	3	a		5	1	3	2	a
3	1	3	3	b		5	1	3	2	b
3	2	2	3	a		5	2	2	2	a
3	2	2	3	b		5	2	2	2	b
3	2	3	3	a		5	2	3	2	a
3	2	3	3	b		5	2	3	2	b
3	3	2	3	a		5	3	2	2	a
3	3	2	3	b		5	3	2	2	b
3	3	3	3	a		5	3	3	2	a
3	3	3	3	b		5	3	3	2	b

Table 4-8 The embodied energy (MJ) with the different criteria for the design alternatives based on heat exchangers made of different materials

Criterion	Heat exchanger material				
	Cast iron	Steel	Stainless steel	Copper	Aluminium
Maximin	4,620	4,340	2,940	5,700	16,400
Maximax	4,800	4,360	3,500	6,590	24,400
Minimin	3,560	3,290	2,440	4,630	15,300
Minimax	4,300	3,850	2,450	6,090	23,900

Table 4-9 The equivalent CO_2 emissions (kg·CO_2) with the different criteria for the design alternatives based on heat exchangers made of different materials

Criterion	Heat exchanger materials				
	Cast iron	Steel	Stainless steel	Copper	Aluminium
Maximin	337	316	215	586	850
Maximax	350	318	256	766	1,205
Minimin	260	240	179	510	773
Minimax	315	281	180	731	1,170

The estimated range of variation of environmental impact, according to the different decision criteria are shown in Table 4-10 for the embodied energy and in Table 4-11 for the equivalent CO_2 emissions.

Table 4-10 The ranges of payoff matrix outcomes for embodied energy

Heat exchanger material	Criterion	Range (MJ)	Design alternatives
Cast iron	Laplace	3930 to 4710	1333b/1122a
	Hurwicz α =0	4300 to 4790	1333b/1122a
	Hurwicz α =1	3560 to 4620	1333b/1122a
Steel	Laplace	3570 to 4350	2333b/2122a
	Hurwicz α =0	4360 to 3850	2333b/2122a
	Hurwicz α =1	3290 to 4340	2333b/2122a
Stainless steel	Laplace	2450 to 3230	3333b/3122a
	Hurwicz α =0	2450 to 3510	3333b/3122a
	Hurwicz α =1	2440 to 2940	3333b/3122a
Copper	Laplace	5370 to 6150	4333b/4122a
	Hurwicz α =0	6090 to 6580	4333b/4122a
	Hurwicz α =1	4630 to 5690	4333b/4122a
Aluminum	Laplace	19,600 to 20,400	5333b/5122a
	Hurwicz α =0	23,900 to 24,400	5333b/5122a
	Hurwicz α =1	15,300 to 16,400	5333b/5122a

Table 4-11 The ranges for equivalent CO_2 emissions

Heat exchanger material	Criterion	Range (kg·CO_2)	Design alternatives
Cast iron	Laplace	290 to 340	1333b/1122a
	Hurwicz α =0	320 to 350	1333b/1122a
	Hurwicz α =1	260 to 350	1333b/1122a
Steel	Laplace	260 to 320	2333b/2122a
	Hurwicz α =0	280 to 320	2333b/2122a
	Hurwicz α =1	240 to 320	2333b/2122a
Stainless steel	Laplace	180 to 240	3333b/3122a
	Hurwicz α =0	180 to 260	3333b/3122a
	Hurwicz α =1	180 to 220	3333b/3122a
Copper	Laplace	620 to 680	4333b/4122a
	Hurwicz α =0	730 to 770	4333b/4122a
	Hurwicz α =1	510 to 590	4333b/4122a
Aluminum	Laplace	970 to 1,030	5333b/5122a
	Hurwicz α =0	1,170 to 1,210	5333b/5122a
	Hurwicz α =1	773 to 850	5333b/5122a

The contribution of each boiler component to the environmental impact of design alternatives 3333b and 5122a is presented in Table 4-12. The heat exchanger and casing jacket contribute to about 90% of the total embodied energy and equivalent CO_2 emissions for the gas-fired heating boiler. The burners, draft blower, and insulation have the relatively less important impact.

Table 4-12 Environmental impacts performance of design alternative 3333b and design alternative 5122a per component

Component	Embodied energy (MJ)		Equiv. CO_2 emissions (kg·CO_2)	
	3333b	5122a	3333b	5122a
Heat exchanger	1,343	23,288	98	1,125
Burners	171	246	13	18
Draft blower	98	86	7	6
Casing (jackets)	831	734	61	54
Insulation	0	37	0	2
Total	2,443	24,391	179	1,205

4.4 Furnaces

There are two types of furnaces: (1) fuel-burning furnaces and (2) electric furnaces. The fuel-burning furnaces may be further categorized by type of fuel: (a) natural gas furnaces, and (b) oil furnaces (ASHRAE, 2000).

4.4.1 Materials

This study is limited to the non-condensing natural gas-fired furnaces. According to the ASHRAE handbook (2000), "a typical residential furnace consists of the following basic components: (1) a cabinet or casing; (2) heat exchangers; (3) a combustion system including burners and controls; (4) a forced-draft blower, induced-draft blower, or draft hood; (5) a circulating air blower and motor; and (6) an air filter and other accessories such as a humidifier, an electronic air cleaner, an air-conditioning coil, or a combination of these elements." The following information about materials in the forced air furnace components is found in (ASHRAE, 2000).

- The casing or cabinet is most commonly formed from painted cold-rolled steel. The inside of the casing adjacent to the heat exchanger is lined with a foil-faced blanket insulation and/or a metal radiation shield to reduce heat losses through the casing and to limit the outside surface temperature of the furnace.
- Heat exchangers are normally made of cold-rolled low-carbon steel. The two types of heat exchangers: individual sectional and cylindrical, are used in gas-fired furnaces (Brumbaugh, 1976). Common corrosion-resistant materials include aluminized steel, ceramic-coated cold-rolled steel, and stainless steel, however, are often used in condensing furnaces that are out of the scope of the present study.
- A gas burner assembly consists of four major parts or sections: a gas valve, an ignition device, a manifold and orifice, and burners with adjustments (Brumbaugh, 1976). Only the burners' part is considered in the present study because of the small amounts of material in the other parts and the lack of manufacturers' data. Burners are most frequently made of stamped sheet metal, although cast iron is also used (ASHRAE, 2000). Fabricated sheet metal burners may be made from cold-rolled steel coated with high-temperature paint or from a corrosion-resistant material such as stainless or aluminized steel.
- The venting component is a small blower to force or induce the flue products through the forced draft furnace.
- Blowers and Motors: centrifugal blowers with forward-curved blades for the double inlet type are used in most forced-air furnaces. Electric motors used to drive furnace

blowers are usually custom designed for each furnace model or model series. Direct-drive motors and belt-drive blower motors are normally used.

- Furnace controls include an ignition device, a gas valve, a fan control, a limit switch, and other components specified by the manufacturer. However, they are not considered in the present study because of their small masses in comparison to the whole furnace.
- Air Filters in the forced air furnace and other accessories such as humidifiers, electronic air cleaners, and automatic vent dampers are not included in the present study due to their small masses in comparison to the whole furnace.

Therefore, based on the descriptions in the literature above, the following components of the boiler are taken into account: the heat exchangers, the burners, the blower, the draft blower, and the casing (body jackets).

4.4.2 Assumptions

The present study focuses on the natural gas fired non-condensing furnace. The heating capacity is selected to be 16 kW based on the calculations of section 3.4 (see Chapter 3) and oversized factor, to take into account the demand during the warming up and the sizes available from manufactures.

Usually, the dimensions and shipping weight are easily obtained from the manufacturer's documents. However, this is not sufficient for calculating embodied energy and emissions, and so the following assumptions are made:

1. The electrical and control systems are not considered in this study.
2. The casing jacket is commonly made with heavy gauge steel (Beaty, 1987) with various finishes. The quantities of materials can be roughly calculated by using the furnace's dimension and the material densities. The cabinet jacket are commonly made with a heavy gauge steel plate (Beaty, 1987) thickness 2.0 mm, density of 7850 kg/m^3 for steel and 7900 kg/m^3 for stainless steel.
3. The insulation layer is usually a foil-faced blanket and/or a metal radiation shield that has a small mass relative to the furnace. It is not considered in the present study.
4. The most important part of a furnace is the heat exchanger, which could be made of steel, aluminized steel or stainless steel (ASHRAE, 2000).
5. The burners in gas-fired furnace could be made of steel (Brumbaugh, 1976; ASHRAE, 2000), or stainless steel (Brumbaugh, 1976; Beaty, 1987).
6. The housing of the blower could be made of steel.
7. The draft blower could also be made of steel exclusively, and its motor is not taken into account.

In general, the gas-fired furnaces are made of steel or stainless steel except for the blower motors, filters, and control devices. Table 4-13 indicates the types of metal for each main component of a furnace with corresponding codes. However, the exact material used in each component in a furnace is not given in the manufacturers' catalogues.

Table 4-13 Codes of materials of component

HEX		Burner		Blower		D-blower		Casing	
1	Steel	1	Steel	1	Steel	1	Steel	1	Steel
2	StlS	2	StlS	2	StlS	2	StlS	2	StlS

Note: "HEX" refers to heat exchanger, "D-blower" refers to draft blower; "StlS" refers to stainless steel.

The blower motor is a major component in a gas-fired furnace. Because of its complex composition, the manufacturer's data are not enough for the calculation of embodied energy and associated greenhouse gas emissions regarding each material of a blower motor. Alternatively, a proportional estimation is employed, based on the information derived from the study carried out by Prek (2004), in which material composition of the motor of a fan coil convector was given in Table 4-14.

Table 4-14 Materials composition of a blower motor (Prek, 2004)

Material	Mass (kg)	%
Copper	1.5	37.5
Aluminum	0.7	17.5
Steel	1.5	37.5
PVC	0.3	7.5
Total	4.0	100

Based on the same proportionality indicated in Table 4-14, the estimated results of the blower motor (mass of 5.85 kg, four speeds, 1200 CFM) used in the selected furnace are presented in Table 4-15 below.

Table 4-15 Estimation of blower motor materials

Material	%	Mass (kg)	Embodied energy (MJ)	Equiv. CO_2 emissions ($kg{\cdot}CO_2/kg$)
Copper	37.5	2.2	107	13.4
Aluminum	17.5	1.02	211	10.2
Steel	37.5	2.2	63.4	4.62
PVC	7.5	0.43	30.1	1.29
Total	100	5.85	411.5	29.51

Therefore, the two scenarios of environmental impacts of the gas fired furnaces are evaluated in terms of embodied energy and GHG emissions. Manufacturers' data are selected and shown in Table 4-16.

- Scenario no.1: steel,
- Scenario no.2: stainless steel.

Table 4-16 Gas furnace data

York gas furnace (http://www.yorkupg.com)

Output (kW)	AFUE %	Model	Dimension (mm)	Blower Dia. × Wid. (in.) × HP	Shipping weight (kg)
15.5-18.7	80	PIDUA12N06401	368*1016*724	10 * 7 * 1/3	52.7
15.5-18.7	80	PIDUB12N08001	446*1016*724	10 * 8 * 1/2	57.6

Luxaire gas furnace (http://www.luxaire.com/heating.asp)

Output (kW)	AFUE %	Model	Dimension (mm)	Blower Dia. × Wid. (in.) × HP	Shipping weight (kg)
15.5-18.7	80	G8D08012UHA11	368*1016*724	N/A	52.7
15.5-18.7	80	G8D10012UHB11	446*1016*724	N/A	57.6

From Table 4-16 the average mass of the furnaces is roughly equal to 55 kg, in which the mass of the blower's motor is estimated to be 5.85 kg (Table 4-15). The embodied energy and the equivalent CO_2 emissions due to the manufacturing of the gas-fired non-condensing furnace (about 16 kW) are estimated as follows (specific values are presented in Table 4-6, Section 4.3.5).

In scenario no.1, assuming that the furnace is made of steel, the embodied energy is: EE = (Mass $_{\text{furnace}}$ – Mass $_{\text{blower motor}}$) × 28.8 MJ/kg = (55 – 5.85) × 28.8 = 1416 MJ. With the value of equivalent CO_2 emissions for steel of 2.1 kg·CO_2/kg·material, the total value of equivalent CO_2 emissions is 103.2 kg.

In scenario no.2, assuming that the furnace is made of stainless steel, the embodied energy is:
EE = (Mass $_{\text{furnace}}$ – Mass $_{\text{blower motor}}$) × 16.3 MJ/kg = (55 – 5.85) × 16.3 = 801 MJ. With the value of equivalent CO_2 emissions for stainless steel of 1.2 kg·CO_2/kg·material, the total value of equivalent CO_2 emissions is 59 kg.

4.4.3 Results and Discussion

The material construction for a furnace is simpler than that of a boiler. Only two metals (steel or stainless steel) are usually used in the major components. The embodied energy and the equivalent CO_2 emissions of a furnace are primarily influenced by the types of metals used and their corresponding quantities. The two scenario analyses of embodied energy and equivalent CO_2 emissions indicate a range from 801 MJ to 1,416 MJ for embodied energy, and a range from 59 kg to 103.2 kg for equivalent CO_2 emissions.

4.5 Validation of the payoff matrix model

In order to validate the decision under uncertainty model used in this chapter, a case study from the literature is used for comparison.

Ardente et al. (2005) carried out the life cycle assessment of a solar thermal collector. The quantity of each main material used for the manufacturing of the solar collector is presented in Table 4-17.

Table 4-17 Materials used in the solar collector (Ardente et al., 2005)

Material	Mass (kg)	(%)
Galvanized steel	112.6	52.1
Thermal fluid	37.5	17.3
Stainless steel	29.1	13.5
Copper	13.6	6.3
Glass	10.5	4.9
Rigid PUR	9	4.2
Aluminum	4	1.8
Total	216.3	100

Table 4-18 shows the specific value of embodied energy, which were used by Ardente et al. (2005). The authors gave either the values of embodied energy for the materials used in the solar collector or the ranges of embodied energy collected from the relative literature.

Table 4-18 Specific embodied energy values (Ardente et al., 2005)

Material	Embodied energy (MJ/kg)
Galvanized steel	30.5
	27.3-37.9
Copper	73.5
	56.6-90.4
Aluminum 30% recycled	146
	28-198
Stainless steel	62
Thermal fluid	29.3
	17-41
Rigid PUR	105-118

On the basis of the detailed material composition, the authors estimated the embodied energy in the solar collector at about 10,200 MJ, with the larger part going to the manufacturing of the absorbing collector (32.2%) and of the water tank (38.7%). A payoff matrix model is applied based on the information from Ardente et al. (2005) about the masses of some components of the solar collector (Table 4-17). In addition, other information concerning the same type of the solar collector is collected from the manufacturer's website (Apricus, 2004). The following assumptions need to be made to apply the payoff matrix:

(i) Only seven materials presented in Table 4-17 are used in the payoff matrix model. The other materials, which contribute about 3% to the total mass of the collector, are not considered.

(ii) The solar thermal collector includes the following components: (1) the absorbing collector, (2) the water tank, (3) the heat exchanger, (4) the thermal fluid, (5) the support, and (6) the insulation. Each material used in a component of the solar collector is coded as shown in Table 4-19. The components (#1, #2, #4, and #5) were mentioned by Ardente et al. (2005). The other two components (#3 and #6) are introduced here to make the structure of the solar collector more reliable and clear according to manufacturers' website (Apricus, 2004).

Table 4-19 Code of material of component

Component	Code	Material	Code	Material
#1 Absorbing collector (A)	**1**	StlS	**2**	Glass
#2 Tank (T)	**3**	GalS		
#3 Heat exchanger (C)	**4**	Cu	**5**	Al.
#4 Fluid (F)	**g**	Glycol		
#5 Support (S)	**3**	GalS		
#6 Insulation (I)	**6**	PUR	**7**	FiberG

The payoff matrix for the solar collector is shown in Table 4-20. The design alternatives in the payoff matrix are represented by the combinations of the components made of different materials. For instance, the design alternative of 314g36 represents a solar collector with: a galvanized steel tank (code 2), a stainless steel absorbing collector (code 1), a copper heat exchanger (code 4), glycol fluid (code g), galvanized steel supports (code 3), and rigid PUR insulation (code 6).

The states of nature are defined as the combinations of various mass percentages for the different components out of the total mass of the solar collector. The outcome is the embodied energy in the solar collector.

Table 4-20 Payoff matrix for the study of a solar collector

						States of nature						
					T	0.40	0.45	0.50	0.52	0.55	0.60	0.65
					A	0.23	0.20	0.18	0.17	0.16	0.14	0.09
					C	0.11	0.10	0.09	0.08	0.07	0.05	0.04
					F	0.13	0.14	0.15	0.17	0.18	0.17	0.18
					S	0.05	0.04	0.03	0.02	0.01	0.01	0.02
T	A	C	F	S	I	0.08	0.07	0.05	0.04	0.03	0.03	0.02
Design Alt.						1	1	1	1	1	1	1
3	1	4	g	3	6	10551.8	10075.8	9494.7	9153.9	8815.6	8494.6	7880.8
3	1	4	g	3	7	9057.1	8767.9	8560.5	8406.5	8255.1	7934.1	7507.1
3	1	5	g	3	6	12274.4	11641.8	10904.1	10406.7	9911.8	9277.6	8507.2
3	1	5	g	3	7	10779.7	10333.9	9969.9	9659.3	9351.3	8717.1	8133.5
3	2	4	g	3	6	8082.7	7928.7	7562.4	7328.9	7098.0	6991.7	6914.6
3	**2**	**4**	**g**	**3**	7	6588.0	6620.8	6628.2	6581.5	6537.5	6431.2	6540.9
3	2	5	g	3	6	9805.3	9494.7	8971.8	8581.7	8194.2	7774.7	7541.0
3	2	5	g	3	7	8310.6	8186.8	8037.6	7834.3	7633.7	7214.2	7167.3

The outcomes of the payoff matrix are analyzed by using different decision criteria (see Table 4-21). The embodied energy of the solar collector varies from 6,430 MJ to 10,200 MJ when the Laplace criterion is used, from 6,430 MJ to 12,300 MJ when the maximax and the minimin criteria are used, and from 6,630 MJ to 8,510 MJ when the minimax and maximin criteria are used. The Hurwicz criterion gives, under the most pessimistic scenario, the range from 6,630 to 12,300 MJ, while in the case of the most optimistic scenario, the range from 6,430 to 8,510 MJ. To compare with the data given by Ardente et al. (2005), the embodied energy value is 10,200 MJ for the solar collector, which varies between -37% and 20%, when the quality of the embodied value is taken into account.

Table 4-21 Embodied energy (MJ) estimates for the solar collector

Criterion	Range	Design alternatives	Ardente et al. (2005)
Laplace	6430 to 10200	324g37/315g36	10,200
Maximax	12300	315g36	
Minimin	6430	324g37	
Maximin	8510	315g36	
Minimax	6630	324g37	
Hurwicz α =0	6630 to 12300	324g37/315g36	
Hurwicz α =1	6430 to 8510	324g37/315g36	

The results presented in Table 4-21 show that the value estimated by Ardente et al. (2005), based on detailed information of the solar collector, is relatively well approximated by the payoff matrix using the Laplace criterion, the minimin/maximax criteria, the maximin criterion, and the Hurwicz criterion under the worst pessimistic scenario. The minimax and the maximin criteria show that the ranges are lower than the original result.

4.6 Discussions and conclusions

The gas-fired hot water boilers with cast iron, steel, or copper heat exchangers have embodied energies with values between that of the boiler with stainless steel heat exchanger and the boiler with aluminum heat exchanger. For simplification, the ranges of embodied energy and equivalent CO_2 emissions for the boiler evaluated by the Laplace criterion are selected for use in the following analysis in the next chapters. Therefore, the ranges of embodied energy are from 2,450 MJ to 3,230 MJ for the boiler with stainless steel heat exchanger, and from 19,630 MJ to 20,410 MJ for the boiler with aluminum heat exchanger; and the ranges of equivalent CO_2 emissions are from 180 kg to 240 kg for the boiler with stainless steel heat exchanger, and from 970 kg to 1,030 kg for the boiler with aluminum heat exchanger (see Section 4.3.5, Tables 4-7 and 4-8).

Due to the lack of the detailed manufacturers' information, the embodied energy and equivalent CO_2 emissions for an electric hot water boiler are approximately estimated based on the results for the gas-fired hot water boiler. An electric hot water boiler with capacity of 15 kW is about 50 kg (Dettson, 2005). The other electric hot water boiler with capacity of 12 kW is about 75 kg (Burnham, 2005). The estimated weight of the gas-fired hot water boiler discussed in Section 4.3 is 150 kg. The embodied energy and CO_2 emissions for the electric hot water boiler is estimated by multiplying the value obtained above for the gas-fired boiler with aluminum heating exchanger with the ratio of 0.42, which equals to (50/150+75/150)/2. Therefore, for the electric boiler, the ranges of embodied energy are from 8,200 MJ to 8,600 MJ; and the ranges of equivalent CO_2 emissions are from 410 kg to 430 kg.

For the gas-fired furnace, the embodied energy ranges from 801 MJ to 1,416 MJ and the emissions ranges from 59 kg to 103 kg.

For the electric furnace, its weight is close to that of the gas-fired furnace. Due to the lack of the detailed manufacturers' information, the embodied energy and equivalent CO_2 emissions for an electric furnace are assumed to be the same values for the gas-fired furnace.

CHAPTER 5

IMPACT IN THE PRE-OPERATING PHASE

The pre-operating phase is the time span before the occupation of the building from the extraction of raw materials to the erection of building. The following indices of the life cycle impact are evaluated for the selected heating systems in the pre-operating phase: the embodied energy, the greenhouse gas emissions, the exergy destruction, and the initial cost. In addition, the impact of the house exterior envelope is also considered. The overall impact of the house exterior envelope and the heating system in the pre-operating phase is analyzed in detail.

5.1 Embodied energy in the hot water heating (HWH) system

Embodied energy is the energy used by all processes associated with the production of a product, from the acquisition of natural resources to product delivery. This includes the mining of raw materials, the manufacturing of components and equipment, and the transport of materials between and within these processes. Chapter 2 presented the compilation of the embodied energy values for most materials used in HVAC system and equipment.

For each material used in the manufacturing of the HWH system, the embodied energy is calculated by multiplying the specific embodied energy value and the quantity of each material used for the piping system, as calculated in Chapter 3; and for the boiler of the hot water heating system, the estimated range of embodied energy is presented in Chapter

4. Table 5-1 shows the embodied energy per system components. Since uncertainty exists in the estimation of embodied energy in the boiler, the range of embodied energy for the boiler is estimated by using the payoff matrix model (see Chapter 4). The lowest value of embodied energy in the boiler is expected when its heat exchanger is made of stainless steel, while the highest value of embodied energy is expected when the heat exchanger is made of aluminum. The boilers with heat exchangers of cast iron, steel or copper have embodied energy values between that of the heat exchanger of stainless steel and the heat exchanger of aluminum. On the other hand, the embodied energy of the electric boiler is also less than that of the gas-fired hot water boiler with the heat exchanger of aluminum. The values of embodied energy for the boiler used in this section, which were estimated by using the Laplace decision criterion (see Chapter 4). The ranges estimated by using other decision criteria discussed in Chapter 4 can also be used. The total embodied energy in the HWH system is about 33,500 MJ in the case of a boiler with the heat exchanger made of stainless steel, and about 50,700 MJ, if the heat exchanger is made of aluminum.

Table 5-1 Embodied energy for the HWH system

Component		Material	Mass (kg)	Embodied energy value (MJ/ kg)	Embodied energy		
					(MJ)	%	
						StlS	**Al
Piping system	Pipes	Copper	69.4	48.6	3,366.0	12.5 to 12.8	8.3 to 8.4
	Tees	Copper	0.88	48.6	42.8		
	Elbows	Copper	0.9	48.6	43.7		
	Gate valves	Bronze	7.9	*62	489.8		
	Strainer	Cast iron	1.35	32.8	44.3		
Expansion tank		Steel	5.4	28.8	155.5		
Pump		Brass	0.9	62	55.8		
Radiators		Cast iron	745	32.8	24,436	73 to 75	48 to 49
Ventilation system	Heat recovery unit	Steel	27.7	28.8	798	4.9 to 5.0	3.2 to 3.3
	Ductwork	Steel	29.28	28.8	843		
Boiler	Heat exchanger, burners, draft blower, casing, insulation	Stainless steel heat exchanger OR Aluminum heat exchanger	150	N/A	2,450 to 3,230 OR 19,630 to 20,410	7.5 to 9.6	39 to 40
Total			1,038		33,505 to 50,685	100	

Note: *specific embodied energy of bronze is assumed to be equal that of brass.
**percentages are corresponding to the embodied energy values when the boiler's heat exchanger is made of aluminum.

The embodied energy of the building components, except the heating system, was previously estimated by Kassab (2002) at 707,863 MJ. The total embodied energy in the house is calculated by integrating the previous results and presented in this study (Table 5-2). The embodied energy in the HWH system (about 33,500 to 50,700 MJ) accounts for 4.5-6.7% of the total embodied energy in the house (741,400 to 758,600 MJ). Figure 5-1 shows the embodied energy in the house per material type, including the boiler and other HWH system components.

Table 5-2 Embodied energy of the house

House component	Embodied energy (MJ)	(%)
Structure	174,100	23 to 23.5
Envelope	430,400	57 to 58
Interior partitions	103,400	13.6 to 13.9
HWH system	33,500 to 50,700	4.5 to 6.7
Total	741,400 to 758,600	100

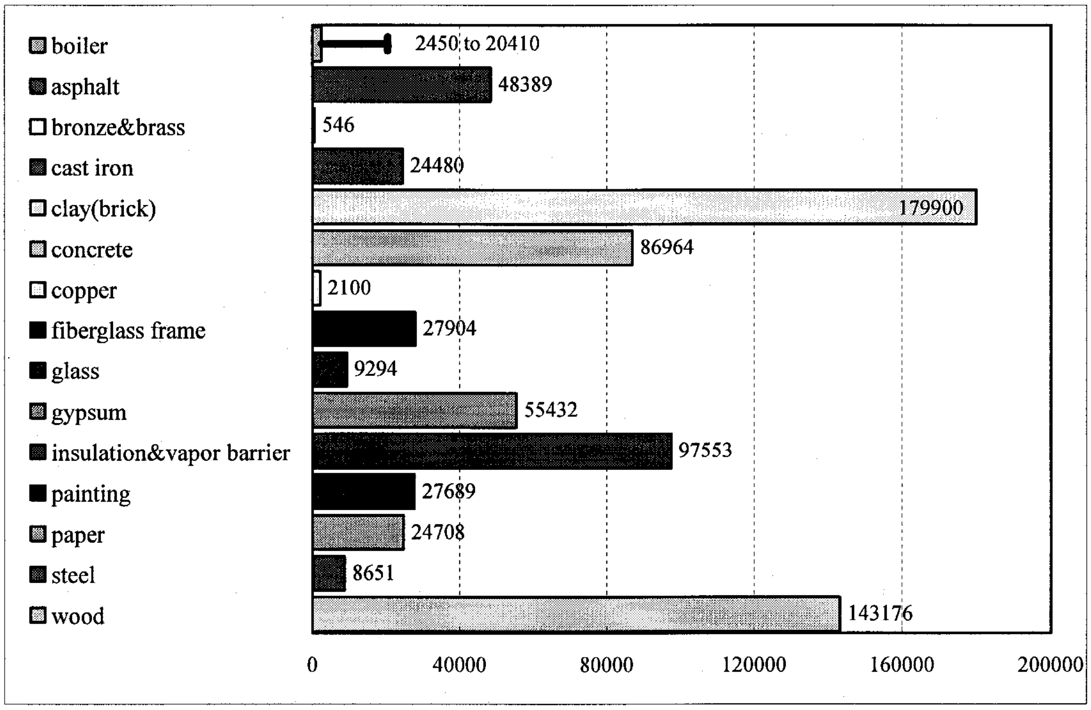


Figure 5-1 Contribution of each material/component to the total embodied energy (MJ) in the house. Case of the HWH system

5.2 Embodied energy in the forced air heating (FAH) system

The overall embodied energy of the FAH system is estimated based on the amount of material used for the ducting system, as calculated in Chapter 3, and for the equipment, as presented in Chapter 4. Table 5-3 shows the embodied energy in the system components.

Since uncertainty exists in the estimation of the embodied energy in a furnace (see Chapter 4), the range is given. The lower value of embodied energy in a furnace corresponds to the heat exchanger made of stainless steel, while the higher value corresponds to the heat exchanger made of steel. Table 5-4 presents the amount of embodied energy and the corresponding contributions by building components, namely, structure, envelope, interior partitions, and FAH system. The embodied energy in the FAH system 13,600 to 14,200 MJ only accounts for 1.9-2.0% of the total embodied energy in the house 721,500 to 722,100 MJ. Figure 5-2 shows the embodied energy per material type, in the house including the furnace and the other FAH system components.

Table 5-3 Embodied energy of the FAH system

Component		Material	Mass (kg)	Embodied energy value (MJ/kg)	Embodied energy		
					(MJ)	(%)	
						StlS	*Steel
Ducting system	Duct	Galvanized steel	309.8	28.8	8922.2	90	86
	Fittings (including elbows, tees, transitions, take-offs, diffusers, boots, dampers, connections)	Galvanized steel	90.3	28.8	2600.6		
	Hangers	Hot-rolled steel	3	28.8	86.4		
Ventilator		Steel	27.7	28.8	798	0.9	0.84
Blower motor		Copper	2.2	48.6	106.9	3.2	3.0
		Aluminum	1.02	207	211.1		
		Steel	2.2	28.8	63.4		
		PVC	0.45	70	31.5		
Furnace	Heat exchanger, burners, blower, draft blower, casing	Stainless steel OR Steel	49.15	16.3 28.8	801 OR 1416	6.2	10.4
Total			458		13,621 to 14,236	100	

Note: *percentages are corresponding to the embodied energy values when the heat exchanger is made of steel.

Table 5-4 Embodied energy of the house (Including FAH system)

House component	Embodied energy (MJ)	(%)
Structure	174,100	24
Envelope	430,400	59.7 to 59.6
Interior partitions	103,400	14.3
FAH system	13,600 to 14,200	1.9 to 2.0
Total	721,500 to 722,100	100

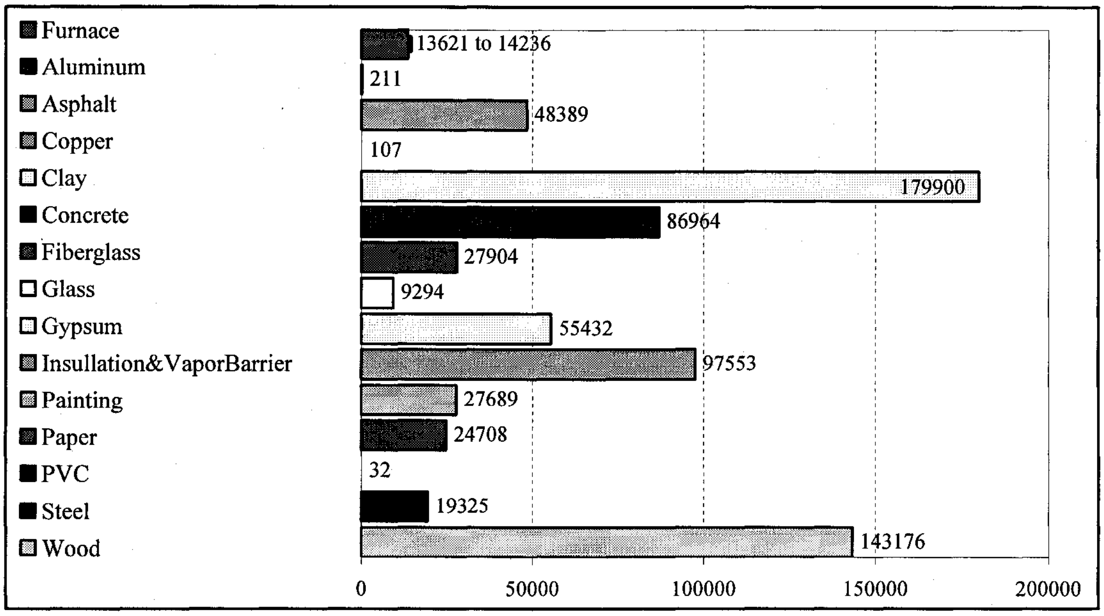


Figure 5-2 Contribution of each material/component to the total embodied energy in the house, case of the FAH system.

5.3 Embodied greenhouse gas (GHG) emissions

Gases such as carbon dioxide (CO_2) and methane (CH_4) are called greenhouse gases. As they build up in the atmosphere, they act like the transparent roof of a greenhouse, which allows in sunlight while trapping the heat. Human activities, such as the burning of fossil fuels, are adding significant quantities of CO_2 and other greenhouse gases to the earth's atmosphere. There is widespread agreement among scientists that elevated levels of greenhouse gases are causing changes to the global climate. Therefore, reducing the life cycle GHG emissions in the building sector becomes more and more important.

The embodied GHG emissions due to the HVAC system in the pre-operating phase are the total GHG emissions due to the manufacturing of HVAC components. They are expressed in kilogram of equivalent CO_2 emissions per kilogram of the produced material.

The estimates of GHG emissions due to the manufacturing of boilers and furnaces were presented in Chapter 4. The GHG emissions due to the manufacturing of other system components are calculated as the product of the specific equivalent CO_2 emission value, in kg·CO_2/kg, by the mass of each material, in kg. The specific equivalent CO_2 emission values of materials are compiled from the existing literature (presented in Chapter 2). Tables 5-5 and 5-6 show the total equivalent CO_2 emissions due to the manufacturing of HWH system and FAH system, respectively.

Table 5-5 Total equivalent CO_2 emissions due to the manufacturing of HWH system

Component		Material	Mass (kg)	CO_2 Emissions ($kg \cdot CO_2$/ kg)	CO_2 Emissions		
					($kg \cdot CO_2$)	(%)	
						StlS	**Al
Piping system	Pipes	Copper	69.4	6.1	423.3	19 to 19.4	14.6 to 14.9
	Tees	Copper	0.88	6.1	5.4		
	Elbows	Copper	0.9	6.1	5.5		
	Gate valves	Bronze	7.9	*6.1	48.2		
	Strainer	Cast iron	1.35	2.4	3.2		
Expansion tank		Steel	5.4	2.1	11.3		
Pump		Brass	0.9	*6.1	5.5		
Radiators		Cast iron	745	2.4	1,788	67.5 to 69	52 to 53
Ventilation system	Heat recovery unit	Steel	27.7	2.1	58.2	4.5 to 4.6	3.5
	Ductwork	Steel	29.28	2.1	61.5		
Boiler	Heat exchanger, burners, draft blower, casing, insulation	Stainless steel heat exchanger OR Aluminum heat exchanger	150	N/A	180 to 240 OR 970 to 1,030	6.9 to 9.1	28.7 to 30
Total			1,038		2,650 to 3,440	100	

Note: *specific embodied emission of bronze is assumed to be equal that of copper.
**percentages are corresponding to the embodied emissions values when the heat exchanger is made of aluminum.

Table 5-6 Total equivalent CO_2 emissions due to the manufacturing of FAH system

Components		Material	Mass (kg)	CO_2 Emissions (kg·CO_2/ kg)	CO_2 Emissions		
					(kg)	(%)	
						StlS	*Steel
Ducting system	Duct	Galvanized steel	309.8	2.1	650.6	65.6	62.7
	Fittings (including elbows, tees, transitions, take-offs, diffusers, boots, dampers, connections)	Galvanized steel	90.3	2.1	189.6	19.7	18.9
	Hangers	Hot-rolled steel	3	2.1	6.3		
Ventilator		Steel	27.7	2.1	58.2	5.9	5.6
Blower motor		Copper	2.2	6.1	13.4	2.8	2.7
		Aluminum	1.02	10	10.2		
		Steel	2.2	2.1	4.6		
		PVC	0.45	N/A			
Furnace	Heat exchanger, burners, blower, draft blower, casing.	Stainless steel OR Steel	49.15	1.2 2.1	59 OR 103.2	5.9	9.9
Total			458		992 to 1,036	100	

Note: *the embodied emissions of the furnace when the steel heat exchanger is made of steel.

The equivalent CO_2 emissions for the HWH system is estimated between 2.7 and 3.4 tons, while in the case of the FAH system, the equivalent CO_2 emissions are estimated at about one ton.

The equivalent CO_2 emissions due to the construction of the house, without the heating system, are estimated by (Kassab, 2002) at 67.11 tons. If the CO_2 emissions due to the manufacturing of the HWH heating system are added, the contribution is from 4 to 5% of the total equivalent CO_2 emissions due to total embodied energy used in the house. In the case of the FAH system, the contribution is about 1.4%.

5.4 Exergy of building materials

In thermodynamics, the concept of exergy is defined as the maximum work that can be extracted from an energy flow or a process of a system. The exergy analysis, based on the second law of thermodynamics, provides a clear view of the energy losses in a system, as it presents quantitative and qualitative evaluation of the different losses (Koroneos et al 2003). The exergy of a system in a certain environment is only the useful part of energy that can be maximally extracted from the system in this environment. This concept can be extended to concern not only energy but also matter. In this study, the quality factors given by Wall (1997) were applied to the material to estimate the exergy value of the material (Chapter 2, Section 2.7). Moreover, Zhang and Reistad (1998) and Cornelissen (1997) stated that for the non-fuel materials especially, metals, the production energy contributes to the major part of the cumulative exergy consumption.

Based on the above assumptions, this study quantifies the exergy from the cumulative energy consumption (embodied energy). The embodied energy, therefore, can be used to evaluate the exergy destruction for a material by multiplying the ratio $(T- T_0)/T$, which is also known as the Carnot efficiency (Wall, 1997). In the present study, T_0 is the absolute temperature of the environment assumed 10°C or 283K (Szargut, 1988). T refers to the temperature of the production process. The temperature of the production process, for an example of the steel production, is about 2600K (Richetts, 2005). The factor of efficiency is thus about 0.9. Therefore, the exergy destruction during the manufacturing of steel is equal to 0.9 times the embodied energy in this material. Due to the lack of industrial data, this ratio is also used to estimate the approximate exergy destruction for other materials used in the HVAC systems such as copper or aluminium.

Based on the above discussion, Table 5-7 presents the total exergy destructions due to the manufacturing of materials used in two HVAC systems discussed in this study.

Table 5-7 Exergy destruction due to the manufacturing of HVAC systems (MJ)

SYSTEM	EMBODIED ENERGY	EXERGY DESTRUCTION
HWH system	33,500 to 50,700	30,150 to 45,630
FAH system	13,600 to 14,200	12,240 to 12,780

5.5 Initial costs

The initial costs of the heating systems are calculated by using RS Means Cost Data catalogue (2005), which includes the costs of materials, labor, contractor profit, and overhead costs. The quantities of the materials in the heating systems are extracted from the design drawings of the heating systems presented in Chapter 3. The initial costs given by RS Means Cost Data are calculated in US dollars, a change factor of 1.25 is used to convert the cost from US dollars to Canadian dollars. The unit price of each component in the piping system is presented in Appendix-9. The total initial cost of the HWH system is presented in Table 5-8. For the forced air heating system, the ductwork cost is estimated by using the cost per pound of material and combined with the unit cost of terminal devices such as diffusers and dampers and then summarized to the total cost. The total initial cost of the FAH system is presented in Table 5-9.

Table 5-8 Initial cost of the HWH system with mechanical ventilation

System component	Quantity	Cost (CAN$)
Heating system, hydraulic, radiators, ventilator, Cast iron boiler, gas, 12.2 kW output, 310m^2 house		
Boiler, gas, hot water, CI, burner, controls & insulation	1	3,156
Pipes, copper, tubing, cplg & hngr 10'oc, including fittings and valves	n/a.	4,740
Radiators, cast iron, 4-tube, 25" high	112	4,060
Strainer, cast iron	1	54
Expansion tank, painted steel, ASME, 15 gal. capacity	1	563
Circulating pump, cast iron, flange connection, 1/100 hp.	1	475
Ventilation system		
Ventilator*	1	131
Ventilation ductwork	65 lb.	508
Total		13,685

Note: *The cost of the ventilator is taken from RS Means 2005, building construction cost data, (Catalogue: 15850-800-2160).

Table 5-9 Initial cost of the FAH system

System component	Quantity	Cost (CAN$)
Heating system, forced air, gas fired, furnace, Steel, gas, 16 kW output, 310 m^2 house		
Furnace, gas, steel, burner, blower, standard controls	1	1,094
Ductwork, galvanized steel, including fittings, joints, and hangers	725 lb.	5,664
Diffusers, 10" by 4"	21	854
Total		7,612

In the HWH system, if an electric boiler is used, the cost of the electric boiler is 5,343 dollars (Appendix 9). The cost of the HWH system increases to 15,872 dollars. In the FAH system, if an electric furnace is used, the cost of this equipment is roughly equal to that of the gas-fired furnace. The cost of the FAH system remains 7,612 dollars.

Comparing with the initial cost of $217,266 for the exterior envelope of the house (Kassab, 2002), the cost of the HWH accounts for 6-6.8% of the total initial cost of the house and the FAH system accounts for 3.5% of the total, respectively.

5.6 Results and discussion

The overall impact of the pre-operating phase of the house is summarized in Table 5-10.

Table 5-10 Impact of the pre-operating phase of the house

Index		HWH system	FAH system	Entire house
Embodied energy	(MJ)	33,500-50,700	13,600-14,200	741,400-758,600
	(%)	4.5-6.7	1.9-2.0	100
Embodied emissions	(Ton·CO_2·equiv.)	2.7-3.4	1.0	69.81-70.51
	(%)	4.0-5.0	1.4	100
Initial cost	CAN$	13,685-15,872	7,612	230,951-233,138
	(%)	6.0-6.8	3.5	100

Data presented above indicate that the hot water heating system may double the impact of the forced air heating system in terms of embodied energy, embodied emissions, and initial cost. However, when the impact of the two heating systems is compared with that of the whole house in the pre-operating phase, the results of this study indicate that the impact of both heating systems is not significant.

CHAPTER 6

MATHEMATICAL MODELS OF THE HEATING SYSTEMS

The performance of the hot water heating system and the forced air heating system is modeled using the first and second laws of thermodynamics. The energy, entropy and exergy balances are used to evaluate important indices such as the first and second law efficiencies. The energy, entropy, and exergy analyses of two residential heating and ventilation systems are presented in this study: (i) the hot water heating (HWH) system with mechanical ventilation, and (ii) the forced air heating (FAH) system. In this study, (1) the energy and exergy efficiencies are evaluated at the house level and power plant level; (2) the exergy destruction associated with the entropy generation due to pressure drop in the piping or ducting systems is considered and is simulated in the models of pump and blower; (3) the exergy destruction and exergy supplied are calculated not only for the whole system but also for each system component; (4) in the annually operating conditions, the part load operation associated with the control strategies for the boiler and furnace are also taken into consideration; and (5) for the ventilation systems, the volume of fresh air and the temperature set-point for the electric heaters are considered in this study.

Based on the mathematical models described in the following sections, the computer programs are then developed using the Engineering Equation Solver (EES) environment (Klein, 2003), and are presented in Appendix-10.

6.1 Hot water heating (HWH) system with mechanical ventilation

In this closed hot water-loop heating system, the components are: a boiler, a circulating pump, radiators, and a piping system (Figure 6-1). The hot water is prepared in the boiler, where energy is transferred from the combustion of natural gas or from an electric coil. The pump circulates the hot water throughout the piping system between boiler and radiators. The ventilating system includes an air to air heat recovery unit, an electric pre-heater and an electric re-heater. The following design parameters are used in this study:

(1) The temperature of water leaving and entering the boiler $T_{w,out,boiler}=90^{\circ}C$ and $T_{w,in,boiler}=70^{\circ}C$; (2) the room air temperature, $T_{room}=21^{\circ}C$; (3) the outside temperature at design conditions, $T_{out}=-23^{\circ}C$; (4) the ventilation air exchange rate, $\dot{m}_{a,fresh}=0.08$ kg/s. The ventilation rate corresponds to 0.35 ach (ASHRAE-62, 2001) for the volume of the house of 868 m^3. The hourly heating loads were obtained from the simulation of an existing house in Montreal, using the BLAST program (Kassab, 2002). The nominal boiler capacity is selected equal to 12.2 kW to satisfy the peak heating load of 11.09 kW (see Chapter 3).

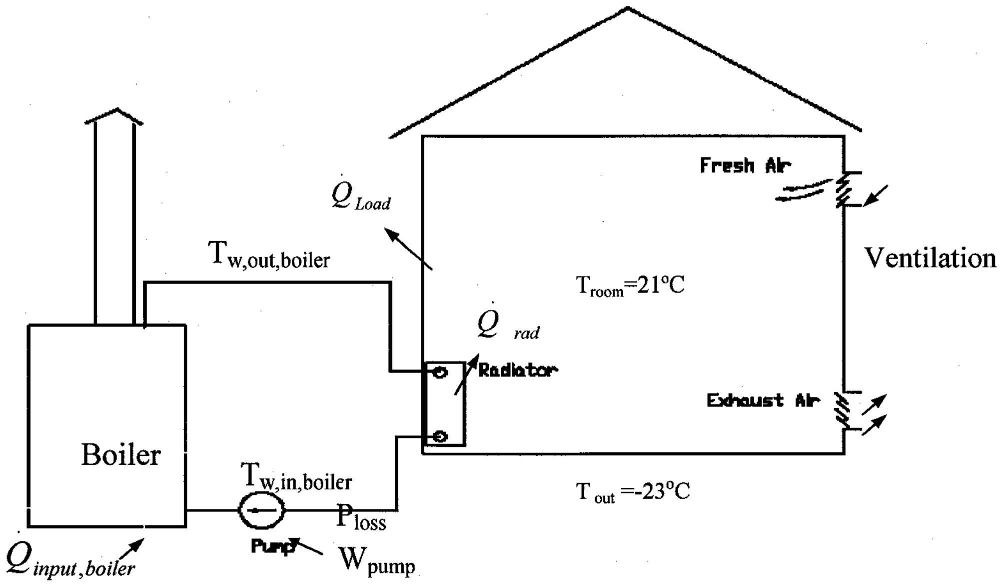


Figure 6-1 Hot water heating system

The steady-state model of each component is presented below.

6.1.1 Gas-fired hot water boiler

Energy balance:

At the design conditions, the energy input to the boiler is equal to the nominal load divided by the boiler efficiency. At the annual operating conditions, the boiler is usually operated at part load conditions, and the energy input to the boiler is expressed as (DOE, 1982):

$$\dot{Q}_{input,boiler} = \dot{Q}_{cap} \cdot HIR_{des} \cdot [HIR(PLR)] \cdot FRAC \qquad (6\text{-}1)$$

where, $\dot{Q}_{input,boiler}$ is the power input to the boiler, in kW;

$\dot{Q}_{cap}$ is the nominal capacity of the boiler, in kW, in this case study $\dot{Q}_{cap}$=12.5 kW;

HIR$_{des}$ is the nominal heating input ratio, which is equal to $1/\eta_{gboiler}$, where $\eta_{gboiler}$ is the boiler efficiency; $\eta_{gboiler}$=80% (Burnham, 2005);

[HIR(PLR)], the heat input ratio correction factor, is the fraction of design energy input required at part load; the function of [HIR(PLR)] is obtained from (Henderson, et al., 1999) for a residential boiler with induced draft:

$$HIR\_PLR = 0.0080472574 + 0.87564457PLR + 0.29249943PLR^2 - 0.17624156PLR^3 \tag{6-2}$$

Part load ratio is (DOE, 1982): $PLR = \dot{Q}_{load}/\dot{Q}_{cap}$ (6-3)

Fraction of the hour during which the boiler is running is (DOE, 1982):

$$FRAC = PLR / RMIN \tag{6-4}$$

The minimum part load ratio RMIN is to be equal to 0.1. If the PLR is less than RMIN, the boiler is cycling on and off. In this mode, the boiler is operated only on a fraction of the hour (FRAC). Otherwise, the boiler is operated continually, while FRAC=1.

The water flow rate through the boiler is calculated from the following relation:

$$\dot{Q}_{rad} = m_{w,boiler} \cdot cp_w \cdot (T_{w,out,boiler} - T_{w,in,boiler}) \tag{6-5}$$

where, $\dot{Q}_{rad} = \dot{Q}_{Load}$; $\dot{Q}_{rad}$ is the heat emitted by the radiators to maintain the indoor air temperature at the design set-point; while $\dot{Q}_{Load}$ is the heating load of the house, in kW;

$\dot{m}_{w,boiler}$ is the mass flow rate of water passing through the boiler, in kg/s;

$T_{w,in,boiler}$ is the temperature of water entering the boiler, in °C;

$T_{w,out,boiler}$ is the temperature of water leaving the boiler, in °C;

Entropy balance:

$$\dot{S}_{gen,boiler} = \dot{m}_{w,boiler} \cdot (s_{w,out,boiler} - s_{w,in,boiler}) - \dot{Q}_{input,boiler} / TK_{flame} + (\dot{Q}_{input,boiler} - \dot{Q}_{rad}) / TK_o \qquad (6\text{-}6)$$

where, $\dot{s}_{w,out,boiler}$ is the specific entropy of water leaving the boiler, in kJ/kg ·K, at T=$T_{w,out,boiler}$, P=101 kPa;

$\dot{s}_{w,in,boiler}$ is the specific entropy of water entering the boiler, in kJ/kg ·K, at T=$T_{w,in,boiler}$, P=101 kPa;

TK_{flame} is the temperature of flame in boiler, in K; TK_{flame}=2200K (Bennett, 2002);

$TK_o = 273 + T_{out}$, TK_o is the reference temperature assumed to be equal to the outdoor temperature, in K. For the annual hourly simulations, when the calculations are performed at peak design conditions, TK_o is equal to -23°C or 250 K (the winter design condition for Montreal).

Exergy destruction:

$$\dot{X}_{de,boiler} = TK_o \cdot \dot{S}_{gen,boiler} \qquad (6\text{-}7)$$

Exergy supplied:

$$\dot{X}_{\sup plied,boiler} = \dot{Q}_{input,boiler} \cdot (1 - TK_o / TK_{flame}) \tag{6-8}$$

The exergy efficiency of the boiler is calculated as follows:

$$\eta_{2,boiler} = 1 - \dot{X}_{de,boiler} / \dot{X}_{\sup plied,boiler} \tag{6-9}$$

6.1.2 Electric boiler

The efficiency of an electric boiler is assumed as $\eta_{eboiler}$ =97%.

Energy balance:

$$\dot{W}_{input,boiler} = \dot{Q}_{cap} \cdot RPLR \cdot FRAC \tag{6-10}$$

where, RPLR is the part load ratio PLR or the minimum part load ratio RMIN, whichever is larger.

Entropy balance:

$$\dot{S}_{gen,boiler} = \dot{m}_{w,boiler} \cdot (\dot{s}_{w,out,boiler} - \dot{s}_{w,in,boiler}) \tag{6-11}$$

Exergy destruction:

$$\dot{X}_{de,boiler} = TK_o \cdot \dot{S}_{gen,boiler} \tag{6-12}$$

Exergy supplied:

$$\dot{X}_{\sup plied,boiler} = \dot{W}_{input,boiler} \tag{6-13}$$

The exergy efficiency is calculated with formulas (6-9), (6-12), and (6-13).

6.1.3 Hot water radiators

Energy balance:

$$\dot{Q}_{rad.} = \dot{m}_{w,rad.} \cdot cp_w \cdot (T_{w,out,boiler} - T_{w,in,boiler}) \tag{6-14}$$

where, $\dot{m}_{w,rad.}$ is the mass flow rate of water through the radiators, $\dot{m}_{w,rad.} = \dot{m}_{w,boiler}$, in kg/s;

cp_w is the specific heat of water, in kJ/kg·K, at the average temperature of the radiators.

Entropy balance:

$$\dot{S}_{gen,rad.} = \dot{m}_{w,rad.} \cdot (s_{w,out,rad} - s_{w,in,rad}) + \dot{Q}_{rad.} / TK_{room} \tag{6-15}$$

where, $\dot{s}_{w,out,rad}$ is the specific entropy of water leaving the radiators, in kJ/kg ·K, at $T=T_{w,in,boiler}$, P=101 kPa;

$\dot{s}_{w,in,rad}$ is the specific entropy of water entering the radiators, in kJ/kg ·K, at $T=T_{w,out,boiler}$, P=101 kPa;

TK_{room} is the indoor air temperature, in K.

Exergy destruction:

$$\dot{X}_{de,rad.} = TK_o \cdot \dot{S}_{gen,rad.} \tag{6-16}$$

Exergy supplied:

$$\dot{X}_{\sup plied,rad} = (1 - TK_o / TK_{avg,rad}) \cdot \dot{Q}_{load} \tag{6-17}$$

where, $TK_{avg,rad}$ is the average temperature of the radiator surface; $TK_{avg,rad}=273+0.5\times(T_{w,out,boiler} + T_{w,in,boiler})$, in K.

Exergy efficiency:

$$\eta_{2,rad} = 1 - \dot{X}_{de,rad} / \dot{X}_{\sup plied,rad} \qquad (6\text{-}18)$$

6.1.4 Circulating pump

Energy balance:

$$\dot{W}_{pump} = FRAC \cdot \dot{V}_{pump} \cdot \dot{P}_{loss} / (\eta_{mech.} \cdot \eta_{hydro}) \qquad (6\text{-}19)$$

where, $\dot{P}_{loss}$ represents the total pressure loss in the piping system, boiler, and radiators, in kPa;

$\dot{V}_{pump} = \dot{m}_{w,boiler} / \rho_w$ is the volumetric flow rate of water circulated by the pump, in m^3/s;

$\eta_{mech.}$ is the mechanical efficiency of the pump, e.g., $\eta_{mech.}$=0.65;

η_{hydro} is the hydro efficiency of the fluid, expressed as the real shaft work to the theoretical shaft work, e.g., η_{hydro} =0.7.

Exergy destruction:

The compression of a liquid inside a pump can be treated as an adiabatic process. Hydraulic friction heat can be determined from the difference between the actual work done by the pump and the theoretical work required to produce the same increase in pressure of the fluid (Szargut, 1998). In this study, the pump is operated with on/off control cycle related to the operation of the boiler. The exergy destruction due to the irreversibility of the pump (including mechanical losses) can be formulized as:

$$\dot{X}_{de,pump} = FRAC \cdot \dot{V}_{pump} \cdot \dot{P}_{loss} \cdot [\frac{1}{\eta_{hydro}} \cdot (\frac{1}{\eta_{mech.}} - 1) + \frac{TK_o}{TK_{w,pump}} \cdot (\frac{1}{\eta_{hydro}} - 1)] \quad (6\text{-}20)$$

where,

$TK_{w,pump}$ is the average temperature of the fluid through the pump, in K;

$TK_{w,pump} = T_{w,in,boiler} + 273$.

Entropy balance:

$$\dot{S}_{gen,pump} = \dot{X}_{de,pump} / TK_o \quad (6\text{-}21)$$

Exergy supplied:

$$\dot{X}_{\sup plied,pump} = \dot{W}_{pump} \quad (6\text{-}22)$$

Exergy efficiency:

$$\eta_{2,pump} = 1 - \dot{X}_{de,pump} / \dot{X}_{\sup plied,pump} \quad (6\text{-}23)$$

6.1.5 Air-to-air heat recovery unit

In order to improve the energy efficiency of the system and meet the requirements of supplying outdoor air into the house, an air-to-air heat recovery unit is used for recovering heat from the exhaust air and preheating the ventilation air during the heating season (Figure 6-2). It is assumed that a balanced ventilation system is used in the house, that is, the mass flow rate of the incoming outdoor air equals the mass flow rate of the exhausted air. The sensible heat recovery efficiency of the unit is about 65% and the power of the both fans is $\dot{FP}$ =0.15 kW (Fantech, 2005). The efficiency of the fan motor is assumed at 70%. These values however can be changed since they are the input variables to the model. When the outside temperature T_{out} is lower than -12°C, the frost may occur on the surface of heat recovery unit (ASHRAE, 2000). To avoid this phenomenon, an electric air pre-heater is used to ensure that the outside air entering the HRU is at least at -12°C.

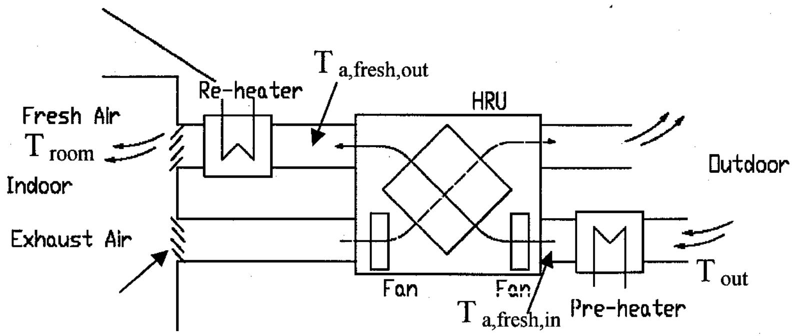


Figure 6-2 Mechanical ventilation system

Energy balance:

For a balanced ventilation system, the following equations are applied:

$$\dot{Q}_{HR} = \dot{m}_{a,exhaust} \cdot cp_a \cdot (T_{a,exhaust,in} - T_{a,exhaust,out}) + 0.5 \times F\dot{P} \tag{6-24a}$$

$$\dot{Q}_{HR} = \dot{m}_{a,fresh} \cdot cp_a \cdot (T_{a,fresh,out} - T_{a,fresh,in}) - 0.5 \times F\dot{P} \tag{6-24b}$$

where, $\dot{m}_{a,fresh} = \dot{m}_{a,exhaust}$, and $T_{a,\,exhaust,\,in} = T_{room}$.

The sensible heat recovery efficiency is expressed as the ratio of the actual heat recovery rate to the maximum potential heat transfer rate:

$$\eta_{HR} = (T_{a,fresh,out} - T_{a,fresh,in}) / (T_{a,exhaust,in} - T_{a,fresh,in}) \tag{6-25a}$$

$$\eta_{HR} = (T_{a,exhaust,in} - T_{a,exhaust,out})/(T_{a,exhaust,in} - T_{a,fresh,in}) \tag{6-25b}$$

Rearranging the equations (6-25a) and (6-25b) to get:

$$T_{a,fresh,out} = T_{a,fresh,in} + \eta_{HR} \cdot (T_{a,exhaust,in} - T_{a,fresh,in}) \tag{6-25c}$$

$$T_{a,exhaust,out} = T_{a,exhaust,in} - \eta_{HR} \cdot (T_{a,exhaust,in} - T_{a,fresh,in}) \tag{6-25d}$$

where, η_{HR} is the sensible recovery efficiency, equal to 0.65 in this case study (Fantech, 2005).

The following temperatures are known:

(1) $T_{a,fresh,in} = T_{out}$, if $T_{out} > -12^{\circ}C$; or $T_{a,fresh,in} = -12^{\circ}C$, if $T_{out} \leq -12^{\circ}C$.

(2) $T_{a,exhaust,in} = T_{room}$.

Equation (6-25c) is used to estimate $T_{a,fresh,out}$, while equation (6-25d) is used to estimate $T_{a,exhaust,out}$.

Entropy balance:

$$\dot{S}_{gen,HR} = \dot{m}_{a,fresh} \cdot (\dot{s}_{a,fresh,out} - \dot{s}_{a,fresh,in}) + \dot{m}_{a,exhaust} \cdot (\dot{s}_{a,exhaust,out} - \dot{s}_{a,exhaust,in}) \tag{6-26}$$

where, $\dot{s}_{a,fresh,out}$ is the specific entropy of the fresh air leaving the mixing box, in kJ/kg ·K, at $T=T_{a,fresh,out}$, P=101 kPa;

$\dot{s}_{a,fresh,in}$ is the specific entropy of the fresh air entering the mixing box, in kJ/kg ·K, at $T=T_{a,fresh,in}$, P=101 kPa;

$\dot{s}_{a,exhaust,out}$ is the specific entropy of the exhaust air leaving the mixing box, in kJ/kg ·K, at $T=T_{a,exhaust,out}$, P=101 kPa;

$\dot{s}_{a,exhaust,in}$ is the specific entropy of the exhaust air entering the mixing box, in kJ/kg ·K, at $T=T_{a,exhaust,in}$, P=101 kPa.

Exergy destruction:

$$\dot{X}_{de,HR} = TK_o \cdot \dot{S}_{gen,HR} + \eta_{FP} \cdot \dot{FP} \tag{6-27}$$

where, η_{FP} is the efficiency of the fan motor, assumed at 70%.

Exergy supplied:

$$\dot{X}_{\sup plied,HR} = \dot{Q}_{HR}' \cdot (1 - TK_o / TK_{avg,exhaust}) + \dot{FP} \tag{6-28}$$

where, $TK_{avg,exhaust}=273+0.5\times(T_{a,exhaust,in} - T_{a,exhaust,out})$

Exergy efficiency:

$$\eta_{2,HR} = 1 - \dot{X}_{de,HR} / \dot{X}_{\sup plied,HR} \tag{6-29}$$

6.1.6 "Room air"

The room air, the air within the heating space, which contains the heat equals to the $\dot{Q}_{load}$, emits heat to the environment through the exterior envelope.

Energy balance:

$$\dot{Q}_{room} = \dot{Q}_{load} \tag{6-30}$$

Entropy balance:

The entropy generation due to the heat contained in the room air lost through the exterior envelope to the environment is taken into account.

$$\dot{S}_{gen,room} = \dot{Q}_{load} / TK_o \tag{6-31}$$

Exergy destruction:

$$\dot{X}_{de,room} = TK_o \cdot \dot{S}_{gen,room} \tag{6-32}$$

Exergy supplied:

$$\dot{X}_{\sup plied,room} = (1 - TK_o / TK_{room}) \cdot \dot{Q}_{load} \tag{6-33}$$

Exergy efficiency:

$$\eta_{2,room} = 1 - \dot{X}_{de,room} / \dot{X}_{\sup plied,room} \tag{6-34}$$

6.1.7 Electric preheater

The electric preheater is used for preheating the fresh air before entering the heat recovery unit to avoid the frost in cold weather. It works only if T_{out}<-12°C.

Energy balance:

$$\dot{W}_{preheater} = \dot{m}_{a,fresh} \cdot cp_a \cdot (T_{a,fresh,in} - T_{out}) \tag{6-35}$$

Entropy balance:

$$\dot{S}_{gen,preheater} = \dot{m}_{a,fresh} \cdot (\dot{s}_{a,fresh,in} - \dot{s}_{a,out}) \tag{6-36}$$

Exergy destruction:

$$\dot{X}_{de,preheater} = TK_o \cdot \dot{S}_{gen,preheater} \tag{6-37}$$

Exergy supplied:

$$\dot{X}_{\sup plied,preheater} = \dot{W}_{preheater} \tag{6-38}$$

Exergy efficiency:

$$\eta_{2,preheater} = 1 - \dot{X}_{de,preheater} / \dot{X}_{\sup plied,preheater} \tag{6-39}$$

6.1.8 Electric reheater

The electric air reheater is used to reheat the fresh air, if its temperature is lower than room temperature T_{room}, after leaving the heat recovery unit and before entering the room.

Energy balance:

$$\dot{W}_{reheater} = \dot{m}_{a,fresh} \cdot cp_a \cdot (T_{room} - T_{a,fresh,out}) \qquad (6\text{-}40)$$

Entropy balance:

$$\dot{S}_{gen,reheater} = \dot{m}_{a,fresh} \cdot (\dot{s}_{a,room} - \dot{s}_{a,fresh,out}) \qquad (6\text{-}41)$$

where, $\dot{s}_{a,room}$ is the specific entropy of indoor air, $\dot{s}_{a,room} = \dot{s}_{a,exhaust,in}$.

Exergy destruction:

$$\dot{X}_{de,reheater} = TK_o \cdot \dot{S}_{gen,reheater} \qquad (6\text{-}42)$$

Exergy supplied:

$$\dot{X}_{\sup plied,reheater} = \dot{W}_{reheater} \qquad (6\text{-}43)$$

Exergy efficiency:

$$\eta_{2,reheater} = 1 - \dot{X}_{de,reheater} / \dot{X}_{\sup plied,reheater} \qquad (6\text{-}44)$$

6.1.9 Energy and exergy efficiencies

Energy and exergy efficiencies of the heating system are calculated in this study: (i) at the house level, and (ii) at the generating power plant level, by taking into account the losses of electrical transmission and the efficiency of the generating power plant. The energy efficiency of the heating system with the heat recovery unit is rather expressed by the coefficient of performance (COP). These results are compared with the energy and exergy efficiencies of the boiler.

The COP of the heating system is calculated at the house level by:

$$COP_{house} = \dot{Q}_{useful} / \dot{Q}_{\sup pplied,house} \tag{6-45}$$

where, $$\dot{Q}_{useful} = \dot{Q}_{load} + \dot{m}_{a,fresh} \cdot cp_a \cdot (T_{room} - T_{out}) \tag{6-46}$$

$$\dot{Q}_{\sup plied,house} = \dot{Q}_{input,boiler} + \dot{W}_{pump} + \dot{W}_{preheater} + \dot{W}_{reheater} + FP \tag{6-47}$$

The COP of the heating system at the power plant is calculated by taking into account the transmission losses and the efficiency of the electricity generation:

$$COP_{pp} = \dot{Q}_{useful} / \dot{Q}_{\sup plied,pp} \tag{6-48}$$

where,

$$\dot{Q}_{\sup plied,pp} = \dot{Q}_{pp,fuel} + IB \cdot \dot{Q}_{input,boiler} \tag{6-49}$$

where, $$\dot{Q}_{pp,fuel} = \dot{W}_{pp} \cdot \sum \alpha_{fuel,i} / \eta_{pp,fuel,i} \tag{6-50}$$

$\dot{Q}_{pp,fuel}$ represents $\dot{Q}_{pp,gas}$, $\dot{Q}_{pp,oil}$, $\dot{Q}_{pp,coal}$, $\dot{Q}_{pp,nuclear}$, and $\dot{Q}_{pp,hydro}$, which represent the energy required by the electricity generation, in kW.

$\alpha_{fuel,i}$ refers to the contribution of different energy sources to the off-site electricity production;

IB=0 is for an electric boiler and IB=1 is for a natural gas boiler.

$$\dot{W}_{pp} = (\dot{W}_{pump} + FP + \dot{W}_{preheater} + \dot{W}_{reheater} + (1 - IB) \cdot \dot{W}_{input,boiler}) / \eta_{trans} \tag{6-51}$$

where, $\dot{W}_{pp}$ is the total electricity demand of the HVAC system, taking into account the transmission loss from the power generating plant to the house, in kW;

$\eta_{pp,fuel,i}$ is the efficiency of the power generating plant.

The contribution of different energy sources and the efficiency of the electricity generation in power plants from different energy sources are compiled from the literature. The contribution $\alpha_{fuel,i}$ of different energy sources to the off-site electricity generation across Canada (Nyboer et al. 2003) is shown in Table 6-1. Calculations are performed in this chapter by using the electricity mix of Quebec.

Table 6-1 Provincial electricity mix of the off-site electricity generation [%]

Province/Country	Coal	Oil	Nat. Gas	Nucl.	Hydro.	Other
British Columbia	2	2	2	0	94	0
Alberta	84	8	8	0	0	0
Ontario	4.33	4.33	4.33	54	26	0
Quebec	0	1.1	1.1	1.1	96.7	0
Canada	19	3.5	3.5	12	62	0

Source: Nyboer et al. (2003)

The efficiency $\eta_{pp,fuel,i}$ of the power plant is 37% for a coal-fired power plant, 43.1% for a natural gas-fired power plant, 33% for an oil-fired power plant, 30% for a nuclear power plant, and 80% for a hydro power plant. The efficiency η_{trans} of transmission and distribution is 86% (Zhang, 1995).

The exergy efficiency (Annex 37, 2002) is expressed as a ratio of the desired exergy output to the exergy used or consumed. The exergy efficiency η_2 at the house level is formulated as:

$$\eta_{2,house} = 1 - \dot{X}_{de,house} / \dot{X}_{\sup plied,house} \tag{6-52}$$

where,

$$\begin{aligned} \dot{X}_{de,house} &= \dot{X}_{de,boiler} + \dot{X}_{de,pump} + \dot{X}_{de,rad} + \dot{X}_{de,HR} \\ &+ \dot{X}_{de,preheater} + \dot{X}_{de,reheater} + \dot{X}_{de,exhaust} \end{aligned} \tag{6-53}$$

$$\begin{aligned} \dot{X}_{\sup plied,house} &= \dot{X}_{\sup plied,boiler} + \dot{X}_{\sup plied,pump} + \dot{X}_{\sup plied,FP} \\ &+ \dot{X}_{\sup plied,preheater} + \dot{X}_{\sup plied,reheater} \end{aligned} \tag{6-54}$$

where, $\dot{X}_{\sup plied,FP}$ is equal to FP (the fans power of heat recovery unit).

The exergy efficiency η_2 at the generating power plant level is given by:

$$\eta_{2,pp} = 1 - (\dot{X}_{de,house} + \dot{X}_{de,trans} + \dot{X}_{de,pp}) / (IB \cdot \dot{X}_{\sup plied,boiler} + \dot{X}_{\sup plied,pp}) \tag{6-55}$$

$$\begin{aligned} \dot{X}_{\sup plied,pp} &= (\dot{Q}_{pp,gas} + \dot{Q}_{pp,oil} + \dot{Q}_{pp,coal}) \cdot (1 - TK_o / TK_{flame}) \\ &+ \dot{Q}_{pp,nuclear} + \dot{Q}_{pp,hydro} \end{aligned} \tag{6-56}$$

6.1.10 Results for the peak design conditions

Based on the model described above, Table 6-2 shows an example of the simulation results in the case of the HWH system with an electric boiler, in which, the energy demand, entropy generation, and exergy destruction for each system component at the peak design conditions are presented.

Table 6-2 Electric demands, entropy generations, and exergy destructions per component of the HWH system at peak winter design conditions

Component	Energy demand (kW)	Entropy generation (kW/K)	Exergy destruction (kW)
Electric boiler	11.43	0.03	7.85
Pump	0.0055	0.00001	0.0027
Radiators	-	0.006	1.58
HR	0.15	0.0003	0.17
Room air	-	0.007	1.66
Preheater	0.89	0.003	0.87
Reheater	0.93	0.003	0.81
Transmission	-	0.009	2.18
Power plant	15.59	0.019	4.64
Total	15.59	0.077	19.75

Figure 6-3 illustrates the exergy destruction in every component of the hot water heating system at peak design conditions. The total exergy destruction in this system is 15.2 kW at peak design conditions when a gas-fired boiler is used. The gas fired boiler accounts for 60% of total exergy destruction, the radiators for 10.4%, the electric heaters for 11%, the heat recovery unit for 1.1%, the room air for 11%, and the transmission and power plant for 6.5% of the total exergy destruction. In the case of the system with an electric boiler, this equipment accounts for 40%, the radiators for 8.0%, the electric heaters for 8.3%, the heat recovery unit for 0.8%, the room air for 8.4%, and transmission and power plant account for 34.5% of the total exergy destruction (19.75 kW).

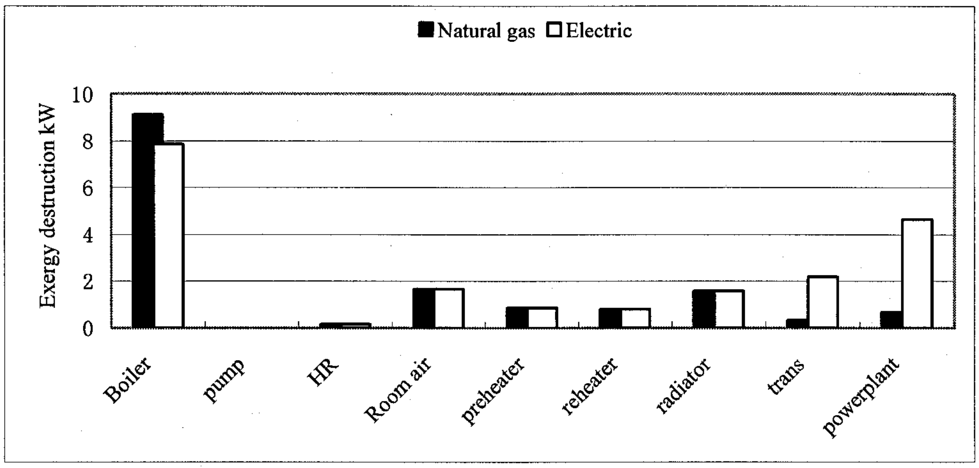


Figure 6-3 Exergy destruction within the HWH system with a gas-fired boiler or an electric boiler (peak design conditions)

The energy efficiency and exergy efficiency of the hot water heating system are shown in Table 6-3. Although the energy efficiency of the electric boiler is considered to be equal to 97% when the transport and generation of electricity is accounted for, the overall efficiency drops to 72%. In the case of a gas-fired boiler, with an efficiency of 80%, the overall efficiency is 86%. On the other hand, the exergy efficiencies at the boiler, house, and power plant levels are much smaller, which demonstrate that there still much potential of improvement of the hot water heating system.

Table 6-3 Energy efficiency and exergy efficiency of the HWH system at peak winter design conditions

	Electricity		Natural gas	
Level	COP or η_1	η_2	COP or η_1	η_2
Boiler	0.97	0.31	0.80	0.26
House	1.10	0.04	0.92	0.01
Power plant	0.72	0.02	0.86	0.01

6.2 Forced air heating system

In the forced air heating system illustrated in Figure 6-4, a furnace is used to satisfy the house heating loads, in order to maintain the design indoor air temperature. The air is circulated through the ducting system by a blower. The system components are the following: a gas-fired or electric furnace, the blower built within the furnace, a mixing box, ducting system, and diffusers.

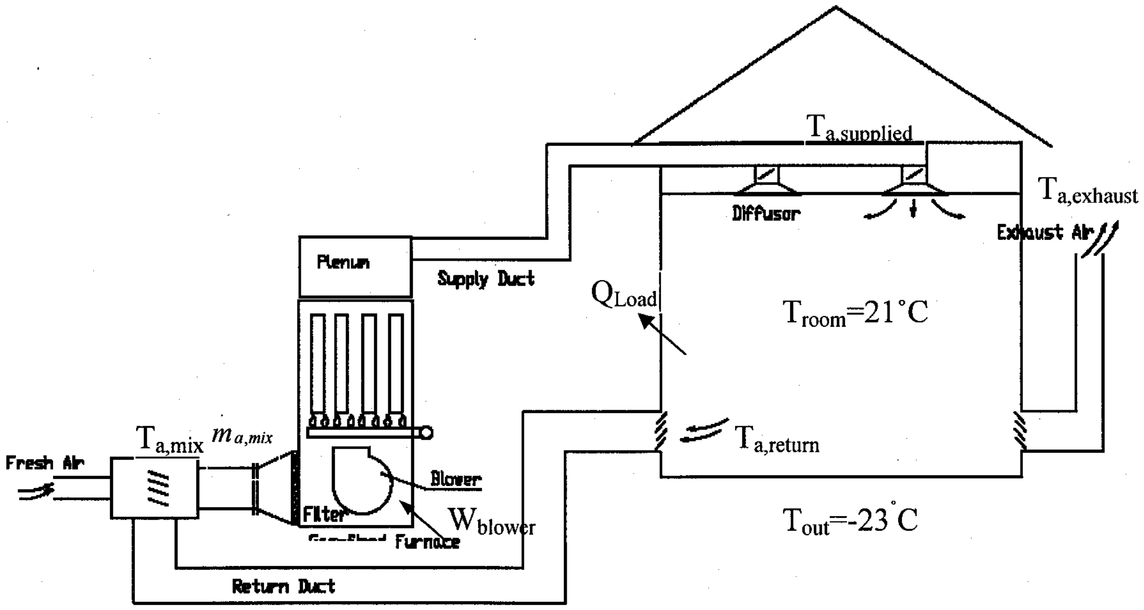


Figure 6-4 Forced air heating system

The following design parameters are considered: (1) the supplied air temperature is $T_{a,supplied}$=43°C; (2) the room air temperature is T_{room}=21°C; (3) the outside temperature at design conditions is T_{out}=-23°C; (4) the ventilation air change rate is $\dot{m}_{a,fresh}$=0.08kg/s, which corresponds to 0.35 ach (ASHRAE-62, 2001). The furnace capacity is selected equal to 16 kW to satisfy the design heating loads of 11.09 kW and ventilation load of 3.5 kW (see Chapter 3).

6.2.1 Gas-fired furnace

Energy balance:

On annually operating conditions, the furnace is usually operated at part load, at which the energy input to the furnace is expressed as (DOE, 1982)

$$\dot{Q}_{input,furnace} = \dot{Q}_{cap} \cdot HIR_{des} \cdot [HIR(PLR)] \cdot FRAC \tag{6-57}$$

where, $\dot{Q}_{input,furnace}$ is the power input to the furnace, in kW;

$\dot{Q}_{cap}$ is the nominal capacity of the furnace, in kW, in this case study $\dot{Q}_{cap}$=16 kW at design conditions;

HIR_{des} is the nominal heating input ratio, which is equal to $1/\eta_{g,furnace}$,

$\eta_{g,furnace}$ is the efficiency of a gas-fired furnace, at design conditions $\eta_{g,furnace}$ =80% (York, 2005);

[HIR(PLR)], the heat input ratio correction factor, is the fraction of design energy input required at part load; the function of [HIR(PLR)] for a residential furnace with induced draft is obtained from (Henderson, et al., 1999):

$$HIR\_PLR = 0.0080472574 + 0.87564457PLR + 0.29249943PLR^2 - 0.17624156PLR^3 \tag{6-58}$$

Part load ratio is (DOE, 1982): $PLR = (\dot{Q}_{load} + \dot{Q}_{a,fresh}) / \dot{Q}_{cap}$ (6-59) where, $\dot{Q}_{a,fresh} = \dot{m}_{a,fresh} \cdot cp_a \cdot (T_{room} - T_{out})$ (6-60)

Fraction of the hour during which the furnace is running is (DOE, 1982),

$FRAC = PLR / RMIN$ (6-61)

The minimum part load ratio RMIN is assumed RMIN=0.1. If the PLR is less than RMIN, the furnace is cycling on and off. In this mode, the furnace is operated only on a fraction of the hour (FRAC). Otherwise, the furnace is operated continually, while FRAC=1.

The air flow rate through the furnace is calculated from the following relation:

$$\dot{m}_{a,mix} = \dot{Q}_{load} / (cp_a \cdot (T_{a,\sup plied} - T_{room})) \tag{6-62}$$

Entropy balance:

$$\dot{S}_{gen,furnace} = \dot{m}_{a,mix} \cdot (\dot{s}_{a,\sup plied} - \dot{s}_{a,mix}) - \dot{Q}_{input,furnace} / TK_{flame} + (\dot{Q}_{input,furnace} - \dot{Q}_{load} - \dot{Q}_{a,fresh}) / TK_o \tag{6-63}$$

where, $\dot{s}_{a,\sup plied}$ is the specific entropy of supplied air, in kJ/kg K, at $T=T_{a,supplied}$, P=101kPa;

$\dot{s}_{a,mix}$ is the specific entropy of mixed air, in kJ/kg K, at $T=T_{a,mix}$, P=101kPa.

Exergy destruction:

$$\dot{X}_{de,furnace} = TK_o \cdot \dot{S}_{gen,furnace} \tag{6-64}$$

Exergy supplied:

$$\dot{X}_{\sup plied,furnace} = \dot{Q}_{input,furnace} \cdot (1 - TK_o / TK_{flame}) \tag{6-65}$$

Exergy efficiency:

$$\eta_{2,furnace} = 1 - \dot{X}_{de,furnace} / \dot{X}_{supplied,furnace} \tag{6-66}$$

6.2.2 Electric furnace

The efficiency of the electric furnace is assumed as $\eta_{e,furnace}$=97%.

Energy balance:

$$\dot{W}_{input,furnace} = \dot{Q}_{cap} \cdot RPLR \cdot FRAC / \eta_{e,furnace} \tag{6-67}$$

where, RPLR is the part load ratio PLR or the minimum part load ratio RMIN, whichever is larger.

Entropy balance:

$$\dot{S}_{gen,furnace} = \dot{m}_{a,mix} \cdot (\dot{s}_{a,supplied} - \dot{s}_{a,mix}) \tag{6-68}$$

Exergy destruction:

$$\dot{X}_{de,furnace} = TK_o \cdot \dot{S}_{gen,furnace} \tag{6-69}$$

Exergy supplied:

$$\dot{X}_{supplied,furnace} = \dot{W}_{input,furnace} \tag{6-70}$$

Exergy efficiency is calculated with formulas (6-66), (6-69) and (6-70).

6.2.3 Furnace blower

Energy balance:

$$\dot{W}_{blower} = \dot{V}_{blower} \cdot \dot{P}_{loss} / (\eta_{mech.} \cdot \eta_{comp}) \tag{6-71}$$

where, $\dot{P}_{loss}$ represents the total pressure difference due to the pressure loss in the ductworks, including the ducting system, furnace, and diffusers, in kPa;

$\dot{V}_{blower} = \dot{m}_{a,mix} / \rho_a$ is the volumetric flow rate of air forced by the blower, in m^3/s;

$\eta_{mech.}$ is the mechanical efficiency of the blower, e.g., $\eta_{mech.}$=0.65;

η_{comp} is the compression efficiency of the fluid, expressed as the real shaft work to the theoretical shaft work, e.g., η_{comp}=0.7.

Exergy destruction:

$$\dot{X}_{de,blower} = \dot{V}_{blower} \cdot \dot{P}_{loss} \cdot [\frac{1}{\eta_{comp}} \cdot (\frac{1}{\eta_{mech.}} - 1) + (TK_o / TK_{a,blower}) \cdot (\frac{1}{\eta_{comp}} - 1)] \tag{6-72}$$

Entropy balance:

$$\dot{S}_{gen,blower} = \dot{X}_{de,blower} / TK_o \tag{6-73}$$

Exergy supplied:

$$X_{\sup plied,furnace} = \dot{W}_{blower} \tag{6-74}$$

Exergy efficiency:

$$\eta_{2,blower} = 1 - \dot{X}_{de,blower} / X_{\sup plied,blower} \tag{6-75}$$

6.2.4 Mixing box

The fresh air flow and recirculation air flow having different temperatures, meet in the mixing box. The most important energy transfer is considered to be between the two flows and not between the flows and the environment. This mixing process is therefore considered as an adiabatic process (Myers, 1989).

Energy balance:

$$\dot{m}_{a,mix} \cdot cp_a \cdot T_{a,mix} = (\dot{m}_{a,heating} - \dot{m}_{a,exhaust}) \cdot cp_a \cdot T_{room} + \dot{m}_{a,fresh} \cdot cp_a \cdot T_{out} \tag{6-76}$$

where, $\dot{m}_{a,mix}$ is the mass flow rate of air leaving the mixing box, in kg/s;

$\dot{m}_{a,heating}$ is the amount of air through the diffusers to heat the rooms corresponding to the $\dot{Q}_{load}$, in kg/s, $\dot{m}_{a,mix} = \dot{m}_{a,heating}$;

$\dot{m}_{a,fresh}$ is the mass flow rate of fresh air entering the mixing box, in kg/s, here, $\dot{m}_{a,fresh} = \dot{m}_{a,exhaust}$;

$T_{a,mix}$ is the temperature of air leaving the mixing box, in °C.

Entropy balance:

$$\dot{S}_{gen,mix} = \dot{m}_{a,mix} \cdot s_{a,mix} - (\dot{m}_{a,heating} - \dot{m}_{a,exhaust}) \cdot s_{a,room} - \dot{m}_{a,fresh} \cdot s_{a,out} \tag{6-77}$$

where, $s_{a,room}$ is the specific entropy of return air, in kJ/kg K, at $T=T_{room}$, P=101kPa.

Exergy destruction:

$$\dot{X}_{de,mix} = TK_o \cdot \dot{S}_{gen,mix} \tag{6-78}$$

Exergy supplied:

Exergy supplied to the mixing box is considered as a portion of the heat transfer occurred in this equipment qualified by the factor that is expressed by $(1 - \frac{TK_o}{273 + T_{a,mix}})$.

$$\dot{X}_{\sup plied,mix} = (1 - \frac{TK_o}{273 + T_{a,mix}}) \cdot cp_a \cdot [(\dot{m}_{a,fresh} \cdot (T_{a,mix} - T_{out}) + (\dot{m}_{a,mix} - \dot{m}_{a,fresh}) \cdot (T_{room} - T_{a,mix})] \quad (6\text{-}79)$$

Exergy efficiency:

$$\eta_{2,mix} = 1 - \dot{X}_{de,mix} / \dot{X}_{\sup plied,mix} \quad (6\text{-}80)$$

6.2.5 Diffusers

Energy balance:

$$\dot{Q}_{diffu} = \dot{Q}_{load} = \dot{m}_{a,heating} \cdot cp_a \cdot (T_{a,\sup plied} - T_{room}) \quad (6\text{-}81)$$

Entropy balance:

$$\dot{S}_{gen,diffu} = \dot{m}_{a,heating} \cdot (\dot{s}_{a,room} - \dot{s}_{a,\sup plied}) \quad (6\text{-}82)$$

Exergy destruction:

$$\dot{X}_{de,diffu} = TK_o \cdot \dot{S}_{gen,diffu} \quad (6\text{-}83)$$

Exergy supplied:

$$\dot{X}_{\sup plied,diffu} = (1 - TK_o / (273 + T_{a,\sup plied})) \cdot \dot{Q}_{diffu} \quad (6\text{-}84)$$

Exergy efficiency:

$$\eta_{2,diffu} = 1 - \dot{X}_{de,diffu} / \dot{X}_{\sup plied,diffu} \quad (6\text{-}85)$$

6.2.6 "Room air"

The room air, the air within the heating space, which contains the heat equals to the $\dot{Q}_{load}$, emits heat to the environment through the exterior envelope.

Energy balance:

$$\dot{Q}_{room} = \dot{Q}_{Load} \tag{6-86}$$

Entropy balance:

The entropy generated due to the heat loss through the exterior envelope to the environment should be taken into account in this analysis.

$$\dot{S}_{gen,room} = \dot{Q}_{load} / TK_o \tag{6-87}$$

Exergy destruction:

$$\dot{X}_{de,room} = TK_o \cdot \dot{S}_{gen,exhaust} \tag{6-88}$$

Exergy supplied:

$$\dot{X}_{\sup plied,room} = (1 - TK_o / TK_{room}) \cdot \dot{Q}_{load} \tag{6-89}$$

Exergy efficiency:

$$\eta_{2,room} = 1 - \dot{X}_{de,room} / \dot{X}_{\sup plied,room} \tag{6-90}$$

6.2.7 Energy and exergy efficiencies

Energy and exergy efficiencies of the heating system are calculated in this study at the house level and at the generating power plant level by taking into account the losses of electrical transmission and of generating power plant. These results are compared with the energy and exergy efficiency of the furnace.

Energy efficiency of the heating system calculated at the house level is given by:

$$\eta_{1,house} = \dot{Q}_{useful} / \dot{Q}_{\sup pplied,house} \tag{6-91}$$

where, $\dot{Q}_{useful} = \dot{Q}_{load} + \dot{m}_{a,fresh} \cdot cp_a \cdot (T_{room} - T_{out})$ (6-92)

$$\dot{Q}_{\sup plied,house} = \dot{Q}_{input,furnace} + \dot{W}_{blower} \tag{6-93}$$

The energy efficiency of the heating system calculated by taking into account the transmission losses and the efficiency of the electricity generation is given by:

$$\eta_{1,pp} = \dot{Q}_{useful} / \dot{Q}_{\sup plied,pp} \tag{6-94}$$

where, $\dot{Q}_{\sup plied,pp} = \dot{Q}_{pp,fuel} + IB \cdot \dot{Q}_{input,furnace}$ (6-95)

where, $\dot{Q}_{pp,fuel} = \dot{W}_{pp} \cdot \sum \alpha_{fuel,i} / \eta_{pp,fuel,i}$ (6-96)

$\dot{Q}_{pp,fuel}$ represents $\dot{Q}_{pp,gas}$, $\dot{Q}_{pp,oil}$, $\dot{Q}_{pp,coal}$, $\dot{Q}_{pp,nuclear}$, and $\dot{Q}_{pp,hydro}$, which represent the energy required for the electricity generation, in kW.

$\alpha_{fuel,i}$ refers to the contribution of different energy sources to the off-site electricity production;

IB=0 is for an electric furnace and IB=1 is for a natural gas furnace.

$$\dot{W}_{pp} = (\dot{W}_{blower} + (1 - IB) \cdot \dot{W}_{input,furnace}) / \eta_{trans} \tag{6-97}$$

where, $\dot{W}_{pp}$ is the total electricity demand of the HVAC system, taking into account the transmission loss from the power generating plant to the house, in kW;

$\eta_{pp,fuel,i}$ is the efficiency of power plant from different energy sources.

The exergy efficiency η_2 at the house level is formulated as:

$$\eta_{2,house} = 1 - \dot{X}_{de,house} / \dot{X}_{\sup plied,house} \tag{6-98}$$

where,

$$\dot{X}_{de,house} = \dot{X}_{de,furnace} + \dot{X}_{de,blower} + \dot{X}_{de,mix} + \dot{X}_{de,diffu} + \dot{X}_{de,exhaust} \tag{6-99}$$

$$\dot{X}_{\sup plied,house} = \dot{X}_{\sup plied,furnace} + \dot{X}_{\sup plied,blower} \tag{6-100}$$

The exergy efficiency η_2 at the generating power plant level is formulated as:

$$\eta_{2,pp} = 1 - (\dot{X}_{de,house} + \dot{X}_{de,trans} + \dot{X}_{de,pp}) / (IB \cdot \dot{X}_{\sup plied,furnace} + \dot{X}_{\sup plied,pp}) \tag{6-101}$$

$$\begin{aligned} \dot{X}_{\sup plied,pp} &= (\dot{Q}_{pp,gas} + \dot{Q}_{pp,oil} + \dot{Q}_{pp,coal}) \cdot (1 - TK_o / TK_{flame}) \\ &+ \dot{Q}_{pp,nuclear} + \dot{Q}_{pp,hydro} \end{aligned} \tag{6-102}$$

6.2.8 Results for the peak design conditions

Based on the model described above, Table 6-4 shows an example of the simulation results in the case of the FAH system with an electric furnace, in which, the energy demand, entropy generation, and exergy destruction for each system component at the peak design conditions are presented.

Table 6-4 Electric demands, entropy generations, and exergy destructions per component (FAH)

Component	Energy demand (kW)	Entropy generation (kW/K)	Exergy destruction (kW)
Electric furnace	15.08	0.05	12.14
Blower	0.062	0.0001	0.034
Diffusers	-	-0.036	-9.1
Mixing box	-	0.0009	0.212
Room air	-	0.044	11.09
Transmission	-	0.01	2.466
Power plant	15.59	0.02	5.241
Total	15.59	0.089	22.08

Figure 6-5 illustrates the exergy destruction in every component of the forced air heating system at peak design conditions. The total exergy destruction in this FAH system with a gas-fired furnace is 16.07 kW. The gas-fired furnace accounts for 86% of the total exergy destruction, the diffusers for -57%, the mixing box for 1.3%, the room air for 69%, and transmission and power plant for 0.2% of the total exergy destruction. In the case of an electric furnace, this equipment accounts for 55%, the diffusers for -41.2%, the mixing box for 1%, the room air for 50.2%, and transmission and power plant account for 35% of the total exergy destruction (22.08 kW).

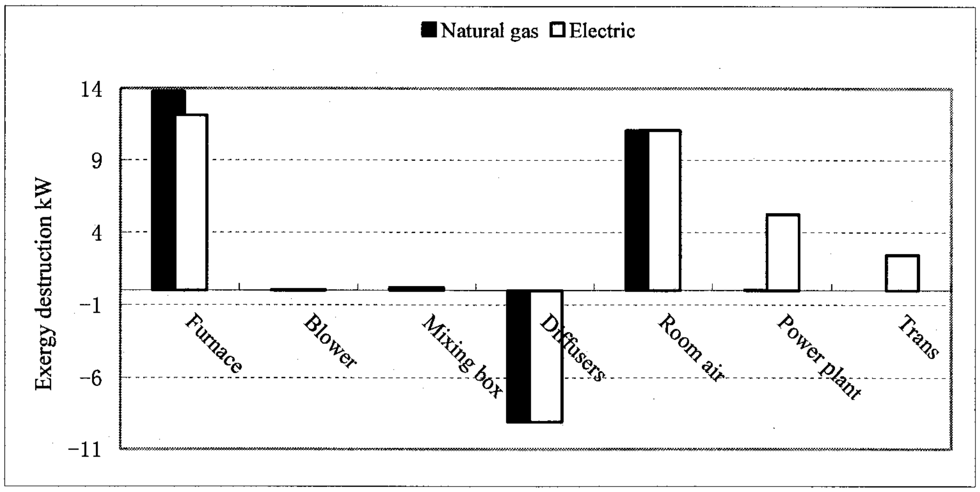


Figure 6-5 Exergy destruction within the FWH system with a gas furnace or an electric furnace (peak design conditions)

The energy efficiency and exergy efficiency of the forced air heating system are shown in Table 6-5. Although the energy efficiency of the electric furnace is considered to be equal to 97% when the transport and generation of electricity is accounted for, the overall efficiency drops to 63%. In the case of a gas-fired furnace, with an efficiency of 80%, the overall efficiency is 79%. On the other hand, the exergy efficiency at the furnace, house, and power plant level is much smaller, which demonstrates that there still much potential of improvement of the forced air heating system.

Table 6-5 Energy efficiency and exergy efficiency (FAH)

	Electricity		Natural gas	
Level	η_1	η_2	η_1	η_2
Furnace	0.97	0.20	0.80	0.15
House	0.96	0.05	0.79	0.02
Power plant	0.63	0.03	0.79	0.02

6.3 Results and discussion

This section presents the results obtained from simulation of the heating season.

6.3.1 Energy and exergy analysis for HWH system and FAH system

Energy analysis

The energy efficiency is calculated at the boiler/furnace level, house level, and generating power plant level (Tables 6-6 and 6-7).

The HWH system, with a gas fired boiler, requires the lowest energy supply of 17,426 kWh. Because of a heat recovery unit applied, the average COP is 1.38 at the house level and 1.11 at the power plant level. The FAH system, with an electric furnace, requires the highest energy supply of 27,887 kWh, and the average energy efficiencies are 0.96 at the house level and 0.64 at the power plant level.

The gas-fired boiler uses energy 11,919 kWh (Table 6-6) compared with the electric boiler (9,977 kWh), however, when the total energy use at power plant is estimated, the hot water system with a gas-fired boiler requires less energy consumption (17,426 kWh) compared with 20,637 kWh in the case of the system with an electric boiler.

Table 6-6 Energy use by the HWH system during the heating season, using electricity and natural gas

Component \ Energy	Electricity (kWh)	Natural gas (kWh)
Q_{load}	9,677	9,677
$Q_{input,boiler}$	9,977	11,919
W_{pump}	4.7	4.7
$W_{preheater}$	217.7	217.7
$W_{reheater}$	2,756	2,756
FP	652.7	652.7
$Q_{\sup plied,house}$	13,608	15,550
$Q_{\sup plied,pp}$	20,637	17,426
$\eta_{1,\text{boiler}}$	0.97	0.8
COP_{house}	1.5	1.38
COP_{pp}	0.99	1.11

The gas-fired furnace uses a energy 21,830 kWh (Table 6-7) compared with the electric furnace (18,319 kWh), however, when the total energy use at power plant is estimated, the forced air system with a gas-fired furnace requires less energy consumption (21,936 kWh) compared with 27,887 kWh in the case of the system with an electric furnace.

Table 6-7 Energy use by the FWH system during the heating season, using electricity and natural gas

Energy / Component	Electricity (kWh)	Natural gas (kWh)
Q_{load}	9,677	9,677
$Q_{input,furnace}$	18,319	21,830
W_{blower}	68.8	68.8
$Q_{\sup plied,house}$	18,388	21,899
$Q_{\sup plied,pp}$	27,887	21,936
$\eta_{1,\text{furnace}}$	0.97	0.8
$\eta_{1,\text{house}}$	0.96	0.81
$\eta_{1,\text{pp}}$	0.64	0.81

Exergy analysis

The exergy analysis presents the exergy destruction in each system component and exergy supplied of the HWH and FAH systems (Tables 6-8 and 6-9). The exergy efficiency is calculated at the boiler/furnace level, house level, and generating power plant level. Based on the results obtained from simulation of the heating season, the exergy are mainly destroyed in a boiler/furnace. Another significant fact is that the exergy is destroyed in the generating power plant, when the electricity is used as the energy source for heating. Comparing exergy efficiencies of the two systems, the hot water heating system performs better than the forced air heating system, as indicated by the exergy efficiency at the house level and the power plant level.

The HWH system, with a gas fired boiler, requires the lowest exergy supply of 15,945 kWh and the average exergy efficiencies is 3% at the power plant level. The FAH system, with an electric furnace, requires the highest exergy supply of 27,734 kWh and the average exergy efficiencies is 4% at the power plant level.

Table 6-8 Exergy performance of the HWH system during the heating season, using electricity and natural gas

Energy source / Component	Electricity (kWh)	Natural gas (kWh)
$X_{de,boiler}$	7,339	8,130
$X_{de,pump}$	2.3	2.3
$X_{de,preheater}$	215	215
$X_{de,reheater}$	2,549	2,549
$X_{de,HR}$	608	608
$X_{de,room}$	865	865
$X_{de,rad.}$	1,473	1,473
$X_{de,trans.}$	2,215	591
$X_{de,pp}$	4,701	1,254
$X_{de,house}$	13,052	13,843
$X_{\sup plied,house}$	13,608	14,100
$X_{de,total}$	19,969	15,689
$X_{\sup plied,tot.}$	20,524	15,945
$\eta_{2,boiler}$	0.24	0.20
$\eta_{2,house}$	0.05	0.03
$\eta_{2,pp}$	0.03	0.03

Table 6-9 Exergy performance of the FWH system using electricity and natural gas

Energy source Component	Electricity (kWh)	Natural gas (kWh)
$X_{de,furnace}$	16,131	17,536
$X_{de,blower}$	38.8	38.8
$X_{de,mix}$	97	97
$X_{de,diffu.}$	-8,515	-8,515
$X_{de,room}$	9,677	9,677
$X_{de,trans.}$	2,993	11
$X_{de,pp}$	6,353	24
$X_{de,house}$	17,429	18,834
$X_{\sup plied,house}$	18,388	19,243
$X_{de,total}$	26,775	18,869
$X_{\sup plied,tot.}$	27,734	19,278
$\eta_{2,\text{furnace}}$	0.11	0.07
$\eta_{2,\text{house}}$	0.05	0.02
$\eta_{2,\text{pp}}$	0.04	0.02

6.3.2 GHG emissions due to the operating energy consumption

The CO_2, NO_2, and CH_4 emissions are the greenhouse gas (GHG) emissions due to the combustion of fossil fuels, which are considered in this study. The GHG emissions during the operating phase over the life span of the house are due to: (i) the on-site fossil fuel consumption, in this case, the natural gas is consumed by a boiler or a furnace and, (ii) the off-site generation of electricity, which may be used by an electric boiler or furnace, and is also used by the auxiliary equipment of the heating system such as pumps, fans of the heat recovery unit, electric heaters, and blowers of the furnace. The GHG emissions are expressed by the equivalent CO_2 emissions.

On-site equivalent CO_2 emissions

The GHG emissions due to the combustion of fossil fuel, for example, natural gas, at the house level are first estimated by using the pollutant coefficients (EnergyPlus, 2005). The pollutant coefficient α for CO_2 is 180.8438 g/kWh, for NO_x is 0.1507 g/kWh, and for CH_4 is 0.0035 g/kWh, for one kWh natural gas used on-site. For the emissions of NOx and CH_4, the GWPs factors for 100-year time horizon (Masters, 1998) are used:

$$CO_{2,emission,house} = (\alpha_{CO2} \cdot E_{gas} + \alpha_{NOx} \cdot E_{gas} \cdot GWP_{NOx} + \alpha_{CH4} \cdot E_{gas} \cdot GWP_{CH4}) / 1000 \qquad (6\text{-}103)$$

where, $CO_{2,emissions,house}$ is the equivalent CO_2 emissions at the house level, in kg·CO_2·Eq.;

α_{CO2}, α_{NOx}, and α_{CH4} are the pollutant coefficients in terms of CO_2, NO_x, and CH_4;

E_{gas} is the natural gas consumption at the house level, in kWh;

GWP_{NOx} =310, for the global warming potential of NO_x over 100-year time horizon;

GWP_{CH4}=21, for the global warming potential of CH_4 over 100-year time horizon.

The natural gas consumption at the house level is 11,919 kWh/year for the HWH system, and 21,830 kWh/year for the FAH system. The equivalent CO_2 emissions at the house level are, therefore, estimated by Formula (6-103) at 2.71 ton/year for the HWH system and 4.97 ton/year for the FAH system.

Off-site equivalent CO_2 emissions

In this study, the provincial energy mix of Quebec is used where the 96.7% electricity is generated from hydro power plant. Only 3.3% electricity comes from oil, natural gas, and nuclear, in which each part accounts for 1.1%, respectively (Baouendi, 2003). The GHG emissions due to electricity generation in power plant are calculated by using the equivalent CO_2 emissions data presented by Gagnon et al. (2002). The following formula is used:

$$CO_{2,emission,pp} = (\alpha_1 \cdot E_{hydro} + \alpha_2 \cdot E_{gas} + \alpha_3 \cdot E_{oil} + \alpha_4 \cdot E_{coal} + \alpha_5 \cdot E_{nuclear})/1000 \qquad (6\text{-}104)$$

where, $CO_{2,emission,pp}$ is the equivalent CO_2 emissions at the generating power plant level, in kg·CO_2·Eq.;

E_{hydro}, E_{gas}, E_{oil}, E_{coal}, and $E_{nuclear}$ represent the annual consumed energy generated by hydro, natural gas, heavy oil, coal, and nuclear power plant respectively, in kWh/year;

$\alpha_{1\text{-}5}$ are the equivalent CO_2 emissions due to the corresponding energy use in power plants, respectively, in kt·CO_2/TWh, (Gagnon, et al. 2002);

α_1=15 kt·CO_2/TWh, for hydro power plant with reservoir;

α_2=443 kt·CO_2/TWh, for natural gas (+2000 km delivery) power plant;

α_3=778 kt·CO_2/TWh, for heavy oil power plant;

α_4=1050 kt·CO_2/TWh, for modern coal (2%S) power plant with SO_2 scrubbing;

α_5=15 kt·CO_2/TWh, for nuclear power plant.

For example, the annual consumed electricity by the HWH system with an electric boiler is 13,608 kWh/year, where 13,159 kWh/year comes from hydro, 150 kWh/year form natural gas, 150 kWh/year form oil, and 150 kWh/year form nuclear. The equivalent CO_2 emissions are:

$CO_{2,emission,pp}$=(15*13,159+443*150+778*150+15*150)/1000=382 kg·CO_2·Eq.

The results of the equivalent CO_2 emissions for the heating systems are summarized in Table 6-10.

Table 6-10 Equivalent CO_2 emissions due to the annual electricity use

	HWH with an electric boiler	HWH with a gas boiler	FAH with an electric furnace	FAH with a gas furnace
Electricity (kWh/yr)	13,608	3,631	18,388	68.8
Eq.CO_2 (kg·CO_2·Eq.)	382	102	517	2

Based on the results obtained from this section, the operating energy use for heating varies with the efficiency of the heating system and the source of energy. For the HWH system with an electric boiler, the total energy consumption and the associated total equivalent CO_2 emissions respectively is 13,608 kWh/year and 0.382 ton/year; while with a gas-fired boiler, the total energy consumption and the associated total equivalent CO_2 emissions respectively is 3,631 + 11,991 = 15,550 kWh/year and 2.812 ton/year (Table 6-11). In the same sequence, the data for FAH system with an electric furnace is respectively 18,388 kWh/year and 0.517 ton/year, whereas the data for using a gas-fired furnace is respectively 68.8 + 21,830 = 21,899 kWh/year and 4.952 ton/year.

Table 6-11 Equivalent CO_2 emissions due to the operating energy use

Type of system	Electricity (kWh/yr)	Eq.CO_2 (Ton·CO_2·Eq.)	Natural gas (kWh/yr)	Eq.CO_2 (Ton·CO_2·Eq.)	Total Eq.CO_2 (Ton·CO_2·Eq.)
HWH with an electric boiler	13,608	0.382	n/a.	n/a.	0.382
HWH with a gas boiler	3,631	0.102	11,919	2.71	2.812
FAH with an electric furnace	18,388	0.517	n/a.	n/a.	0.517
FAH with a gas furnace	68.8	0.002	21,830	4.97	4.972

The results of Table 6-11 reveal that: i) the HWH system requires less energy and emits less GHG emissions than that of the FAH system; ii) if the heating systems use electricity instead of natural gas, less GHG emissions are caused, because of the specific electricity mix in Quebec (96.7% hydro-electricity).

6.3.3 Operating energy cost

The calculation for the operating energy cost, in case of the HWH system with a gas-fired boiler, is presented as follows. The results for other design alternatives are summarized in Table 6-12.

The annual natural gas consumption is 11,919 kWh or 42.91GJ. The volume of natural gas used in the boiler is 1147 m^3 per year, ($1m^3$ NG=0.0381GJ). The price of natural gas in Montreal on Jan.18, 2005 was 17.2$/GJ (Gazmetro, 2005). Hence, the annual cost of natural gas is 42.91*17.2= $738. The annual electricity consumption is 3,631 kWh, which is composed as follows: 4.7 kWh for the pump, 2,973 kWh for the electrical heaters, and 652.7 kWh for the fans of the heat recovery unit. The current electricity price from Hydro-Quebec (2005) is 0.4064 \$/per day, 0.0502 \$/kWh for the first 30 kWh per month, and plus 0.0633 \$/kWh for the remaining consumption. The annual cost of electricity is calculated at \$256. Hence, the annual cost of the operating energy used for heating is 994 dollars.

Table 6-12 Annual operating cost for heating

Type of system	Natural gas		Electricity		Annual cost
	(kWh)	(\$)	(kWh)	(\$)	(\$)
HWH with an electric boiler	n/a	n/a	13,608	864	864
HWH with a gas-fired boiler	11,919	738	3,631	256	994
FAH with an electric furnace	n/a	n/a	18,388	1,166	1,166
FAH with a gas-fired furnace	21,830	1,352	68.8	77	1,429

The cost difference between the maximal and minimal value is about \$565 per year for the operating cost (Table 6-12). The hot water heating system with an electric boiler operates at the lowest energy cost, while the forced air heating system with a gas-fired furnace operates at the highest energy cost.

6.4 Summary

A comprehensive comparison is conducted in this section in Table 6-13 in order to illustrate the overall picture of the heating systems in their operating phases.

Table 6-13 Comparison of the heating system performance in the operating phase

Type of system	Natural gas		Electricity		Exergy destruction	COP or η_1	η_2	Total equ.CO_2	Annual cost
	(kWh)	($T\cdot CO_2\cdot Eq.$)	(kWh)	($T\cdot CO_2\cdot Eq.$)	(kWh)	-	-	($T\cdot CO_2\cdot Eq.$)	($)
HWH with an electric boiler	n/a	n/a.	13,608	0.382	13,052	1.50	0.05	0.382	864
HWH with a gas-fired boiler	11,919	2.71	3,631	0.102	13,843	1.38	0.03	2.812	994
FAH with an electric furnace	n/a	n/a.	18,388	0.517	17,429	0.96	0.05	0.517	1,166
FAH with a gas-fired furnace	21,830	4.97	68.8	0.002	18,834	0.81	0.02	4.972	1,429

CHAPTER 7

LIFE CYCLE ANALYSIS OF TWO RESIDENTIAL HEATING SYSTEMS

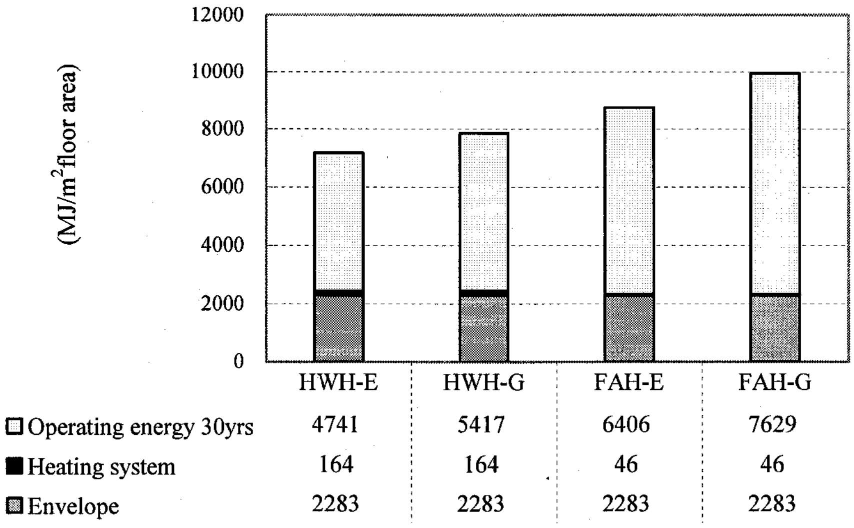
This chapter presents the life cycle analysis of the residential heating systems in terms of the following indicators: life cycle energy use, life cycle exergy, life cycle equivalent CO_2 emissions, and life cycle cost. The life cycle analysis usually evaluates the impact of the object from "cradle to grave". With respect to a building or building subsystems, a life cycle analysis usually includes the following phases: the production (includes all processes from raw material extraction up to the completion of the product), the erection, the operation, the maintenance, the renovation, and the demolition. Due to the lack of reliable data on the maintenance, renovation and demolition phases, the scope of this study covers only the pre-operating (production and erection) and operating phases only.

7.1 Life cycle energy use

Life cycle energy use includes the total energy input over the entire life cycle of a building or its subsystems. Within the scope of this study, the embodied energy due to the manufacturing of the building materials and the heating system in the pre-operating phase, and the energy use for heating in the operating phase are evaluated.

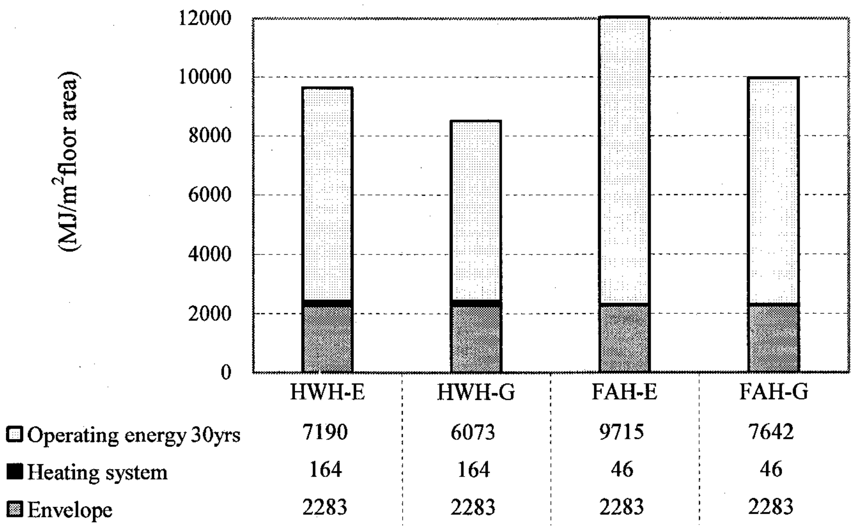
In chapter 5 (see Sections 5.1 and 5.2), it was shown that the total embodied energy of the entire house ranges from 741,400 MJ to 758,600 MJ, in which the embodied energy of the hot water heating system ranges from 33,500 to 50,700 MJ, and of the forced air heating system ranges from 13,600 to 14,200 MJ. The annual operating energy use at the house level is 49,000 MJ (or 13,608 kWh) for the HWH system with an electric boiler, or 56,000 MJ (or 15,550 kWh) for this system with a gas-fired boiler (see Chapter 6, Table 6-6); while it is 66,200 MJ (or 18,388 kWh) for the FAH system with an electric furnace, or 78,800 MJ (or 21,899 kWh) for this system with a gas-fired furnace (see Chapter 6, Table 6-7). Therefore, the total embodied energy of the house is equal to about 8 to 15 years of the annual operating energy use. This number roughly agrees with the estimate of 7-10 years of the annual operating energy use according to Cole's data (Malin, 1993). With respect to the heating system, the embodied energy of the HWH system is approximately equal to 0.65-0.85 year of the annual operating energy use, while the embodied energy of the FAH system is approximately equal to 0.14-0.18 year of the annual operating energy use. The results indicate that the HWH system has more embodied energy than the FAH system, while the total operating energy use is less than that of the FAH system.

Assuming that the annual heating energy consumption is constant over a 30-year life span regardless of the efficiency decrease of the heating system or equipment, the total operating energy consumption is thus equal to 30 times the annual operating energy use. Figures 7-1 and 7-2 present the life cycle energy use per square meter (the total floor area of the house is 310 m^2) for the different types of heating systems, at the house level and the power plant level respectively. The upper limit of the embodied energy for the house is used in Figures 7-1 and 7-2.



	HWH-E	HWH-G	FAH-E	FAH-G
□ Operating energy 30yrs	4741	5417	6406	7629
■ Heating system	164	164	46	46
▨ Envelope	2283	2283	2283	2283

Figure 7-1 Embodied energy versus operating energy over the life cycle, at the house level



	HWH-E	HWH-G	FAH-E	FAH-G
□ Operating energy 30yrs	7190	6073	9715	7642
■ Heating system	164	164	46	46
▨ Envelope	2283	2283	2283	2283

Figure 7-2 Embodied energy versus operating energy over the life cycle, at the power plant level

The relationship between the embodied energy and the total operating energy consumption is illustrated in Figures 7-3 and 7-4. The thick horizontal lines indicate the range of embodied energy for the building envelope and heating systems. From these two figures, one can also see that the embodied energy equals about 8 to 15 equivalent years of energy consumption, at the house level (Figure 7-3), while at the power plant level is between 8 to 12 years (Figure 7-4).

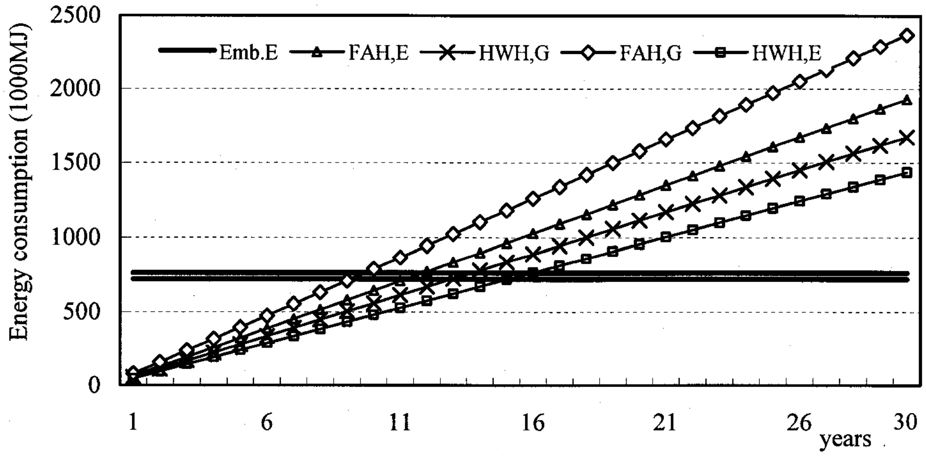


Figure 7-3 The relationship between the embodied energy of the entire house and cumulative heating energy use (house level).

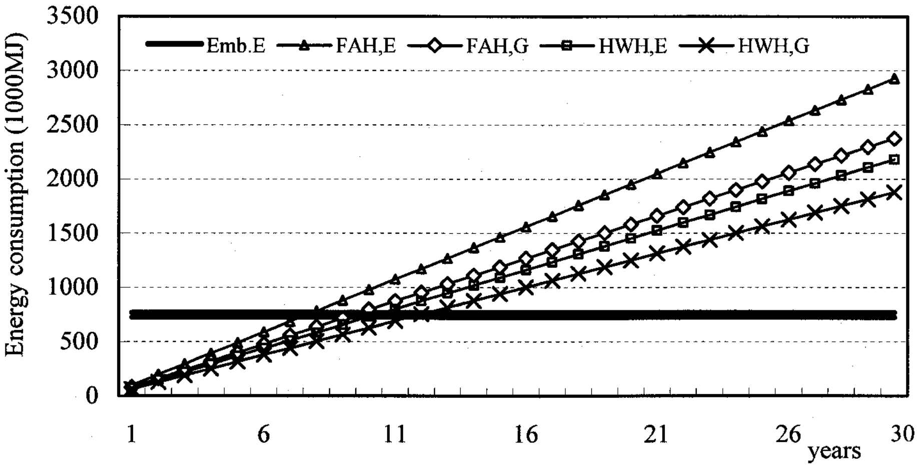


Figure 7-4 The relationship between the embodied energy of the entire house and cumulative heating energy use (power plant level).

At the house level

The HWH system with an electric boiler has the lowest operating energy consumption, while the embodied energy of the materials used in the heating system as well as in the envelope presents the largest portion of the life cycle energy consumption. On the other hand, the FAH system with a gas-fired furnace has the highest operating energy consumption; while the embodied energy of the materials used in the heating system as well as in the building envelope presents the smallest portion of the life cycle energy use.

At the power plant level

The HWH system with a gas-fired boiler has the lowest operating energy consumption at the power plant level, while the embodied energy of the materials used in the heating system as well as in the envelope presents the largest portion of the life cycle energy use. On the other hand, the FAH system with an electric furnace has the highest operating energy consumption, while the embodied energy of the materials used in the heating system as well as in the building envelope presents the smallest portion of the life cycle energy consumption.

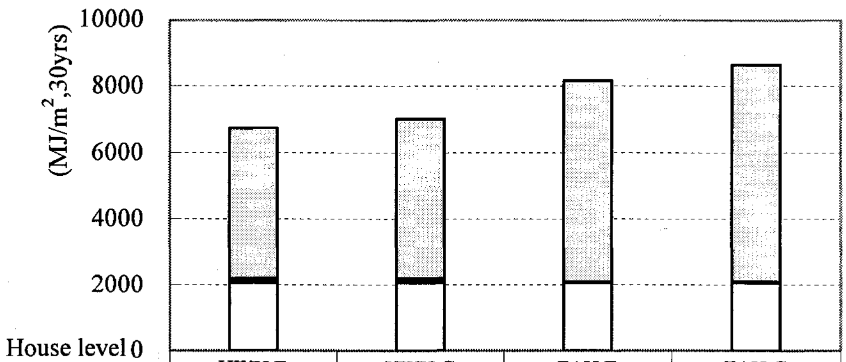
7.2 Life cycle exergy analysis

Life cycle exergy destruction includes all the exergy destroyed over the entire life cycle of a building or its subsystems. Here, both the exergy destruction due to the manufacturing the HVAC systems and due to the operating energy used are evaluated within the scope of this study. In the pre-operating phase, the exergy for the materials that compose the HVAC systems is estimated in Chapter 5 (see Section 5.4). In the operating phase, the exergy supplied to the HVAC systems is calculated with the simulation models, considering the type of energy source and the efficiency of the generating power plant and the transmission losses of electricity. The exergy destruction in the heating systems and components are also calculated with simulation models and presented in Chapter 6. Table 7-1 presents the life cycle exergy for the different heating systems. The exergy analysis indicates that a large portion of the exergy is destroyed.

Table 7-1 Life cycle exergy analysis of the heating systems (MJ)

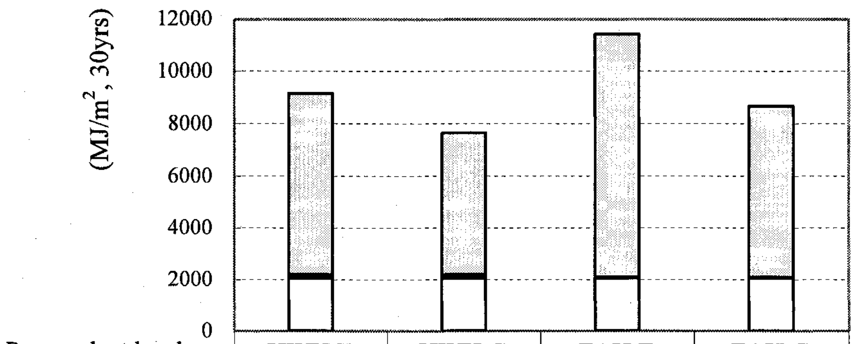
Type of system	Pre-operating	Operating phase (30 yrs)			
	Mat. Exergy	Exergy (house level)		Exergy (power plant level)	
	(range)	Supplied	Destroyed	Supplied	Destroyed
HWH with an electric boiler	33,150-45,630	1,470,000	1,410,000	2,217,000	2,157,000
HWH with a gas-fired boiler	33,150-45,630	1,523,000	1,495,000	1,722,000	1,694,000
FAH with an electric furnace	12,240-12,780	1,986,000	1,882,000	2,995,000	2,892,000
FAH with a gas-fired furnace	12,240-12,780	2,078,000	2,034,000	2,082,000	2,038,000

Figures 7-5 and 7-6 illustrate the total exergy destroyed during the life cycle at the house level and the power plant level, respectively. The comparison of these two figures reveals the impact of the heating systems on the environment at two different levels. The heating systems using natural gas lead to more exergy destruction than using electricity, when the comparison is performed at the house level. The heating systems using electricity lead to more exergy destruction than those using natural gas, when the scope of analysis is expanded to consider the transmissions losses and the generation of electricity on the remote power plant. In this study, the electricity mix of Quėbec is used.



	HWH,E	HWH,G	FAH,E	FAH,G
▨ Exergy de.30yrs	4547	4823	6072	6562
■ HVACExergy	147	147	41	41
□ Envelope Exergy	2055	2055	2055	2055

Figure 7-5 Life cycle exergy destruction in the heating systems at the house level



	HWH,E	HWH,G	FAH,E	FAH,G
▨ Exergy de. 30yrs	6957	5466	9328	6574
■ HVAC Exergy	147	147	41	41
□ Envelope Exergy	2055	2055	2055	2055

Figure 7-6 Life cycle exergy destruction in the heating systems at the power plant level

7.3 Life cycle equivalent CO_2 emissions

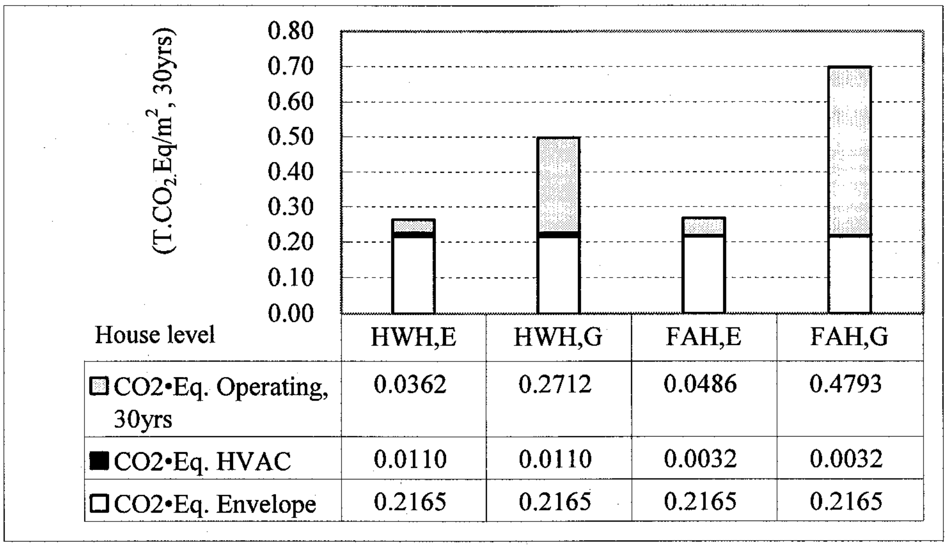
The life cycle equivalent CO_2 emissions include all emissions due to the house and its subsystems including the manufacturing of the exterior envelope and the HVAC systems, and the operating energy use. Table 7-2 presents the equivalent CO_2 emissions per square meter over the life cycle of the house, when the operating energy use is calculated at the house level and the generating power plant level, respectively (see Chapter 6).

Table 7-2 Life cycle equivalent CO_2 emissions ($T\cdot CO_2\cdot eq./m^2$)

Type of system	Pre-operating		Operating phase (30 yrs)		Total*
	HVAC	Envelope	House level	Power plant level	
	(1)	(2)	(3)	(4)	(5)
HWH with an electric boiler	0.011	0.217	0.036	0.055	0.282
HWH with a gas-fired boiler	0.011	0.217	0.271	0.276	0.505
FAH with an electric furnace	0.003	0.217	0.049	0.074	0.293
FAH with a gas-fired furnace	0.003	0.217	0.479	0.480	0.699

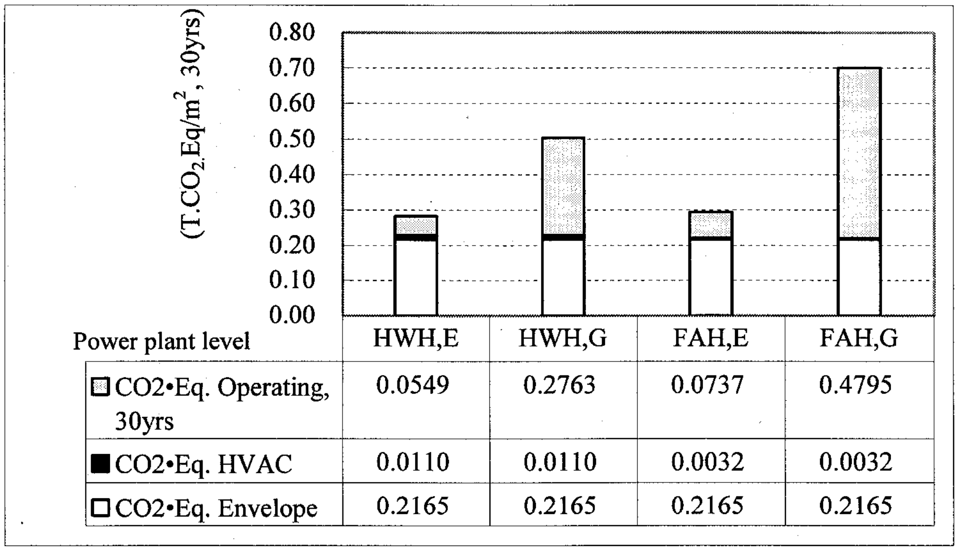
Note: *the column (5) is the sum of columns (1), (2), and (4).

Figures 7-7 and 7-8 illustrate the total equivalent CO_2 emissions for the whole life cycle at the house level and the power plant level.



	HWH,E	HWH,G	FAH,E	FAH,G
▨ CO2•Eq. Operating, 30yrs	0.0362	0.2712	0.0486	0.4793
■ CO2•Eq. HVAC	0.0110	0.0110	0.0032	0.0032
□ CO2•Eq. Envelope	0.2165	0.2165	0.2165	0.2165

Figure 7-7 Life cycle CO_2 emissions at the house level



Power plant level	HWH,E	HWH,G	FAH,E	FAH,G
▨ CO2•Eq. Operating, 30yrs	0.0549	0.2763	0.0737	0.4795
■ CO2•Eq. HVAC	0.0110	0.0110	0.0032	0.0032
□ CO2•Eq. Envelope	0.2165	0.2165	0.2165	0.2165

Figure 7-8 Life cycle CO_2 emissions at the power plant level

When the recurring embodied energy due to maintenance and replacement is not taken into account, the embodied energy of the house remains constant during the lifetime. The embodied CO_2 emissions, therefore, remain constant. In the pre-operating phase, the HWH system causes three times more CO_2 emissions than the FAH system, but the absolute magnitude is marginal when compared with the value for the envelope. However, the equivalent CO_2 emissions of the house vary significantly in the operating phase. The amount of energy consumed by the heating and the type of energy source are the two major factors that contribute to this variation. The life cycle CO_2 emissions proportionally increase with the energy consumption, which is indicated in the comparison between the HWH system and the FAH system. The emissions also are influenced by energy source associated with electricity production. In this study, when the energy use in the heating systems with an electric boiler/furnace and a gas-fired boiler/furnace are compared, combusting natural gas at the house level causes more pollution than using electricity generated from a power plant. However, this is true because of the lower equivalent CO_2 emissions coefficient of hydro-electricity as found in a region such as Québec (Gagnon et al. 2002).

7.4 Life cycle cost

The life cycle cost evaluates the costs of a building or its subsystems over its entire life cycle. The scope of this study considers the initial cost of the HVAC systems and the cost of operating energy consumption. The cost for maintenance, retrofit, and demolition are not included. The estimation of the initial cost is based on the RS Means Cost Data (2005) as presented in Chapter 5. The cost of the operating energy use is estimated based on the simulation results of hourly heating energy use during the six month heating season (see Chapter 6).

The annual operating energy use is assumed yearly over the house lifetime. The present worth value method is used to calculate the energy cost in the operating phase over 30 years lifetime (MNECCB, 1997). The present worth value method is used in order to express the life cycle operating cost in "today's money". The following formula is employed:

$$PW = C \times [1-(1+a)^{-n}]/a \tag{7-1}$$

where, PW is the present worth value of energy costs, in dollars;

C is the annual energy cost in the first year, in dollars;

a is the effective interest rate and is equal to $(i - e)/(1 + e)$;

e is the rate at which energy cost are expected to increase;

i is the discount rate of the cost of money (including inflation); and

n is the lifetime, in years.

The MNECCB (1997) suggests the following design values: a discount rate of 0.09, and an expected increased rate of 0.03. For example, if the first year operating cost is 864 dollars (see Chapter 6) for the house with a HWH system equipped with an electric boiler. Then during a 30 year life span, the total cost for the operating energy consumption is calculated by using formula (7-1) at 12,119 dollars.

Table 7-3 presents the life cycle costs of the house with different heating systems. The initial costs were calculated in Chapter 5. The annual operating energy cost is calculated by using the domestic electricity price from Hydro-Quebec (2005) based on the energy use at the house level, while the price of natural gas based on the residential price from GazMetro (2005).

Table 7-3 Cost comparison among different types of heating systems (CAN$)

Type of system	Pre-operating	Operating (30 yrs)		Life cycle cost
	Initial cost	Operating cost		
		Annual cost	PW	
HWH with an electric boiler	15,872	864	12,119	27,991
HWH with a gas-fired boiler	13,685	994	13,941	27,626
FAH with an electric furnace	7,612	1,166	16,354	23,967
FAH with a gas-fired furnace	7,612	1,429	20,043	27,655

Although the HWH system has a higher initial cost than the FAH system, the HWH system has a lower operating cost than the FAH system. Compare to the HWH system, the FAH system has a lower initial cost than the HWH system, the operating cost, however, is higher than the HWH system. The life cycle costs of these two heating systems are close together. When comparing the cost in terms of sources of energy, the natural gas has a higher life cycle cost than electricity.

7.5 Summary

Table 7-4 presents a summary of the life cycle impacts per square meter of the floor area of the house. Data reflect the situation of Montreal, Canada.

Table 7-4 Overall life cycle impacts of the house with the different heating systems

Type of system	Life cycle energy use	Life cycle exergy destruction	Life cycle eq.CO_2 emissions	Life cycle cost
	(MJ/m^2)	(MJ/m^2)	($T\cdot CO_2\cdot Eq./m^2$)	($CAN\$/m^2$)
HWH with an electric boiler	9,637	9,159	0.284	90
HWH with a gas-fired boiler	8,520	7,668	0.505	89
FAH with an electric furnace	12,045	11,424	0.293	77
FAH with a gas-fired furnace	9,972	8,670	0.699	89

In the condition of Montreal, the results in Table 7-4 indicate that the HWH system with a gas-fired heating boiler has the lowest environmental impacts with respect to life cycle energy use and life cycle exergy destruction, while the HWH system with an electric heating boiler has the lowest impact with respect to the equivalent CO_2 emissions. The FAH system with an electric furnace has the lowest life cycle cost.

CHAPTER 8

CONCLUSIONS, CONTRIBUTIONS, AND FUTURE WORK

8.1 Conclusions

This research has presented the life cycle impacts of the HVAC systems and their components compared with that of a house located in Montréal, Canada. The life-cycle assessment methodology has been employed to evaluate the environmental performance and costs of two alternative heating systems for a house. For the evaluation of environmental impacts of the heating systems, the system inventory compilation is an important and time consuming task. Two heating systems, the hot water heating system and forced air heating system, have been evaluated with respect to life cycle energy use, GHG emissions, exergy destruction, and costs, all of which have global, regional, and long-lasting impacts on the environment and economy. The results of the present study lead to the following conclusions:

- Life cycle analysis reveals that in the pre-operating phase, the impacts of the heating systems are not significant comparied with that of the entire house. The impacts of the heating systems account for 1.9 to 6.7%, 1.4 to 5.0%, and 3.5 to 6.8% of the total impacts of the entire house, in terms of embodied energy, equivalent CO_2 emissions, and initial cost.
- In the operating phase, the HVAC systems have significant portions of life cycle impacts. The exergy analysis combined with the energy analysis based on mathematical models for operating energy consumption indicate to what extent the exergy is destroyed within the different components and also affected by the

electricity generation in the power plants. The exergy efficiency instead of the energy efficiency tells a different scenario that there are a lot of potentials to improve the inefficiencies in the systems.

- Based on the life cycle analysis, the electric hot water heating system causes the lowest greenhouse gas emissions, the gas hot water heating system causes the lowest energy use and exergy destruction, and the electric forced air heating system has the lowest life costs.

8.2 Contributions

This thesis brought the following contributions to the field of life cycle assessment for the HVAC systems in residential buildings:

- Developed the mathematical models in EES environment for the simulation of hot water heating system and forced air heating system that facilitate the energy and exergy analyses of the systems and components.
- Employed the decision models under uncertainty to the analysis of environmental impacts of the HVAC systems in residential buildings, specifically, conducted a payoff matrix model to evaluate the ranges of embodied energy and equivalent CO_2 emissions of the heating systems.
- Compiled and analyzed the existing embodied energy and CO_2 emissions values for materials commonly used in the heating systems.
- Revealed the life cycle impacts and compared with the building envelope in terms of embodied energy, equivalent greenhouse gas emissions, exergy destruction, and costs of the heating systems in a house in Montreal.

8.3 Recommendations for the future work

The present study focused on the life cycle analysis of the HVAC systems in Montreal. There are still some limitations in this research, therefore, future works are recommended as follows:

- The scope of the life cycle analysis is limited to the impacts in the pre-operating and the operating phases, the other life cycle phases such as the maintenance, replacement or renovation, and demolition are excluded due to the minor impact and the lack of reliable data. However, the impacts in these phases should be taken into account in the future work if the more detailed analysis is needed;
- This research focused on evaluating the impacts of the selected HVAC systems only on the heating conditions. This research could be expanded to explore the effect when the cooling conditions are applied. In addition, other types of HVAC systems or components such as heat pump, electrical baseboards, fan coil etc. should be evaluated in the future;
- In order to further understand the life cycle environmental impact of buildings, the future work could be extended to evaluate some more complex systems, such as, those used in commercial and institutional buildings;
- The other energy sources such as heating oil, coal, solar energy, and geothermal energy should be considered in the future.
- The other cities in Canada should be considered because of their different mix of energy use for the generation of electricity and different construction and energy costs.

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APPENDIX-1 Information of existing LCA databases

Country	**Database name**	**Short description**	**Language**	**Author/ Provider**
Canada	OPTIMISE	Embodied energy, water use & air emissions for 42 building materials	English French	Statistics Canada
Canada	Canadian Raw Material Database	LCI data	English	Environment Canada
Canada	ATHENA	Envir. LCA model used to assess envelope materials. & assemblies	English	Athena Sustainable Material Institute
USA	DEAM™ US	LCI db (US data), to be used with TEAM™ software	English French	Ecobalance
USA	Environmental Knowledge Base	Software tool for facility design, construction & operation	English	US Army CERL, IL
USA	LEED™	A green building rating system	English	
Japan	BRI LCA for buildings	Program calculating the energy use & CO2 emissions of a building	Japanese	Jap. Building Res. Institute
Japan	NIRE-LCA v. 2	Education of LCA (refrigerator)	Japanese	Atushi Inaba
Australia	SimaPro-5	LCI data, Embodied Energy for 14 materials	English	

Country	Database name	Short description	Language	Author/ Provider
Swiss	Oekobase	LCI db embedded into a LCA software aimed to assess packagings	German	Migros
Swiss	EcoInvent	LCI data for energy, transport & waste treatment for CH & Europe	German	ESU-ETH/EN ET
Swiss	REGIS 2.0	Site specific ecobalance software. 1000 items: ETH energy syst. & waste treat., BUWAL 250, infrastructure & transp. processes, etc.	German English	Sinum GmbH Lerchenfeldstr. 5 CH-9014, St-Gallen
Swiss	OekoPro 1.5 (EMPA)	Product-oriented LCA software. 1000 items: ETH energy syst. & waste treat., BUWAL 250 packag. mater., infras trp processes, etc.	German English	EMPA Lerchenfeldstr. 5 CH-9014, St-Gallen
Swiss	BUWAL 250	LCI of packaging materials	German English French	BUWAL/OFE FP
Denmark	Edip	LCI db for energy sources, transport & industrial products	Danish	
Denmark	SBI's LCA DB & Inventory tool	db integrated into an LCI tool with uncertainty calculations	English Danish	Danish Building Research Institute
French	DEAM (TM) EU	LCI db (European data), to be used with TEAM (TM) software	English French	Ecobilan M. P. Osset
Germany	GaBi 3	LCA software. 1500 items: 30 plastics, 140 intermediate chem., 50 power plant processes, 50 transport, etc.	English German	IKP Universität Stuttgart
Germany	Heraklit 4.8	LCA software. 900 items: energy syst., trp, waste treat., raw mater., basic mater., mater. conversion, services, recycling	German English	Fraunhofer-Institut (ILV) Munich
Germany	TEMIS 2 GEMIS 3	LCI tool. Few emissions for numerous energy & transport.	English German	Öko-Institut Darmstadt

		proces. in selected countries		
Germany	Umberto 2.0	LCA & site specific ecobalance software. 200 items: energy syst., trp, solid waste & waste water treat., raw & basic mat. (pack., etc.)	English German	IFU Hamburg
NL	IVAM LCA Data 2.0	LCI building products orient. data (mainly Dutch) for SimaPro 4 soft.	English (Dutch)	IVAM Environmental Research
NL	Energi- og miljøregnskap for bygg	LCI building materials data	German Norwegian	Norweg. Building Research Inst., Oslo
Swiss	SPINE@CPM	Data administration unit within CPM	English	CPM, Chalmers Tekniska Högskola, Göteborg
UK	The Boustead Model for LCI calculation.	LCI software. 4500 items db: APME data for plastics, electr. For 23 countries, etc.	English	Boustead Consulting Ltd

Note: NL--Netherlands

APPENDIX-2 Embodied Energy coefficients of Materials

Material	Description	*Level	MJ/kg	Original source	Ref. No.
Aluminum			170	Lawson, 1996	8
		1	150-240	Davis Langdon Consult.	3
Aluminum, virgin			129.5		2
		1	159.5	SIMAPRO	4
			145		6
			207.7	Franklin Association	11
		1	207.8	Deam database	9
		1	65-211	Samuels R. and Prasad US	10
		1	54-130	Samuels R. and Prasad NZ	10
		1	96	Samuels R. and Prasad UK	10
Aluminum, virgin		3	191	companies in New Zealand and Australia. Published data for carbon anodes. Process analysis of Trans-Tasman shipping operation	1
	extruded	3	201		
	extruded, anodised	3	227		
	extruded, factory painted	3	218		
	foil	3	204		
	sheet	3	199		
	extruded		145		2
	foil		154		2
Aluminum, recycled			11-40	Davis Langdon Consult.	3
			28-198	EU AL. Association	13
			8.1	Measures of sust. (web)	12
		1	8.1	manufacturer	1
	extruded	3	17.3		
	extruded, anodised	3	42.9		
	extruded, factory painted	3	34.3		

	foil	3	20.1		
	sheet	3	14.8		
Brass		4	62	manufacturer	1
			62.0	Measures of sust. (web)	
			49.3		2
polypropylene		4	95.4	manufacturer	1
Copper		3	70.6	manufacturer	7
			70.6	Measures of sust. (web)	12
		1	71-85	Davis Langdon Consult.	3
			100	Lawson, 1996	8
			45.9		2
			57-91	ANPA, Boustead Ltd.	13
	extruded	2	48.7	Deam database	9
Copper recycled			40-50	Davis Langdon Consult.	3
Copper tube			65.8	Deam database	5
high density polyethylene (HDPE)			103	manufacturer	1
	extrusion		87.5	Deam database	9
low density polyethylene (LDPE)			103	manufacturer	1
			112	Baird & Chan	2
PVC		2	70	manufacturer, industry data	1
			70	Measures of sust. (web)	12
			96		2
Glass			15	AIA	10
Glass, recycled			10	AIA	10
Steel			3	Krogh&Hansen	11
			80-115	Treloar	8
			30.2	Measures of sust. (web)	12
			64.6	SIMAPRO	4
		1	25-40	Davis Langdon Consult.	3
Steel	extruding, galvanizing		37.3	Deam database	9
	galvanizing		38	Lawson, 1996	8

	galvanized		27-38	GEMIS, IIASI	13
Steel, electrical furnace			6.7	JMITI	11
Steel, blast furnace			16.8	JMITI	11
Steel, recycled		4	10.1	manufacturer	1
			8.9	Measures of sust. (web)	12
			9-12	Davis Langdon Consult.	3
			20-60	Treloar	8
Steel, virgin, general		2	32	Lawson, 1994	1
			35		2
Steel cold rolled		1	28.8	Deam database	9
Steel secondary hot rolled			14.1	Deam database	5
Stainless Steel		1	16.3	Deam database	9
			62	EUROFER	13
Steel, pipe		1	28.74	Athena	10
Zinc		2	51	Lawson, 1994	1
			51.0	Measures of sust. (web)	12
	galvanising (per kg steel)	2	2.8	manufacturer	1
Cast iron			32.8	Deam database	5
Cellulose insulation			3.3	Measures of sust. (web)	12
Mineral insulation			14.6	Measures of sust. (web)	12
Fiberglass insulation			30.3	Measures of sust. (web)	12
Polystyrene insulation			117	Measures of sust. (web)	12
Rigid PUR			105-118	ANPA, GEMIS	13

Note: * IFIAS, 1974.

APPENDIX-3 Equivalent CO_2 emissions Coefficients of materials

Material	**kg·CO_2/kg·material**	**Original source**	**Ref. No.**
Aluminum, primary	10	Deam database	9
Aluminum, recycled	1.3-11.3	EU AL. Association	13
copper	6.1	Deam database	9
copper	3.24-5.88	ANPA, Boustead Ltd.	13
stainless steel	1.2	Deam database	9
	6.2	EUROFER	13
steel cold rolled	2.1	Deam database	9
steel	3.2	Deam database	9
steel	1.775		10
steel	1.956		10
steel	1.910	Frankl.P.	10
steel, electrical furnace	440	JMITI	11
steel, blast furnace	1467	JMITI	11
Steel, galvanized	1.8-2.8	GEMIS, IIASI	13
high density polyethylene (HDPE) extrusion	3	Deam database	9
Rigid PUR	3.4-3.8	ANPA, GEMIS	13

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Appendix-4 The data for HVAC equipment and components

Steel, Copper, PVC&CPVC pipe, approximate weight (lbs/ft). (Howell, 2004)

Nom. Size (in)	Schedule 40 steel pipe	Copper pipe	Schedule 40 PVC/CPVC pipe
1/4	0.424	0.145	n/a
3/8	0.567	0.269	n/a
½	0.850	0.344	0.17
¾	1.13	0.641	0.22
1	1.68	0.839	0.33

Source: www.howellpipe.com/howpipe.htm

Steel, Copper, and PVC/CPVC fittings, approximate weight (lbs/piece). (Howell, 2004)

Nom. Size	150# Galvanized malleable fittings		Copper		PVC/CPVC Weight (oz.)	
(in)	90Elbow	Tee	90Elbow	Tee	90Elbow	Tee
1/4	0.12	0.16	0.02	0.02	n/a	n/a
3/8	0.17	0.24	0.03	0.04	n/a	n/a
½	0.27	0.37	0.04	0.06	0.89	1.25
¾	0.43	0.58	0.10	0.15	1.25	1.71
1	0.65	0.92	0.20	0.30	1.79	3.21

Source: www.howellpipe.com/howpipe.htm

Strainers: body—cast iron, screen—stainless steel, approximate weight (lbs/piece).

Diameter (in)	½	¾	1	1-1/2	2
Weight	2-1/2	3	5	10	16

(Keckley, 2004) Source: http://www.keckley.com/style_b.htm

Steel expansion tank (Amtrol, 2004)

Tank size (gal.)	Diameter (in.)	Amtrol model	Weight (lbs)
2.0	8	15	4.7
4.4	11	30	5.0
7.6	11	60	12.0

Source: www.grainger.com

Air system accessories (steel) (Ameri-Flow®, 2004)

Maximum duct size (in.) H×W	Overall size (in.) H×W	Ameri-Flow model	Shipping weight (lbs)
Registers, two-way wallside			
10*4	11½*5½	356W10*4	1.0
10*6		356W10*6	1.4
Registers, Floor			
2½*12	4*13-3/8	413B2*12	0.9
4*10	5½*11-3/8	413B4*10	1.5
1*12	5½*13-3/8	413B4*12	1.2
Grilles Return air			
10*6	11½*7½	372W10*6	0.7
12*6	13½*7½	372W12*6	1.2
12*12	13½*13½	372W12*12	2.0
14*6	15½*7½	372W14*6	1.0

Source: www.grainger.com

Balancing dampers* (galvanized steel) (Phllips-aire®, 2004)

Nom. Duct size (in.) W×H	Actual Damper size (in.) W×H	Model	Shipping weight (lbs)
Rectangular			
6*6	7¾*5¾	PA11-6*6	3.0
8*8	5¾*7¾	PA11-8*8	3.0
10*6	9¾*5¾	PA11-10*6	3.0
12*8	11¾*7¾	PA11-12*8	4.0
Round			
6"	5 1/4	PA12-6	2.0
8"	7 3/4	PA12-8	2.4

Note: *Damper frame is 3 1/2" deep × 5/8" x 16 gage galvanized steel with 20 gage blades for rectangular dampers, and is 4 1/2" deep × 20 gage galvanized steel with 22 gage blades for round dampers.

Source: www.grainger.com.

Circulating pumps

Solar hot water circulating pumps (energy supermarket, 2005)

Pump	Models	Body materials	Weight (lbs)
3.5 W	EI SID 3.5 B	Brass and Stainless steel	2.0
5.0 W	EI SID 5.0 B	Brass and Stainless steel	2.0
10 W	EI SID 10 B	Brass and Stainless steel	2.0

Source: http://shop.solardirect.com/product_info.php?cPath=69_71_84_72_73&products_id=167

Furnace:

Gas-fired furnaces (Dayton®, 2004)

Input (MBH)	AFUE	Dimension (in.) H×W×D	Approx. weight (lbs)
50	80%	31½*17½*29¾	120
75	80%	31½*17½*29¾	148

Source: www.grainger.com

Gas-fired furnaces (York®, 2004)

Input (MBH)	AFUE %	Model	Blower Dia. × Wid. × hp.	Shipping weight (lbs)
60	94	PIXUB12N05501	11 * 8 * ½	130
80	94	PIXUB12N07501	11 * 8 * ½	145

Source: www.yorkupg.com

Blowers

Blowers: welded steel construction. (Dayton®, 2004)

Model no.	Wheel Dia. × Wid	Motor (hp)	Weight (lbs)
2C938	9 * 4½	1/3	24
2C890	10-5/8 * 5¼	¾	33
2C939	10-5/8 * 5¼	¾	35

Source: www.grainger.com

Blower Motors

Blower motors (Dayton®, 2004)

Model no.	Motor (hp)	Weight (lbs)
2C938	1/3	13
2C890	¾	20
2C939	¾	18

Source: www.grainger.com

Appendix-5 The calculation tables of the heating systems and the estimated quantities of the heating system components

Table A5-1 Tabular calculation of the hot water heating system

Pipe section	Diameter (mm)	Mass flow rate (kg/s)	Length m	Head loss m/m	Fittings	G a	T r	T b	E l	Eq. length (m)	Total length (m)	Total head loss (m)
1	15	0.069	8.5	0.024		1	1	1	1	1.67	10.20	0.24
2	10	0.027	1.2	0.038		1	1	1		0.52	1.72	0.07
3	10	0.018	2.7	0.022			2			0.00	2.70	0.06
4	10	0.009	2.1	0.006				1	1	0.58	2.68	0.02
5	10	0.009	0.9	0.006	add a balance valve (7 m)	1			5	8.20	9.10	0.05
6	10	0.027	5.8	0.038		1	1		1	0.36	6.16	0.23
7	15	0.054	4.9	0.016			2		1	0.37	5.27	0.08
8	15	0.069	3	0.024		1	1	1		1.30	4.30	0.10
											0.00	0.94
9	12	0.063	0.9	0.06		1	1	1		0.69	1.59	0.10
10	10	0.018	4	0.022		1	1	1		0.52	4.52	0.10
11	10	0.009	1.8	0.006				1	1	0.58	2.38	0.01
12	10	0.009	0.9	0.006	add a balance valve (7 m)	2			7	8.77	9.67	0.06
13	10	0.018	11.6	0.022		1	1		2	0.57	12.17	0.27
14	10	0.036	3.7	0.058			2			0.00	3.70	0.21
15	12	0.063	1.8	0.06		1	2		2	0.76	2.56	0.15
											0.00	0.92
											0.00	
50	15	0.132	6.4	0.07		2	1			0.60	7.00	0.49
51	15	0.132	3	0.07	Boiler=3EL	1	2		3	1.41	4.41	0.31
16	12	0.042	4.3	0.03			2			0.00	4.30	0.13
17+18	10	0.015	6.7	0.013			2		2	0.42	7.12	0.09
19	10	0.018	2.7	0.022			2			0.00	2.70	0.06
20	10	0.009	1.8	0.006			1	1	1	0.58	2.38	0.01
21	10	**0.027**	1.2	0.038		1	1	1		0.52	1.72	0.07
22	10	**0.018**	2.7	0.022			2			0.00	2.70	0.06
23	10	**0.009**	2.1	0.006				1	1	0.58	2.68	0.02
24	10	**0.009**	0.9	0.006	add a balance valve (7 m)	1			5	8.20	9.10	0.05
25	10	**0.027**	1.5	0.038		1	1		1	0.36	1.86	0.07
26	10	0.009	1.8	0.006			1	1	1	0.58	2.38	0.01
27	10	0.018	2.7	0.022			2			0.00	2.70	0.06
28	10	**0.015**	1.2	0.013		1	1	1		0.52	1.72	0.02
29	10	**0.01**	2.7	0.006			2			0.00	2.70	0.02
30	10	0.005	2.1	0.002				1	1	0.58	2.68	0.01
31	10	0.005	0.9	0.002	add a balance valve (40 m)	2			5	41.35	42.25	0.08
32	10	0.015	1.5	0.013		1	1	1		0.52	2.02	0.03
33	10	0.01	2.7	0.006		1	1	1		0.52	3.22	0.02
34	10	0.005	1.8	0.002		1	1	1		0.52	2.32	0.005
35	10	0.018	4.3	0.022		1	1	1		0.52	4.82	0.11

Pipe section	Diameter (mm)	Mass flow rate (kg/s)	Length m	Head loss m/m	Fittings	G a	T r	T b	E L	Eq. length (m)	Total length (m)	Total head loss (m)
36	10	**0.009**	2.1	0.006				1	1	0.58	2.68	0.02
37	10	**0.009**	0.9	0.006	add a balance valve (7 m)	1			5	8.20	9.10	0.05
38	10	0.018	4.3	0.022		1	1	1		0.52	4.82	0.11
39	10	0.009	1.8	0.006		1	1	1		0.52	2.32	0.01
40	10	**0.027**	1.2	0.038		1	1	1		0.52	1.72	0.07
41	10	**0.018**	2.7	0.022			2			0.00	2.70	0.06
42	10	**0.009**	2.1	0.006				1	1	0.58	2.68	0.02
43	10	**0.009**	0.9	0.006	add a balance valve (7 m)	1			5	8.20	9.10	0.05
44	10	**0.027**	5.8	0.038		1	1		1	0.36	6.16	0.23
45	10	0.009	1.8	0.006			1	1	1	0.58	2.38	0.01
46	10	0.018	2.7	0.022			2			0.00	2.70	0.06
47	10	0.009	1.8	0.006		1	1	1		0.52	2.32	0.01
48	12	0.045	6.1	0.032			2		1	0.28	6.38	0.20
49	10	0.027	3	0.035			1		1	0.21	3.21	0.11

Note: Loops balancing:

1) “L1+L2+L3+L4+L5+L6+L7+L8+L19+L20”=0.94
2) "L1+L16+L21+L22+L23+L24++L26+L27+L25+L7+L8"=0.9
3) "L1+L16+L17+L18+L28+L29+L30+L31+L34+L33+L32+L8"=0.75
4) “L9+L10+L11+L12+L13+L14+L15+L47”=0.92
5) "L9+L48+L35+L36+L37+L39+L38+L14+L15"=0.96
6) "L9+L48+L49+L40+L41+L42+L43+L45+L46+L44+L15"=1.07

The loop 6 is the critical path, which causes the maximal pressure loss. The pressure loss requirement for the pump is calculated at the sum of the pressure loss in the critical path and in the sections 50 and 51, which is equal to 1.87m H_2O or 18.5 kPa.

Table A5-2 Rectangular duct size in SI unit and in IP unit

Side A (mm)	Side B (mm)	Side A (in.)	Side B (in.)
150	150	6	6
175	150	7	6
275	150	11	6
325	150	13	6
375	250	15	10
425	250	17	10
550	250	22	10
700	300	28	12

Table A5-3 Tabular calculation of the duct system

Duct section	**Duct element**	**Air flow rate** (cfm)	**Rectangular duct size** (in.)		**Eq. Round Duct size** (in.)	**Friction loss rate*** (in.wg/100ft)	**Equiv. length** (ft)	**Duct Length** (ft)	**Total pressure loss** (in.wg.)
			A	B					
Return trunk									
4	duct	1171.6	28	12	19.6	**0.050**		21.0	0.033
	fittings						45		
Supply trunk									
6	duct	55.72			5.0	**0.075**		3.9	0.052
	fittings						65		
7	duct	111.44			6.0	**0.110**		1.0	0.018
	fittings						15		
8	duct	55.72			5.0	**0.075**		8.5	0.111
	fittings						140		
9	duct	55.72			5.0	**0.075**		9.5	0.112
	fittings						140		
10	duct	167.37	6	6	6.6	**0.150**		7.9	0.087
	fittings						50		
11	duct	396.19	13	6	9.5	**0.120**		10.5	**0.109**
	fittings						80		
12	duct	225.42	7	6	7.1	**0.170**		3.6	**0.108**
	fittings						60		
13	duct	55.72			5.0	**0.075**		8.2	0.062
	fittings						75		
14	duct	167.37	6	6	6.6	**0.150**		10.5	**0.031**
	fittings						10		
15	duct	111.44			6.0	**0.110**		8.5	0.064
	fittings						50		
16	duct	55.72			5.0	**0.075**		5.2	0.101
	fittings						130		
17	duct	55.72			5.0	**0.075**		5.2	0.101
	fittings						130		
18	duct	55.72			5.0	**0.075**		15.1	**0.068**
	fittings						75		
19	duct	55.72			5.0	**0.075**		2.0	0.043
	fittings						55		
20	duct	111.44			6.0	**0.110**		3.6	0.020
	fittings						15		
21	duct	55.72			5.0	**0.075**		2.0	0.065
	fittings						85		
22	duct	111.44			6.0	**0.110**		7.5	0.074
	fittings						60		
23	duct	55.72			5.0	**0.075**		2.0	0.065
	fittings						85		
24	duct	111.44			6.0	**0.110**		7.5	0.074
	fittings						60		
25	duct	225.42	7	6	7.1	**0.170**		1.0	0.010
	fittings						5		
26	duct	338.98	11	6	8.8	**0.130**		7.9	0.017
	fittings						5		

27	duct	55.72			5.0	**0.075**		2.0	0.043
	fittings						55		
28	duct	111.44			6.0	**0.110**		6.2	0.034
	fittings						25		
29	duct	733.05	15	10	13.5	**0.070**		3.0	**0.013**
	fittings						15		
30	duct	847.46	17	10	14.1	**0.070**		14.4	**0.024**
	fittings						20		
31	duct	55.72			5.0	**0.075**		2.0	0.065
	fittings						85		
32	duct	111.44			6.0	**0.110**		3.3	0.059
	fittings						50		
33	duct	55.72			5.0	**0.075**		2.0	0.065
	fittings						85		
34	duct	111.44			6.0	**0.110**		3.3	0.059
	fittings						50		
35	duct	225.42	7	6	7.1	**0.170**		8.5	0.057
	fittings						25		
36	duct	55.72			5.0	**0.075**		2.0	0.065
	fittings						85		
37	duct	111.44			6.0	**0.110**		3.3	0.031
	fittings						25		
38	duct	1059.3	22	10	15.9	**0.055**		6.6	**0.059**
	fittings						100		
39	duct	1171.6	22	10	15.9	**0.068**		3.0	**0.026**
	fittings						35		

Note: 1. *The friction loss rate is obtained from the ASHRAE handbook of fundamentals, 1977.

2. Assuming the duct along the sections 39 +38 +30 +29 +11 +12 +14 +18 is the critical path. The total pressure losses of the critical path =0.44 in. wg, or =109 Pa.

Table A5-4 Equivalent lengths of the fittings

Duct section	**Type of fitting**	**Parameters**	***Equivalent length (ft)**
4	return grille		
	Elbow 90	700*300	15
	Square elbow	700*300	30
	Σ		45
6	floor diffuser	universal boot, 71cfm	
	boot	4-H	50
	elbow	Φ125	10
	tee strai.	Φ150/125/125	5
	Σ		65
7	tee strai.	150*150	5
	transition	150*150 to Φ150	10
	Σ		15
8	diffuser		
	boot	fitting 4-G	80
	elbow	Φ125	10
	transition	150*150 to Φ125	
	tee branch	150*150	50
	Σ		140
9	diffuser		
	boot	fitting 4-G	80
	elbow	Φ125	10
	tee branch	Φ150/125/125	50
	Σ		140
10	transition	325*150 to 150*150	
	tee branch	325*150	50
	Σ		50
11	tee branch	375*250	50
	transition	375*250 to 325*150	10
	elbow*2	325*150	20
	Σ		80
12	transition	325*150 to 175*150	10
	tee branch	325*150	50
	Σ		60
13	take-off	Φ125	25
	boot	4-H	50
	diffuser		
	Σ		75
14	transition	175*150 to 150*150	10
	Σ		10

Duct section	**Type of fitting**	**Parameters**	***Equivalent length (ft)**
15	tee branch	150*150	50
	transition	150*150 to Φ150	
	Σ		50
16	diffuser		
	boot	fitting 4-G	80
	tee branch	Φ150/125/125	50
	Σ		130
17	diffuser		
	boot	fitting 4-G	80
	tee branch	Φ150/125/125	50
	Σ		130
18	diffuser		
	boot	fitting 4-H	50
	elbow	Φ125	10
	transition	150*150 to Φ125	10
	tee straight	150*150	5
	Σ		75
19	diffuser	angle boot	
	boot	fitting 4-H	50
	tee straight	Φ150/125/125	5
	Σ		55
20	elbow	Φ150	10
	transition	175*150 to Φ150	
	tee straight	175*150	5
	Σ		15
21	diffuser		
	boot	fitting 4-G	80
	tee straight	Φ150/125/125	5
	Σ		85
22	elbow	Φ150	10
	transition	275*150 to Φ150	
	tee branch	275*150	50
	Σ		60
23	diffuser		
	boot	fitting 4-G	80
	tee straight	Φ150/125/125	5
	Σ		85

Duct section	**Type of fitting**	**Parameters**	***Equivalent length (ft)**
24	elbow	Φ150	10
	transition	175*150 to Φ150	
	tee branch	175*150	50
	Σ		60
25	tee straight	275*150	5
	Transition	275*150 to 175*150	
	Σ		5
26	tee straight	375*250	5
	Transition	375*250 to 275*150	
	Σ		5
27	Diffuser	angle boot	
	Boot	fitting 4-H	50
	tee straight	Φ150/125/125	5
	Σ		55
28	take-off	Φ150	25
	Σ		25
29	tee straight	425*250	5
	Transition	425*250 to 375*250	10
	Σ		15
30	Elbow	550*250 r/w >0.5	10
	Transition	550*250 to 425*250	10
	Σ		20
31	Diffuser		
	Boot	fitting 4-G	80
	tee straight	Φ150/125/125	5
	Σ		85
32	Transition	200*150 to Φ150	
	tee branch	200*150	50
	Σ		50
33	Diffuser		
	Boot	fitting 4-G	80
	tee straight	Φ150/125/125	5
	Σ		85
34	Transition	175*150 to Φ150	
	tee branch	175*150	50
	Σ		50
35	take-off	175*150	25
	Σ		25

Duct section	**Type of fitting**	**Parameters**	***Equivalent length (ft)**
36	Diffuser		
	Boot	fitting 4-G	80
	tee straight	Φ150/125/125	5
	Σ		85
37	take-off	Φ150	25
	Σ		25
38	tee branch	550*250	50
	tee branch	550*250	50
	Σ		100
39	Transition	entrance of plenum fitting 1-C	35
	Σ		35

Note: *The equivalent lengths of the fittings are given by ASHRAE handbook, systems and equipment, 2000.

Table A5-5 Quantities of ducts

Duct size A × B		**Length (m)**	**Thickness (mm)**	**Gage**	**kg/m^2**	**Mass (kg)**
150	150	5.6	0.6	24	4.88	16.4
175	150	4	0.6	24	4.88	12.69
275	150	2.4	0.7	22	6.1	12.44
325	150	3.2	0.7	22	6.1	18.54
375	250	0.9	0.7	22	6.1	6.863
425	250	4.4	0.9	20	7.32	43.48
550	250	2.9	0.9	20	7.32	33.96
700	300	6.4	0.9	20	7.32	93.7
	Φ125	21.2	0.6	24	4.88	40.66
	Φ150	13.5	0.6	24	4.88	31.03
					Sum=	**309.8**

Table A5-6 Quantities of fittings

Fittings	**Description**	**Quantity**	**Surface area♦ (m^2/ea.)**	**Thickness (mm)**	**Mass (kg/ea.)**	**Mass (kg)**
Elbow						
700*300	R=1.5W, 90°	1	2.198	0.9	15.826	15.83
Φ125*	R=1.5d, 90°	4	0.164	0.6	0.790	3.16
Φ150*	R=1.5d, 90°	3	0.223	0.6	1.070	3.21
325*150	R=1.5W, 90°	2	0.485	0.6	2.327	4.65
550*250	R=1.5W, 90°	1	1.382	0.9	9.948	9.95

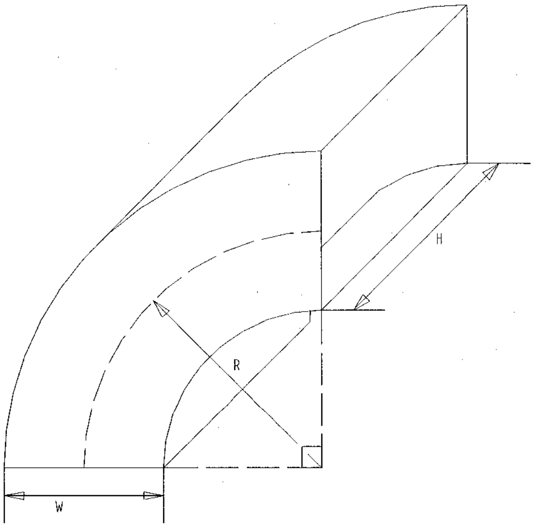
Tee						
Φ150/125/125*		9	0.195	0.6	0.940	8.46
150*150		2	0.158	0.6	0.760	1.52
325*150		1	0.341	0.6	1.638	1.638
175*150		1	0.184	0.6	0.882	0.882
275*150		1	0.289	0.6	1.386	1.386
375*250		1	0.656	0.7	3.675	3.675
425*250		1	0.744	0.7	4.165	4.165
Diffuser						
10" * 4"†		21			0.670	14.07
Take-off						
Φ125*		1	0.026	0.6	0.120	0.12
Φ150*		2	0.031	0.6	0.150	0.3
175*150		1				0
Transitions						
150*150 to Φ125[c]	4 seg. 60°	2	0.022	0.6	0.107	0.214
150*150 to Φ150[c]		2	0.015	0.6	0.072	0.144
175*150 to Φ150*		3	0.085	0.6	0.408	1.224
275*150 to Φ150*		1	0.157	0.7	0.881	0.881
175*150 to 150*150[a]		1	0.015	0.6	0.070	0.070
275*150 to 175*150[a]		1	0.069	0.6	0.331	0.331
325*150 to 150*150[a]		1	0.125	0.6	0.598	0.598
325*150 to 175*150[a]		1	0.110	0.6	0.528	0.528
375*250 to 275*150[b]		1	0.091	0.6	0.437	0.437
375*250 to 325*150[b]		1	0.102	0.6	0.491	0.491
425*250 to 375*250[a]		1	0.060	0.7	0.334	0.334
550*250 to 425*250[a]		1	0.168	0.7	0.942	0.942
Balancing Dampers	Rectangular					
150*150†		1			1.35	1.35
175*150†	Rectangular	2			1.35	2.7
Φ150†	Round	9			0.9	8.1
					Sum=	**102.62**

Notes: *data from manufacturer's website (www.frapol.com.pl/katalogi/kk_gb.pdf)

†data from manufacturers' websites (www.grainger.com), Rectangular and round dampers data are compiled from (Phillips-aire, 2005).

♦The surface areas A_s of fittings, which are not available on the manufacturer's data, are calculated as follows:

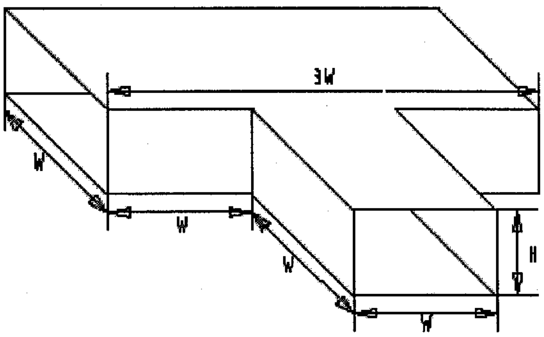
1. Elbow



Condition: R/W=1.5.

$$A_s = \pi \cdot W \cdot (W + H)$$

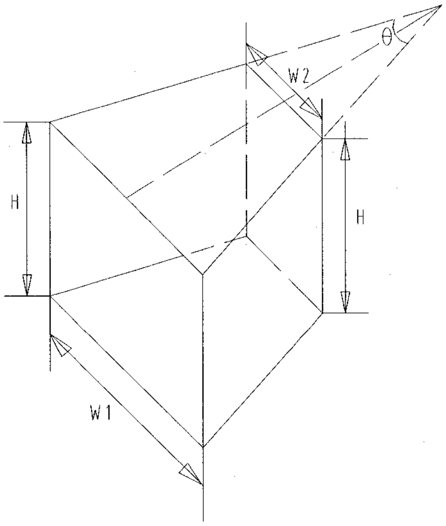
2. Tee



$$A_s = 7 \times W \cdot H + 4 \times W^2$$

3. Transitions

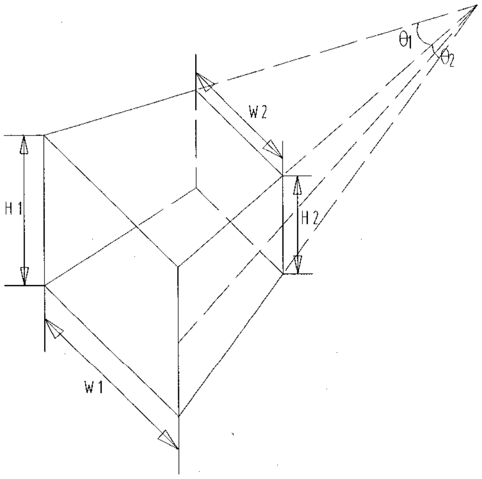
a.



Condition: θ = 60°.

$$A_s = 0.5 \times (W_1 + W_2) \cdot (W_1 - W_2) / \tan\frac{\theta}{2} + H \cdot (W_1 - W_2) / \sin\frac{\theta}{2}$$

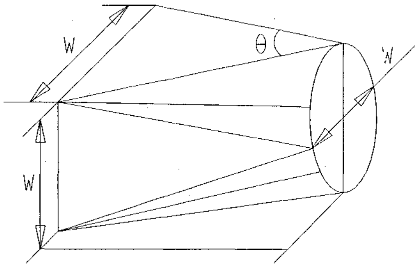
b.



Conditions: θ_1=60°; θ_2=30°.

$$A_s = 0.5 \times (W_1 + W_2) \cdot (W_1 - W_2) / \tan\frac{\theta_1}{2} + (H_1 + H_2) \cdot (H_1 - H_2) / \tan\frac{\theta_2}{2}$$

c.



Condition: θ=60°.

$$A_s = \sqrt{3} \times W^2 + \frac{\pi \cdot W}{2} \cdot \sqrt{W^2 - (\frac{\pi \cdot W}{8})^2}$$

Table A5-7 Quantities of duct hangers

Rectangular ducts	**Strap hangers**	**Length (m/ea.)**	**Mass (kg)**
550*250	2	1.9	0.6
425*250	2	1.65	0.52
375*250	2	1.55	0.48
175*150	1	0.95	0.15
200*150	3	1.0	0.48
150*150	1	0.9	0.15
Round ducts	**Wire hangers**	**Length (m/ea.)**	**Mass (kg)**
Φ 125	16	0.7	0.5
Φ 150	3	0.77	0.1
		Sum=	**3.0**

Appendix-6 Boiler's data

Boiler (http://www.grainger.com, http://www.viessmann.ca)

Manufacturer	Boiler1	Boiler2	Boiler3
	hydroTherm	Viessmann	Viessmann
Model	EW-65-INT	Vitogas 100	Vitogas050 ECD-65
Output KW	15.2	15	16
AFUE %	81.4	93	83.7
Dimension (mm)	628*333*826	663*500*780	1003*340*502
Weight Kg	121	101	106
Fuel type	Natural gas	Natural gas	Natural gas
Materials			
Heat exchanger	Cast iron	Gray Cast iron	Gray Cast iron
Burner		Stainless steel	Stainless steel
Draft blower or draft hood	Draft hood		Draft hood
Casing/cabinet	Insulated stainless steel		Insulated jacket
Insulation	Yes, 1" fiberglass	Yes	Yes
Other components of standard equipment which are not considered in study	ASME pressure relief valve, Combination gas valve, Aquastat relay, Circulator, 24 V transformer, Temperature and pressure gauges, Pre-wired plug in vent damper, Intermittent pilot	30 psi pressure relief valve, Pressure gauge, Installation fittings, Cleaning brush	30 psi pressure relief valve, Pressure gauge, Installation fittings, Cleaning brush

Boiler (http://www.burnham.com, http://www.olsenhvac.com)

Manufacturer	Boiler4	Boiler5	Boiler6	Boiler7
	Oslen	Oslen	Oslen	Oslen
Model	Q 90-50	ODV -50B	OSC3	OMGB-50
Output KW	13	12.3	13	12.3
AFUE %	90%	83%	87%	84%
Dimension (mm)	1002*502*711	781*286*686	781*380*686	781*284*686
Weight Kg	100	92	142	N/A
Fuel type	Natural gas	Natural gas	Natural gas	Natural gas

Materials				
Heat exchanger	Cast aluminum	Cast iron	Cast iron	Cast iron
Burner	Stainless steel	Stainless steel	Stainless steel	Stainless steel
Draft blower or draft hood	Draft fan	Draft fan	Draft fan	Draft hood
Casing/cabinet	Baked enamel finish	Powder coat Paint finish	Powder coat Paint finish	N/A
Insulation	No	No	No	No
Other components of standard equipment which are not considered in study	Honeywell L4080 hi limit aquastat. Transformer. 1 1/4" Taco (or Groundfos) circulator with isolation (ball) valves. Temperature and pressure gauges. 30 psi ASME relief valve. Hoffman air vent. Service Switch. Microprocessor based Integrated Boiler Control. Automatic gas valve. Hot surface igniter. Casting and vent temperature safety switches. Airflow proving switches.	Combination Aquastat Relay, Theraltimeter Gauge, Circulator, Electronic Ignition System, A.S.M.E. Relief Valve, Drain Cock, Safety Pressure Switch.	Limit Control, Removable Transformers, Plug-In Relay, Theraltimeter Gauge, Circulator, Hot Surface Pilot, A.S.M.E. Relief Valve, Drain Cock, Safety Pressure Switch, Combination Intake/Exhaust Termination Kit.	Combination aquastat relay, theraltimeter gauge, Circulator, combination 24-volt gas control, A.S.M.E. relief valve, drain cock, stack damper wiring harness, blocked-vent roll-out safety switches, thermocouple, non-linting safety pilot.

Continues

Manufacturer	Boiler8	Boiler9	Boiler10
	Burnham	Burnham	Burnham
Model	Series 2-203	Sp3	IN3
Size KW	15.2	15.2	15
AFUE %	80%	84%	81%
Dimension (mm)	790*304*628	914*368*628	1016*368*635
Weight Kg	123	120	158
Fuel type	Natural gas	Natural gas	Natural gas
Materials			
Heat exchanger	Cast iron	Cast iron	Cast iron
Burner	Stainless steel	Stainless steel	Stainless steel
Draft blower or draft hood	Draft hood	Draft fan	Draft fan
Casing/cabinet	Insulated jacket	Insulated jacket	Insulated jacket
Insulation	Yes	Yes	Yes
Other components of standard equipment which are not considered in study	Circulator & Piping - Shipped Loose Pressure/Temperature Gauge Drain Valve High Limit Circulator Relay Transformer and Junction Box 100% Shut-off Combination Step Opening Gas Valve Safety Relief Valve Vent Damper Blocked Vent Switch Flame Roll-Out Switch	Circulator -& Shipped Loose Pressure Temperature Gauge Drain Valve High Limit 30 sec Prepurge & Continuous Retry for Ignition Flame Roll-Out Switch J-Box with Transformer/Relay Control 100% Shut-Off Redundant Combination Gas Valve Safety Relief Valve Differential Pressure Switch Vent Connector/Terminal Air Inlet Terminal Vent Terminal for (sidewall) venting	Combustible Floor Certified Flame Roll Out Switch (FRS) Blocked Vent Switch (BVS) Concealed Step Opening Gas Valve Safety Relief Valve Pressure Temperature Gauge Thermostat Isolation Relay Vent Damper - IN3-IN9 2" Supply Tapping 2" Return Tapping 1-1/4" Indirect Water Heater Tappings 3" AL29-4C® Stainless Steel Vent Connector/Terminal

Appendix-7 Payoff matrix model (Embodied energy)

Boiler total mass =150 kg,
H—heat exchanger, B—burners, D—draft blower, C—casing, I—insulation
Outcomes: Embodied energy (MJ)

Embodied Energy					States of nature						
				H	0.45	0.5	0.55	0.6	0.65	0.7	0.75
				B	0.07	0.05	0.07	0.06	0.05	0.06	0.05
				D	0.04	0.03	0.04	0.02	0.02	0.03	0.02
				C	0.42	0.4	0.34	0.31	0.27	0.21	0.17
H	B	D	C	I	0.02	0.02	0	0.01	0.01	0	0.01
Alt.											
1	1	2	2	a	4619.1	4637.1	4692.0	4709.6	4733.6	4776.0	4793.6
1	1	2	2	b	4592.4	4610.4	4692.0	4696.2	4720.2	4776.0	4780.2
1	1	2	3	a	3831.6	3887.1	4054.5	4128.3	4239.3	4400.3	4486.8
1	1	2	3	b	3804.9	3860.4	4054.5	4115.0	4214.0	4382.3	4461.5
1	1	3	2	a	4544.1	4580.9	4617.0	4672.1	4696.1	4719.8	4756.1
1	1	3	2	b	4517.4	4554.2	4617.0	4658.7	4682.7	4719.8	4742.7
1	1	3	3	a	3756.6	3830.9	3979.5	4090.8	4189.8	4326.0	4437.3
1	1	3	3	b	3729.9	3804.2	3979.5	4077.5	4176.5	4326.0	4424.0
1	2	2	2	a	4577.1	4607.1	4650.0	4673.6	4703.6	4740.0	4763.6
1	2	2	2	b	4550.4	4580.4	4650.0	4660.2	4690.2	4740.0	4750.2
1	2	2	3	a	3789.6	3857.1	4012.5	4092.3	4197.3	4346.3	4444.8
1	2	2	3	b	3762.9	3830.4	4012.5	4079.0	4184.0	4346.3	4431.5
1	2	3	2	a	4502.1	4550.9	4575.0	4636.1	4666.1	4683.8	4726.1
1	2	3	2	b	4475.4	4524.2	4575.0	4622.7	4652.7	4683.8	4712.7
1	2	3	3	a	3714.6	3800.9	3937.5	4054.8	4159.8	4290.0	4407.3
1	2	3	3	b	3687.9	3774.2	3937.5	4041.5	4146.5	4290.0	4394.0
1	3	2	2	a	4445.9	4513.4	4518.8	4561.1	4609.8	4627.5	4669.8
1	3	2	2	b	4419.2	4486.7	4518.8	4547.7	4596.5	4627.5	4656.5
1	3	2	3	a	3658.4	3763.4	3881.3	3979.8	4103.6	4233.8	4351.1
1	3	2	3	b	3631.7	3736.7	3881.3	3966.5	4090.2	4233.8	4337.7
1	3	3	2	a	4370.9	4457.1	4443.8	4523.6	4572.3	4571.3	4632.3
1	3	3	2	b	4344.2	4430.4	4443.8	4510.2	4559.0	4571.3	4619.0
1	3	3	3	a	3714.6	3800.9	3937.5	4054.8	4159.8	4290.0	4407.3
1	3	3	3	b	3556.7	3680.4	3806.3	3929.0	4052.7	4177.5	4300.2
2	1	2	2	a	4349.1	4337.1	4362.0	4349.6	4343.6	4356.0	4343.6
2	1	2	2	b	4322.4	4310.4	4362.0	4336.2	4330.2	4356.0	4330.2
2	1	2	3	a	3561.6	3587.1	3724.5	3768.3	3837.3	3962.3	4024.8
2	1	2	3	b	3534.9	3560.4	3724.5	3755.0	3824.0	3962.3	4011.5
2	1	3	2	a	4274.1	4280.9	4287.0	4312.1	4306.1	4299.8	4306.1
2	1	3	2	b	4247.4	4254.2	4287.0	4298.7	4292.7	4299.8	4292.7
2	1	3	3	a	3486.6	3530.9	3649.5	3730.8	3799.8	3906.0	3987.3
2	1	3	3	b	3459.9	3504.2	3649.5	3717.5	3786.5	3906.0	3974.0
2	2	2	2	a	4307.1	4307.1	4320.0	4313.6	4313.6	4320.0	4313.6

2	2	2	2	b	4280.4	4280.4	4320.0	4300.2	4300.2	4320.0	4300.2
2	2	2	3	a	3519.6	3557.1	3682.5	3732.3	3807.3	3926.3	3994.8
2	2	2	3	b	3492.9	3530.4	3682.5	3719.0	3794.0	3926.3	3981.5
2	2	3	2	a	4232.1	4250.9	4245.0	4276.1	4276.1	4263.8	4276.1
2	2	3	2	b	4205.4	4224.2	4245.0	4262.7	4262.7	4263.8	4262.7
2	2	3	3	a	3444.6	3500.9	3607.5	3694.8	3769.8	3870.0	3957.3
2	2	3	3	b	3417.9	3474.2	3607.5	3681.5	3756.5	3870.0	3944.0
2	3	2	2	a	4175.9	4213.4	4188.8	4201.1	4219.8	4207.5	4219.8
2	3	2	2	b	4149.2	4186.7	4188.8	4187.7	4206.5	4207.5	4206.5
2	3	2	3	a	3388.4	3463.4	3551.3	3619.8	3713.6	3813.8	3901.1
2	3	2	3	b	3361.7	3436.7	3551.3	3606.5	3700.2	3813.8	3887.7
2	3	3	2	a	4100.9	4157.1	4113.8	4163.6	4182.3	4151.3	4182.3
2	3	3	2	b	4074.2	4130.4	4113.8	4150.2	4169.0	4151.3	4169.0
2	3	3	3	a	3444.6	3500.9	3607.5	3694.8	3769.8	3870.0	3957.3
2	3	3	3	b	3286.7	3380.4	3476.3	3569.0	3662.7	3757.5	3850.2
3	1	2	2	a	3505.4	3399.6	3330.8	3224.6	3124.8	3043.5	2937.3
3	1	2	2	b	3478.7	3372.9	3330.8	3211.2	3111.5	3043.5	2924.0
3	1	2	3	a	2717.9	2649.6	2693.3	2643.3	2618.6	2649.8	2618.6
3	1	2	3	b	2691.2	2622.9	2693.3	2630.0	2605.2	2649.8	2605.2
3	1	3	2	a	3430.4	3343.4	3255.8	3187.1	3087.3	2987.3	2899.8
3	1	3	2	b	3403.7	3316.7	3255.8	3173.7	3074.0	2987.3	2886.5
3	1	3	3	a	2642.9	2593.4	2618.3	2605.8	2581.1	2593.5	2581.1
3	1	3	3	b	2616.2	2566.7	2618.3	2592.5	2567.7	2593.5	2567.7
3	2	2	2	a	3463.4	3369.6	3288.8	3188.6	3094.8	3007.5	2907.3
3	2	2	2	b	3436.7	3342.9	3288.8	3175.2	3081.5	3007.5	2894.0
3	2	2	3	a	2675.9	2619.6	2651.3	2607.3	2588.6	2613.8	2588.6
3	2	2	3	b	2649.2	2592.9	2651.3	2594.0	2575.2	2613.8	2575.2
3	2	3	2	a	3388.4	3313.4	3213.8	3151.1	3057.3	2951.3	2869.8
3	2	3	2	b	3361.7	3286.7	3213.8	3137.7	3044.0	2951.3	2856.5
3	2	3	3	a	2600.9	2563.4	2576.3	2569.8	2551.1	2557.5	2551.1
3	2	3	3	b	2574.2	2536.7	2576.3	2556.5	2537.7	2557.5	2537.7
3	3	2	2	a	3332.1	3275.9	3157.5	3076.1	3001.1	2895.0	2813.6
3	3	2	2	b	3305.4	3249.2	3157.5	3062.7	2987.7	2895.0	2800.2
3	3	2	3	a	2544.6	2525.9	2520.0	2494.8	2494.8	2501.3	2494.8
3	3	2	3	b	2517.9	2499.2	2520.0	2481.5	2481.5	2501.3	2481.5
3	3	3	2	a	3257.1	3219.6	3082.5	3038.6	2963.6	2838.8	2776.1
3	3	3	2	b	3230.4	3192.9	3082.5	3025.2	2950.2	2838.8	2762.7
3	3	3	3	a	2600.9	2563.4	2576.3	2569.8	2551.1	2557.5	2551.1
3	3	3	3	b	**2442.9**	2442.9	2445.0	2444.0	2444.0	2445.0	2444.0
4	1	2	2	a	5692.4	5829.6	6003.8	6140.6	6283.8	6445.5	6582.3
4	1	2	2	b	5665.7	5802.9	6003.8	6127.2	6270.5	6445.5	6569.0
4	1	2	3	a	4904.9	5079.6	5366.3	5559.3	5777.6	6051.8	6263.6
4	1	2	3	b	4878.2	5052.9	5366.3	5546.0	5764.2	6051.8	6250.2
4	1	3	2	a	5617.4	5773.4	5928.8	6103.1	6246.3	6389.3	6544.8
4	1	3	2	b	5590.7	5746.7	5928.8	6089.7	6233.0	6389.3	6531.5
4	1	3	3	a	4829.9	5023.4	5291.3	5521.8	5740.1	5995.5	6226.1
4	1	3	3	b	4803.2	4996.7	5291.3	5508.5	5726.7	5995.5	6212.7
4	2	2	2	a	5650.4	5799.6	5961.8	6104.6	6253.8	6409.5	6552.3

4	2	2	2	b	5623.7	5772.9	5961.8	6091.2	6240.5	6409.5	6539.0
4	2	2	3	a	4862.9	5049.6	5324.3	5523.3	5747.6	6015.8	6233.6
4	2	2	3	b	4836.2	5022.9	5324.3	5510.0	5734.2	6015.8	6220.2
4	2	3	2	a	5575.4	5743.4	5886.8	6067.1	6216.3	6353.3	6514.8
4	2	3	2	b	5548.7	5716.7	5886.8	6053.7	6203.0	6353.3	6501.5
4	2	3	3	a	4787.9	4993.4	5249.3	5485.8	5710.1	5959.5	6196.1
4	2	3	3	b	4761.2	4966.7	5249.3	5472.5	5696.7	5959.5	6182.7
4	3	2	2	a	5519.1	5705.9	5830.5	5992.1	6160.1	6297.0	6458.6
4	3	2	2	b	5492.4	5679.2	5830.5	5978.7	6146.7	6297.0	6445.2
4	3	2	3	a	4731.6	4955.9	5193.0	5410.8	5653.8	5903.3	6139.8
4	3	2	3	b	4704.9	4929.2	5193.0	5397.5	5640.5	5903.3	6126.5
4	3	3	2	a	5444.1	5649.6	5755.5	5954.6	6122.6	6240.8	6421.1
4	3	3	2	b	5417.4	5622.9	5755.5	5941.2	6109.2	6240.8	6407.7
4	3	3	3	a	4787.9	4993.4	5249.3	5485.8	5710.1	5959.5	6196.1
4	3	3	3	b	4629.9	4872.9	5118.0	5360.0	5603.0	5847.0	6089.0
5	1	2	2	a	16377.6	17702.1	19063.5	20387.6	21718.1	23067.0	**24391.1**
5	1	2	2	b	16350.9	17675.4	19063.5	20374.2	21704.7	23067.0	24377.7
5	1	2	3	a	15590.1	16952.1	18426.0	19806.3	21211.8	22673.3	24072.3
5	1	2	3	b	15563.4	16925.4	18426.0	19793.0	21198.5	22673.3	24059.0
5	1	3	2	a	16302.6	17645.9	18988.5	20350.1	21680.6	23010.8	24353.6
5	1	3	2	b	16275.9	17619.2	18988.5	20336.7	21667.2	23010.8	24340.2
5	1	3	3	a	15515.1	16895.9	18351.0	19768.8	21174.3	22617.0	24034.8
5	1	3	3	b	15488.4	16869.2	18351.0	19755.5	21161.0	22617.0	24021.5
5	2	2	2	a	16335.6	17672.1	19021.5	20351.6	21688.1	23031.0	24361.1
5	2	2	2	b	16308.9	17645.4	19021.5	20338.2	21674.7	23031.0	24347.7
5	2	2	3	a	15548.1	16922.1	18384.0	19770.3	21181.8	22637.3	24042.3
5	2	2	3	b	15521.4	16895.4	18384.0	19757.0	21168.5	22637.3	24029.0
5	2	3	2	a	16260.6	17615.9	18946.5	20314.1	21650.6	22974.8	24323.6
5	2	3	2	b	16233.9	17589.2	18946.5	20300.7	21637.2	22974.8	24310.2
5	2	3	3	a	15473.1	16865.9	18309.0	19732.8	21144.3	22581.0	24004.8
5	2	3	3	b	15446.4	16839.2	18309.0	19719.5	21131.0	22581.0	23991.5
5	3	2	2	a	16204.4	17578.4	18890.3	20239.1	21594.3	22918.5	24267.3
5	3	2	2	b	16177.7	17551.7	18890.3	20225.7	21581.0	22918.5	24254.0
5	3	2	3	a	15416.9	16828.4	18252.8	19657.8	21088.1	22524.8	23948.6
5	3	2	3	b	15390.2	16801.7	18252.8	19644.5	21074.7	22524.8	23935.2
5	3	3	2	a	16129.4	17522.1	18815.3	20201.6	21556.8	22862.3	24229.8
5	3	3	2	b	16102.7	17495.4	18815.3	20188.2	21543.5	22862.3	24216.5
5	3	3	3	a	15473.1	16865.9	18309.0	19732.8	21144.3	22581.0	24004.8
5	3	3	3	b	15315.2	16745.4	18177.8	19607.0	21037.2	22468.5	23897.7

Appendix-8 Payoff matrix model (Equivalent CO_2 emissions)

Boiler total mass =150 kg,
H—heat exchanger, B—burners, D—draft blower, C—casing, I—insulation
Outcomes: Equiv. CO_2 Emissions (kg·CO_2)

Equiv. CO_2 Emissions					States of nature						
				H	0.45	0.5	0.55	0.6	0.65	0.7	0.75
				B	0.07	0.05	0.07	0.06	0.05	0.06	0.05
				D	0.04	0.03	0.04	0.02	0.02	0.03	0.02
				C	0.42	0.4	0.34	0.31	0.27	0.21	0.17
H	B	D	C	I	0.02	0.02	0	0.01	0.01	0	0.01
Alt.											
1	1	2	2	a	336.6	338.0	342.9	343.8	345.6	349.2	350.1
1	1	2	2	b	335.1	336.5	342.9	343.1	344.9	349.2	349.4
1	1	2	3	a	279.9	284.0	297.0	302.0	310.1	322.2	328.1
1	1	2	3	b	278.4	282.5	297.0	301.2	308.4	320.9	326.4
1	1	3	2	a	331.2	333.9	337.5	341.1	342.9	345.2	347.4
1	1	3	2	b	329.7	332.4	337.5	340.4	342.2	345.2	346.7
1	1	3	3	a	274.5	279.9	291.6	299.3	306.5	316.8	324.5
1	1	3	3	b	273.0	278.4	291.6	298.5	305.7	316.8	323.7
1	2	2	2	a	333.5	335.7	339.8	341.1	343.4	346.5	347.9
1	2	2	2	b	332.0	334.2	339.8	340.4	342.6	346.5	347.1
1	2	2	3	a	276.8	281.7	293.9	299.3	306.9	318.2	324.9
1	2	2	3	b	275.3	280.2	293.9	298.5	306.2	318.2	324.2
1	2	3	2	a	328.1	331.7	334.4	338.4	340.7	342.5	345.2
1	2	3	2	b	326.6	330.2	334.4	337.7	339.9	342.5	344.4
1	2	3	3	a	271.4	277.7	288.5	296.6	304.2	314.1	322.2
1	2	3	3	b	269.9	276.2	288.5	295.8	303.5	314.1	321.5
1	3	2	2	a	324.0	329.0	330.3	333.0	336.6	338.4	341.1
1	3	2	2	b	322.5	327.5	330.3	332.3	335.9	338.4	340.4
1	3	2	3	a	267.3	275.0	284.4	291.2	300.2	310.1	318.2
1	3	2	3	b	265.8	273.5	284.4	290.4	299.4	310.1	317.4
1	3	3	2	a	318.6	324.9	324.9	330.3	333.9	334.4	338.4
1	3	3	2	b	317.1	323.4	324.9	329.6	333.2	334.4	337.7
1	3	3	3	a	271.4	277.7	288.5	296.6	304.2	314.1	322.2
1	3	3	3	b	260.4	269.4	279.0	287.7	296.7	306.0	314.7
2	1	2	2	a	316.4	315.5	318.2	316.8	316.4	317.7	316.4
2	1	2	2	b	314.9	314.0	318.2	316.1	315.6	317.7	315.6
2	1	2	3	a	259.7	261.5	272.3	275.0	279.9	289.4	293.4
2	1	2	3	b	258.2	260.0	272.3	274.2	279.2	289.4	292.7
2	1	3	2	a	311.0	311.4	312.8	314.1	313.7	313.7	313.7
2	1	3	2	b	309.5	309.9	312.8	313.4	312.9	313.7	312.9
2	1	3	3	a	254.3	257.4	266.9	272.3	277.2	285.3	290.7
2	1	3	3	b	252.8	255.9	266.9	271.5	276.5	285.3	290.0
2	2	2	2	a	313.2	313.2	315.0	314.1	314.1	315.0	314.1

2	2	2	2	b	311.7	311.7	315.0	313.4	313.4	315.0	313.4
2	2	2	3	a	256.5	259.2	269.1	272.3	277.7	286.7	291.2
2	2	2	3	b	255.0	257.7	269.1	271.5	276.9	286.7	290.4
2	2	3	2	a	307.8	309.2	309.6	311.4	311.4	311.0	311.4
2	2	3	2	b	306.3	307.7	309.6	310.7	310.7	311.0	310.7
2	2	3	3	a	251.1	255.2	263.7	269.6	275.0	282.6	288.5
2	2	3	3	b	249.6	253.7	263.7	268.8	274.2	282.6	287.7
2	3	2	2	a	303.8	306.5	305.6	306.0	307.4	306.9	307.4
2	3	2	2	b	302.3	305.0	305.6	305.3	306.6	306.9	306.6
2	3	2	3	a	247.1	252.5	259.7	264.2	270.9	278.6	284.4
2	3	2	3	b	245.6	251.0	259.7	263.4	270.2	278.6	283.7
2	3	3	2	a	298.4	302.4	300.2	303.3	304.7	302.9	304.7
2	3	3	2	b	296.9	300.9	300.2	302.6	303.9	302.9	303.9
2	3	3	3	a	251.1	255.2	263.7	269.6	275.0	282.6	288.5
2	3	3	3	b	240.2	246.9	254.3	260.7	267.5	274.5	281.0
3	1	2	2	a	255.6	248.0	243.9	235.8	228.6	223.2	215.1
3	1	2	2	b	254.1	246.5	243.9	235.1	227.9	223.2	214.4
3	1	2	3	a	198.9	194.0	198.0	194.0	192.2	194.9	192.2
3	1	2	3	b	197.4	192.5	198.0	193.2	191.4	194.9	191.4
3	1	3	2	a	250.2	243.9	238.5	233.1	225.9	219.2	212.4
3	1	3	2	b	248.7	242.4	238.5	232.4	225.2	219.2	211.7
3	1	3	3	a	193.5	189.9	192.6	191.3	189.5	190.8	189.5
3	1	3	3	b	192.0	188.4	192.6	190.5	188.7	190.8	188.7
3	2	2	2	a	252.5	245.7	240.8	233.1	226.4	220.5	212.9
3	2	2	2	b	251.0	244.2	240.8	232.4	225.6	220.5	212.1
3	2	2	3	a	195.8	191.7	194.9	191.3	189.9	192.2	189.9
3	2	2	3	b	194.3	190.2	194.9	190.5	189.2	192.2	189.2
3	2	3	2	a	247.1	241.7	235.4	230.4	223.7	216.5	210.2
3	2	3	2	b	245.6	240.2	235.4	229.7	222.9	216.5	209.4
3	2	3	3	a	190.4	187.7	189.5	188.6	187.2	188.1	187.2
3	2	3	3	b	188.9	186.2	189.5	187.8	186.5	188.1	186.5
3	3	2	2	a	243.0	239.0	231.3	225.0	219.6	212.4	206.1
3	3	2	2	b	241.5	237.5	231.3	224.3	218.9	212.4	205.4
3	3	2	3	a	186.3	185.0	185.4	183.2	183.2	184.1	183.2
3	3	2	3	b	184.8	183.5	185.4	182.4	182.4	184.1	182.4
3	3	3	2	a	237.6	234.9	225.9	222.3	216.9	208.4	203.4
3	3	3	2	b	236.1	233.4	225.9	221.6	216.2	208.4	202.7
3	3	3	3	a	190.4	187.7	189.5	188.6	187.2	188.1	187.2
3	3	3	3	b	**179.4**	**179.4**	180.0	179.7	179.7	180.0	179.7
4	1	2	2	a	586.4	615.5	648.2	676.8	706.4	737.7	766.4
4	1	2	2	b	584.9	614.0	648.2	676.1	705.6	737.7	765.6
4	1	2	3	a	529.7	561.5	602.3	635.0	669.9	709.4	743.4
4	1	2	3	b	528.2	560.0	602.3	634.2	669.2	709.4	742.7
4	1	3	2	a	581.0	611.4	642.8	674.1	703.7	733.7	763.7
4	1	3	2	b	579.5	609.9	642.8	673.4	702.9	733.7	762.9
4	1	3	3	a	524.3	557.4	596.9	632.3	667.2	705.3	740.7
4	1	3	3	b	522.8	555.9	596.9	631.5	666.5	705.3	740.0
4	2	2	2	a	583.2	613.2	645.0	674.1	704.1	735.0	764.1

4	2	2	2	b	581.7	611.7	645.0	673.4	703.4	735.0	763.4
4	2	2	3	a	526.5	559.2	599.1	632.3	667.7	706.7	741.2
4	2	2	3	b	525.0	557.7	599.1	631.5	666.9	706.7	740.4
4	2	3	2	a	577.8	609.2	639.6	671.4	701.4	731.0	761.4
4	2	3	2	b	576.3	607.7	639.6	670.7	700.7	731.0	760.7
4	2	3	3	a	521.1	555.2	593.7	629.6	665.0	702.6	738.5
4	2	3	3	b	519.6	553.7	593.7	628.8	664.2	702.6	737.7
4	3	2	2	a	573.8	606.5	635.6	666.0	697.4	726.9	757.4
4	3	2	2	b	572.3	605.0	635.6	665.3	696.6	726.9	756.6
4	3	2	3	a	517.1	552.5	589.7	624.2	660.9	698.6	734.4
4	3	2	3	b	515.6	551.0	589.7	623.4	660.2	698.6	733.7
4	3	3	2	a	568.4	602.4	630.2	663.3	694.7	722.9	754.7
4	3	3	2	b	566.9	600.9	630.2	662.6	693.9	722.9	753.9
4	3	3	3	a	521.1	555.2	593.7	629.6	665.0	702.6	738.5
4	3	3	3	b	510.2	546.9	584.3	620.7	657.5	694.5	731.0

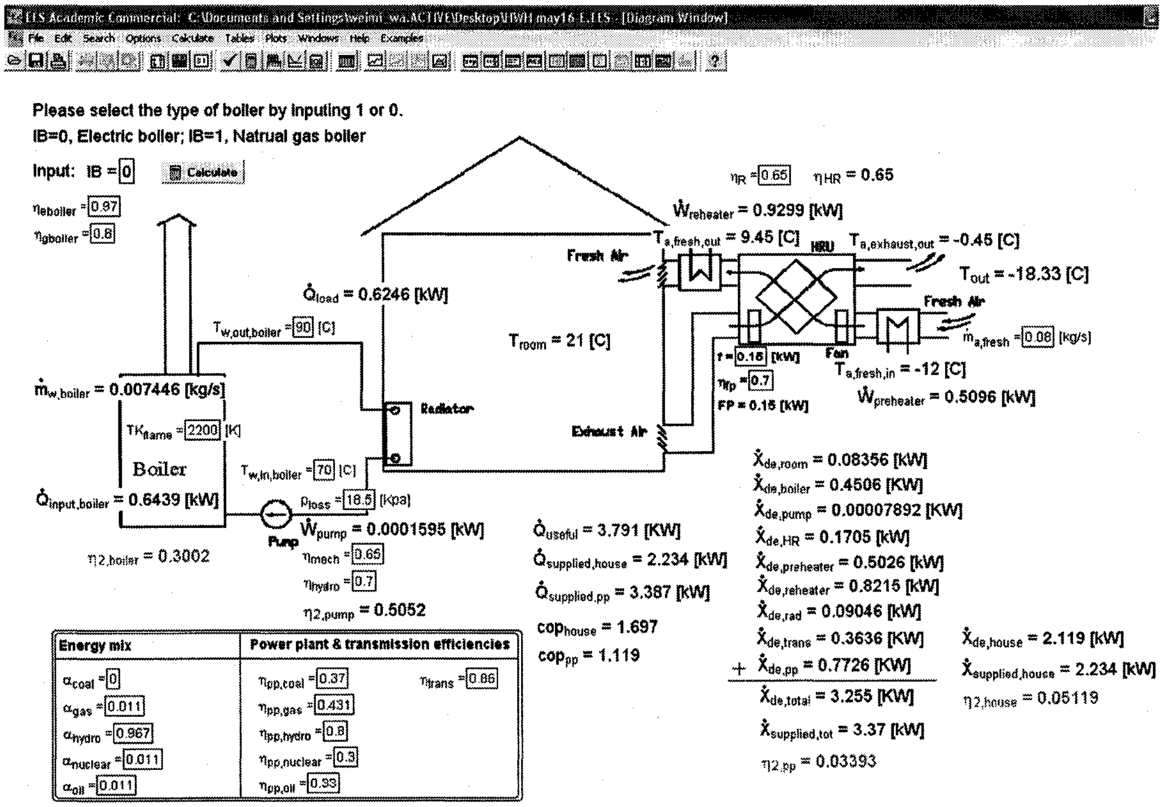
5	1	2	2	a	849.6	908.0	969.9	1027.8	1086.6	1147.2	**1205.1**
5	1	2	2	b	848.1	906.5	969.9	1027.1	1085.9	1147.2	1204.4
5	1	2	3	a	792.9	854.0	924.0	986.0	1050.2	1118.9	1182.2
5	1	2	3	b	791.4	852.5	924.0	985.2	1049.4	1118.9	1181.4
5	1	3	2	a	844.2	903.9	964.5	1025.1	1083.9	1143.2	1202.4
5	1	3	2	b	842.7	902.4	964.5	1024.4	1083.2	1143.2	1201.7
5	1	3	3	a	787.5	849.9	918.6	983.3	1047.5	1114.8	1179.5
5	1	3	3	b	786.0	848.4	918.6	982.5	1046.7	1114.8	1178.7
5	2	2	2	a	846.5	905.7	966.8	1025.1	1084.4	1144.5	1202.9
5	2	2	2	b	845.0	904.2	966.8	1024.4	1083.6	1144.5	1202.1
5	2	2	3	a	789.8	851.7	920.9	983.3	1047.9	1116.2	1179.9
5	2	2	3	b	788.3	850.2	920.9	982.5	1047.2	1116.2	1179.2
5	2	3	2	a	841.1	901.7	961.4	1022.4	1081.7	1140.5	1200.2
5	2	3	2	b	839.6	900.2	961.4	1021.7	1080.9	1140.5	1199.4
5	2	3	3	a	784.4	847.7	915.5	980.6	1045.2	1112.1	1177.2
5	2	3	3	b	782.9	846.2	915.5	979.8	1044.5	1112.1	1176.5
5	3	2	2	a	837.0	899.0	957.3	1017.0	1077.6	1136.4	1196.1
5	3	2	2	b	835.5	897.5	957.3	1016.3	1076.9	1136.4	1195.4
5	3	2	3	a	780.3	845.0	911.4	975.2	1041.2	1108.1	1173.2
5	3	2	3	b	778.8	843.5	911.4	974.4	1040.4	1108.1	1172.4
5	3	3	2	a	831.6	894.9	951.9	1014.3	1074.9	1132.4	1193.4
5	3	3	2	b	830.1	893.4	951.9	1013.6	1074.2	1132.4	1192.7
5	3	3	3	a	784.4	847.7	915.5	980.6	1045.2	1112.1	1177.2
5	3	3	3	b	773.4	839.4	906.0	971.7	1037.7	1104.0	1169.7

Appendix-9 Unit price for the piping system

Means catalogue	**Dia.** (in.)	**Unit** (LF)	**Total** ($/LF.)	**Cost** (US$)
Pipes				
15107-420-2120	3/8	80.4	7.25	582.9
15107-420-2140	1/2	85	7.7	654.5
15107-420-2180	3/4	14.7	8.85	130.095
15107-420-2200	1	28.2	10.6	298.92
90 Elbows		Unit (Ea)	Total $/Ea.	
15107-460-0090	3/8	4	24	96
15107-460-0100	1/2	3	25	75
15107-460-0120	3/4	2	27	54
15107-460-0130	1	3	33.5	100.5
Tees				
15107-460-0470	3/8	6	38	228
15107-460-0480	1/2	19	39	741
15107-460-0500	3/4	4	43	172
15107-460-0510	1	3	55.5	166.5
Ball valves				
15108-160-1450	1/2	2	30	60
Gate valves				
15110-160-2900	3/8	2	40.5	81
15110-160-2920	1/2	2	38	76
15110-160-2940	3/4	2	52	104
15110-160-2950	1	2	64	128
Radiators				
15700-600-3150		112	29	3248
Strainer				
15120-840-0140	1	1	43	43
Pump				
15180-200-2040	1	1	380	380
Gas boiler				
15500-400-6010	1	1	2525	2525
Electric boiler (as an alternative to the gas boiler)				
15500-300-2020	1	1	4275	4275
Expansion tank				
15120-320-2000	1	1	450	450
Ventilator				
15850-800-2160	1	1	105	105
Total cost ($)				**10,500**

Appendix-10 EES input files

A10.1 Input file for HWH system



Please select the type of boiler by inputing 1 or 0.
IB=0, Electric boiler; IB=1, Natrual gas boiler

Input: IB = 0

$\eta_{eboiler}$ = 0.97
$\eta_{gboiler}$ = 0.8
$\dot{Q}_{load}$ = 0.6246 [kW]
$T_{w,out,boiler}$ = 90 [C]
$\dot{m}_{w,boiler}$ = 0.007446 [kg/s]
TK_{flame} = 2200 [K]
$\dot{Q}_{input,boiler}$ = 0.6439 [kW]
$\eta_{2,boiler}$ = 0.3002
$T_{w,in,boiler}$ = 70 [C]
p_{loss} = 18.5 [Kpa]
$\dot{W}_{pump}$ = 0.0001595 [kW]
η_{mech} = 0.65
η_{hydro} = 0.7
$\eta_{2,pump}$ = 0.5052
T_{room} = 21 [C]
η_R = 0.65
η_{HR} = 0.65
$\dot{W}_{reheater}$ = 0.9299 [kW]
$T_{a,fresh,out}$ = 9.45 [C]
$T_{a,exhaust,out}$ = -0.45 [C]
T_{out} = -18.33 [C]
$\dot{m}_{a,fresh}$ = 0.08 [kg/s]
f = 0.15 [kW]
η_{fp} = 0.7
FP = 0.15 [kW]
$T_{a,fresh,in}$ = -12 [C]
$\dot{W}_{preheater}$ = 0.5096 [kW]
$\dot{Q}_{useful}$ = 3.791 [KW]
$\dot{Q}_{supplied,house}$ = 2.234 [kW]
$\dot{Q}_{supplied,pp}$ = 3.387 [kW]
cop_{house} = 1.697
cop_{pp} = 1.119
$\dot{X}_{de,room}$ = 0.08356 [kW]
$\dot{X}_{de,boiler}$ = 0.4506 [KW]
$\dot{X}_{de,pump}$ = 0.00007892 [KW]
$\dot{X}_{de,HR}$ = 0.1705 [kW]
$\dot{X}_{de,preheater}$ = 0.5026 [kW]
$\dot{X}_{de,reheater}$ = 0.8215 [kW]
$\dot{X}_{de,rad}$ = 0.09046 [kW]
$\dot{X}_{de,trans}$ = 0.3636 [KW]
\+ $\dot{X}_{de,pp}$ = 0.7726 [KW]
$\dot{X}_{de,total}$ = 3.255 [KW]
$\dot{X}_{supplied,tot}$ = 3.37 [kW]
$\eta_{2,pp}$ = 0.03393
$\dot{X}_{de,house}$ = 2.119 [kW]
$\dot{X}_{supplied,house}$ = 2.234 [kW]
$\eta_{2,house}$ = 0.05119

Energy mix	Power plant & transmission efficiencies	
α_{coal} = 0	$\eta_{pp,coal}$ = 0.37	η_{trans} = 0.86
α_{gas} = 0.011	$\eta_{pp,gas}$ = 0.431	
α_{hydro} = 0.967	$\eta_{pp,hydro}$ = 0.8	
$\alpha_{nuclear}$ = 0.011	$\eta_{pp,nuclear}$ = 0.3	
α_{oil} = 0.011	$\eta_{pp,oil}$ = 0.33	

Figure A10-1 One result screen display of HWH system

```
{! EES file for the heating systems with a gas fired boiler or an electric boiler}
"To select the type of boiler, IB=1, for a gas boiler; IB=0, for an electric boiler"
"In the design conditions, the Q_dot_load and T_out, as inputs, are needed, and then click the 'solve' button to run."
"The program can also be run at annually operating condition, if the Q_dot_load and T_out are set as outputs in diagram window and click the 'solve table' button."
function BoilerE(a,b,c)
if (a=1) then x=b else x=c
BoilerE=x
end
function BoilerS(a,b,c)
if (a=1) then x=b else x=c
BoilerS=x
end
function BoilerX(a,b,c)
if (a=1) then x=b else x=c
BoilerX=x
end
"Fraction of hour in which the boiler and pump run"
function FRAC (a,b)
if (a<=b) then x=1 else x=b/a
FRAC=X
```

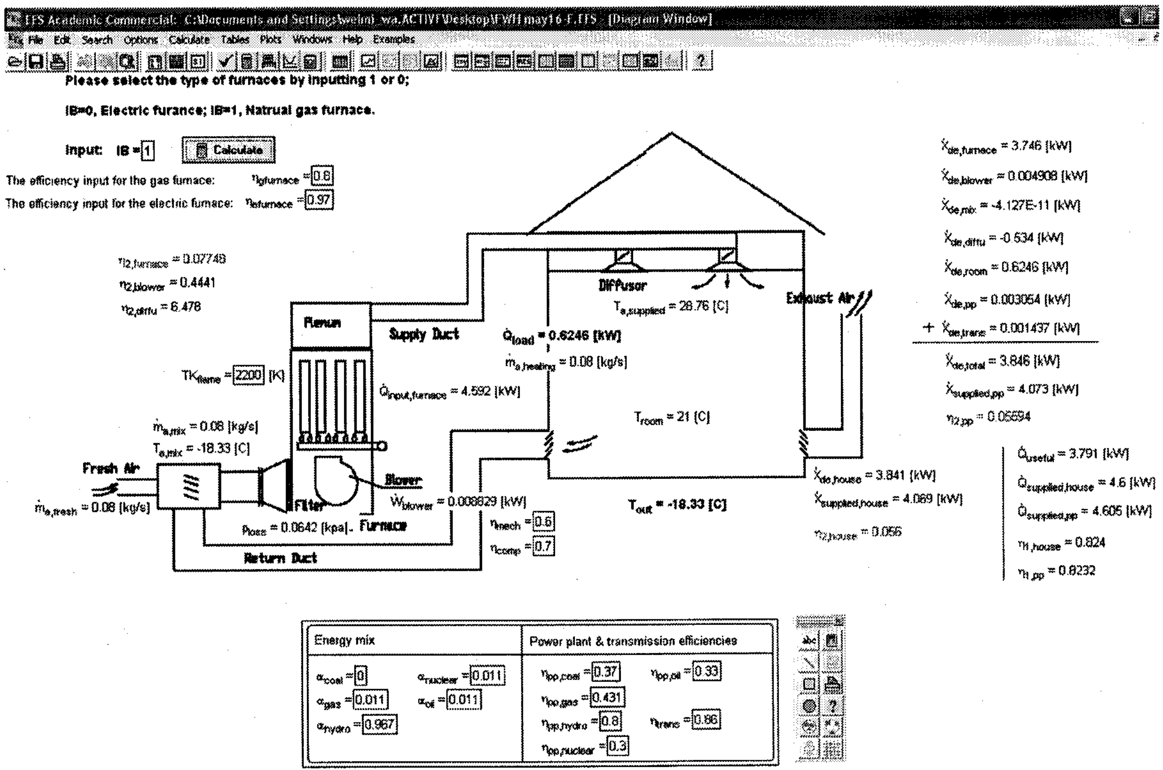
```
end
"Part load ratio of boiler"
function RPLR(a,b)
if (a<b) then x=b else x=a
RPLR=X
end
"Elec air preheater"
procedure Preheater(a,b,c,T:W)   {theT_a_fresh_in is set as T_out less than -12C to prevent
frosting effect, otherwise, the preheater turns on }
if (T<-12) then
c=-12; W=a*b*(c-T)
else
W=0; c=T
endif
end
function Reheater (a,b)
if (a>21) then x=0 else x=b
Reheater=x
end
function ReheaterXde (a,b)
if (a=0) then x=0 else x=b
ReheaterXde=x
end
function PreheaterXde (a,b)
if (a=0) then x=0 else x=b
PreheaterXde=x
end
function eff2pump(a,b)
if(b=0) then x=0 else x=1-a/b
eff2pump=x
end
function eff2boiler(a,b)
if(b=0) then x=0 else x=1-a/b
eff2boiler=x
end
function eff2rad(a,b)
if(b=0) then x=0 else x=1-a/b
eff2rad=x
end
function eff1house(a,b)
if(b=0) then x=0 else x=a/b
eff1house=x
end
function eff1pp(a,b)
if(b=0) then x=0 else x=a/b
eff1pp=x
end
function eff2house(a,b)
if(b=0) then x=0 else x=1-a/b
eff2house=x
end
function eff2pp(a,b)
if(b=0) then x=0 else x=1-a/b
eff2pp=x
end
Procedure T(f,e,a:b,c,d)
```

```
if (a<21) then
b=21;c=e;d=f
else
b=a;c=0;d=0
endif
end
Call T(f,eta_R,T_out:T_room,eta_HR,FP)
Call Preheater(m_dot_a_fresh,cp_a,T_a_fresh_in,T_out:W_dot_preheater)
eff1house=eff1house(Q_dot_useful,Q_dot_supplied_house)
eff1pp=eff1pp(Q_dot_useful,Q_dot_supplied_pp)
eff2house=eff2house(X_dot_de_house,X_dot_supplied_house)
eff2pp=eff2pp(X_dot_de_total,X_dot_supplied_tot)
eff2rad=eff2rad(X_dot_de_rad,X_dot_supplied_rad)
eff2boiler=eff2boiler(X_dot_de_boiler,X_dot_supplied_boiler)
eff2pump=eff2pump(X_dot_de_pump,X_dot_supplied_pump)
BoilerE=BoilerE(IB,E_ng,E_elec)
BoilerS=BoilerS(IB,S_ng,S_elec)
BoilerX=BoilerX(IB,X_ng,X_elec)

RPLR=RPLR(PLR,RMIN)
FRAC=FRAC(RMIN,PLR)

Reheater=Reheater(T_a_fresh_out,W_dot_reh)
ReheaterXde=ReheaterXde(W_dot_reheater,X_dot_de_reh)
PreheaterXde=PreheaterXde(W_dot_preheater,X_dot_de_preh)

"System design parameters"
"T_room=21 [C]"
TK_room=(273+T_room) "[K]"
"T_out=-23 [C]"                {this the parameter at design conditions, however for hourly outdoor
temperature it will be substituted by the values in parameter table}
TK_o=(273+T_out) "[K]"

"f=0.15 [kW]"           "the power of fans in HRU if they are used"
"eta_fp=0.7"            "efficiency of the fans"
c_pw=cp(water, T=0.5*(T_w_in_boiler+T_w_out_boiler),p=101.3)
rho_w=density(water, T=0.5*(T_w_in_boiler+T_w_out_boiler),p=101.3)
cp_a=cp(air,t=(T_a_exhaust_in+T_a_fresh_in)/2)

"Boiler"
RMIN=0.1
PLR=Q_dot_load/CAP
E_ng=HIR_RPLR*CAP*FRAC/eta_gboiler
"E_elec=RPLR*CAP*FRAC"
E_elec=RPLR*CAP*FRAC/eta_eboiler
Q_dot_input_boiler=BoilerE
HIR_RPLR=0.0080472574+0.87564457*RPLR+0.29249943*RPLR^2-0.17624156*RPLR^3
CAP=12.5 [kW]

m_dot_w_boiler=Q_dot_rad/(c_pw*(T_w_out_boiler-T_w_in_boiler))
v_dot_boiler=m_dot_w_boiler/rho_w
s_dot_w_in_boiler=entropy(water, T=T_w_in_boiler,p=101.3)
s_dot_w_out_boiler=entropy(water,T=T_w_out_boiler,p=101.3)
S_dot_gen_boiler=BoilerS
S_ng=m_dot_w_boiler*(s_dot_w_out_boiler-s_dot_w_in_boiler)-Q_dot_input_boiler/TK_flame+(Q
_dot_input_boiler-Q_dot_rad)/TK_o
```

```
S_elec=m_dot_w_boiler*(s_dot_w_out_boiler-s_dot_w_in_boiler)
X_dot_de_boiler=TK_o*s_dot_gen_boiler
X_dot_supplied_boiler=BoilerX
X_ng=Q_dot_input_boiler*(1-TK_o/TK_flame)
X_elec=Q_dot_input_boiler
eta_2_boiler=eff2boiler

"Pump"
TK_w_pump=(273+T_w_in_boiler) "[K]"
W_dot_pump=FRAC*v_dot_pump*p_loss/(eta_mech*eta_hydro)          {The pump is running
only if the boiler runs}
v_dot_pump=v_dot_boiler
X_dot_de_pump=FRAC*(v_dot_pump*p_loss*((1/eta_hydro)*((1/eta_mech)-1)+(TK_o/TK_w_pu
mp)*((1/eta_hydro)-1)))
S_dot_gen_pump=X_dot_de_pump/TK_o
X_dot_supplied_pump=W_dot_pump
eta_2_pump=eff2pump

"Radiators"
Q_dot_rad=Q_dot_load
m_dot_w_rad=Q_dot_rad/(c_pw*(T_w_out_boiler-T_w_in_boiler))
s_dot_w_in_rad=s_dot_w_out_boiler
s_dot_w_out_rad=s_dot_w_in_boiler
S_dot_gen_rad=m_dot_w_rad*(s_dot_w_out_rad-s_dot_w_in_rad)+Q_dot_rad/TK_room
X_dot_de_rad=TK_o*S_dot_gen_rad
X_dot_supplied_rad=(1-TK_o/(273+0.5*(T_w_in_boiler+T_w_out_boiler)))*Q_dot_load
eta_2_rad=eff2rad

"Air to air heat recovery unit"
m_dot_a_exhaust=m_dot_a_fresh
T_a_exhaust_in=T_room

"Room air"
S_dot_gen_room=m_dot_a_fresh*(s_dot_a_exhaust_in-s_dot_a_room)-Q_dot_rad/TK_room+Q_
dot_load/TK_o
X_dot_de_room=TK_o*S_dot_gen_room

{!Sensible heat recovery efficiency}
"eta_R=0.65"
Q_dot_HR_exhaust=m_dot_a_exhaust*cp_a*(T_a_exhaust_in-T_a_exhaust_out)+0.5*FP
"Q_dot_HR_fresh=m_dot_a_fresh*cp_a*(T_a_fresh_out-T_a_fresh_in)-0.5*FP"
T_a_fresh_out=eta_HR*(T_a_exhaust_in-T_a_fresh_in)+T_a_fresh_in
T_a_exhaust_out=T_a_exhaust_in-eta_HR*(T_a_exhaust_in-T_a_fresh_in)
S_dot_gen_HR=m_dot_a_fresh*(s_dot_a_fresh_out-s_dot_a_fresh_in)+m_dot_a_exhaust*(s_dot
_a_exhaust_out-s_dot_a_exhaust_in)
s_dot_a_fresh_out=entropy(air, T=T_a_fresh_out, p=101.3)
s_dot_a_fresh_in=entropy(air, T=T_a_fresh_in, p=101.3)
s_dot_a_exhaust_in=entropy(air, T=T_room, p=101.3)
s_dot_a_exhaust_out=entropy(air, T=T_a_exhaust_out, p=101.3)
X_dot_de_HR=TK_o*S_dot_gen_HR+FP*eta_fp
TK_av_exhaust=273+0.5*(T_a_exhaust_in+T_a_exhaust_out)
X_dot_supplied_HR=Q_dot_HR_exhaust*(1-TK_o/TK_av_exhaust)+FP

"Electric air pre-heater"
W_dot_preheater=m_dot_a_fresh*cp_a*(T_a_fresh_in-T_out)
S_dot_gen_preheater=m_dot_a_fresh*(s_dot_a_fresh_in-s_dot_a_out)
```

```
X_dot_de_preheater=PreheaterXde
X_dot_de_preh=TK_o*S_dot_gen_preheater
X_dot_supplied_preheater=W_dot_preheater

"Electric air re-heater"
W_dot_reheater=Reheater
W_dot_reh=m_dot_a_fresh*cp_a*(T_room-T_a_fresh_out)
S_dot_gen_reheater=m_dot_a_fresh*(s_dot_a_room-s_dot_a_fresh_out)
s_dot_a_room=entropy(air, T=T_room, p=101.3)
X_dot_de_reheater=ReheaterXde
X_dot_de_reh=TK_o*S_dot_gen_reheater
X_dot_supplied_reheater=W_dot_reheater

"Power   transmission"
S_dot_gen_trans=W_dot_pp*(1-eta_trans)/TK_o
X_dot_de_trans=TK_o*S_dot_gen_trans
S_dot_gen_pp=S_dot_gen_gas+S_dot_gen_oil+S_dot_gen_coal+S_dot_gen_nuclear+S_dot_gen_hydro
S_dot_gen_gas=Q_dot_pp_gas*(1-eta_pp_gas)/TK_o-Q_dot_pp_gas/TK_flame
Q_dot_pp_gas=alpha_gas*W_dot_pp/eta_pp_gas
S_dot_gen_oil=Q_dot_pp_oil*(1-eta_pp_oil)/TK_o-Q_dot_pp_oil/TK_flame
Q_dot_pp_oil=alpha_oil*W_dot_pp/eta_pp_oil
S_dot_gen_coal=Q_dot_pp_coal*(1-eta_pp_coal)/TK_o-Q_dot_pp_coal/TK_flame
Q_dot_pp_coal=alpha_coal*W_dot_pp/eta_pp_coal
S_dot_gen_nuclear=Q_dot_pp_nuclear*(1-eta_pp_nuclear)/TK_o
Q_dot_pp_nuclear=alpha_nuclear*W_dot_pp/eta_pp_nuclear
S_dot_gen_hydro=Q_dot_pp_hydro*(1-eta_pp_hydro)/TK_o
Q_dot_pp_hydro=alpha_hydro*W_dot_pp/eta_pp_hydro
W_dot_pp=(Q_dot_input_boiler*(1-IB)+W_dot_pump+FP+W_dot_preheater+W_dot_reheater)/eta_trans
X_dot_de_pp=TK_o*S_dot_gen_pp
X_dot_supplied_pp=(Q_dot_pp_gas+Q_dot_pp_oil+Q_dot_pp_coal)*(1-TK_o/TK_flame)+Q_dot_pp_nuclear+Q_dot_pp_hydro

"First law efficiency at the house level and the power plant level"

Q_dot_useful=Q_dot_load+m_dot_a_fresh*cp_a*(T_room-T_out)
Q_dot_supplied_house=Q_dot_input_boiler+W_dot_pump+FP+W_dot_preheater+W_dot_reheater
Q_dot_supplied_pp=Q_dot_pp_gas+Q_dot_pp_oil+Q_dot_pp_coal+Q_dot_pp_nuclear+Q_dot_pp_hydro+Q_dot_input_boiler*IB
cop_house=eff1house
cop_pp=eff1pp

"Second law efficiency at the house level and the power plant level"

X_dot_de_house=X_dot_de_boiler+X_dot_de_pump+X_dot_de_rad+X_dot_de_exhaust+X_dot_de_HR+X_dot_de_preheater+X_dot_de_reheater+X_dot_de_room
X_dot_supplied_house=X_dot_supplied_boiler+X_dot_supplied_pump+FP+X_dot_supplied_preheater+X_dot_supplied_reheater
X_dot_de_total=X_dot_de_boiler+X_dot_de_pump+X_dot_de_rad+X_dot_de_HR+X_dot_de_preheater+X_dot_de_reheater+X_dot_de_trans+X_dot_de_pp+X_dot_de_exhaust+X_dot_de_room
X_dot_supplied_tot=X_dot_supplied_pp+X_dot_supplied_boiler*IB
eta_2_house=eff2house
eta_2_pp=eff2pp
$sumrow on
```

A10.2 Input file for FAH system



Please select the type of furnaces by inputting 1 or 0;

IB=0, Electric furance; IB=1, Natrual gas furnace.

Input: IB = 1

The efficiency input for the gas furnace: $\eta_{gfurnace}$ = 0.8

The efficiency input for the electric furnace: $\eta_{efurnace}$ = 0.97

$\eta_{2,furnace}$ = 0.07748

$\eta_{2,blower}$ = 0.4441

$\eta_{2,diffu}$ = 6.478

TK_{flame} = 2200 [K]

$\dot{Q}_{input,furnace}$ = 4.592 [kW]

$\dot{m}_{a,mix}$ = 0.08 [kg/s]

$T_{a,mix}$ = -18.33 [C]

$\dot{m}_{a,fresh}$ = 0.08 [kg/s]

p_{loss} = 0.0642 [kpa]

$\dot{W}_{blower}$ = 0.008829 [kW]

η_{mech} = 0.6

η_{comp} = 0.7

$T_{a,supplied}$ = 28.76 [C]

$\dot{Q}_{load}$ = 0.6246 [kW]

$\dot{m}_{a,heating}$ = 0.08 [kg/s]

T_{room} = 21 [C]

T_{out} = -18.33 [C]

$\dot{X}_{de,furnace}$ = 3.746 [kW]

$\dot{X}_{de,blower}$ = 0.004908 [kW]

$\dot{X}_{de,mix}$ = -4.127E-11 [kW]

$\dot{X}_{de,diffu}$ = -0.534 [kW]

$\dot{X}_{de,room}$ = 0.6246 [kW]

$\dot{X}_{de,pp}$ = 0.003054 [kW]

+ $\dot{X}_{de,trans}$ = 0.001437 [kW]

$\dot{X}_{de,total}$ = 3.846 [kW]

$\dot{X}_{supplied,pp}$ = 4.073 [kW]

$\eta_{2,pp}$ = 0.05694

$\dot{X}_{de,house}$ = 3.841 [kW]

$\dot{X}_{supplied,house}$ = 4.069 [kW]

$\eta_{2,house}$ = 0.056

$\dot{Q}_{useful}$ = 3.791 [kW]

$\dot{Q}_{supplied,house}$ = 4.6 [kW]

$\dot{Q}_{supplied,pp}$ = 4.605 [kW]

$\eta_{I,house}$ = 0.824

$\eta_{I,pp}$ = 0.8232

Energy mix

α_{coal} = 0

$\alpha_{nuclear}$ = 0.011

α_{gas} = 0.011

α_{oil} = 0.011

α_{hydro} = 0.967

Power plant & transmission efficiencies

$\eta_{pp,coal}$ = 0.37

$\eta_{pp,oil}$ = 0.33

$\eta_{pp,gas}$ = 0.431

$\eta_{pp,hydro}$ = 0.8

η_{trans} = 0.86

$\eta_{pp,nuclear}$ = 0.3

Figure A10-2 One result screen display of FAH system

```
{! EES file for the heating systems with a gas fired furnace or an electric furnace}
"Please select the type of furnace, IB=1, for a gas furnace; IB=0, for an electric furnace"
"In the design conditions, the Q_dot_load and T_out, as inputs, are needed, and then click the
'solve' button to run."
"The program also can be run at annually operating condition, if the Q_dot_load and T_out are set
as outputs in diagram window and click the 'solve table' button."
function FurnaceE(a,b,c)
if (a=1) then x=b else x=c
FurnaceE=x
end
function FurnaceS(a,b,c)
if (a=1) then x=b else x=c
FurnaceS=x
end
function FurnaceX(a,b,c)
if (a=1) then x=b else x=c
FurnaceX=x
end
"fraction of hour in which the furnace and blower run"
function FRAC (a,b)
if (a<=b) then x=1 else x=b/a
FRAC=X
end
"Part load ratio of furnace"
```

```
function RPLR(a,b)
if (a<b) then x=b else x=a
RPLR=X
end
function eff1house(a,b)
if(b=0) then x=0 else x=a/b
eff1house=x
end
function eff1pp(a,b)
if(b=0) then x=0 else x=a/b
eff1pp=x
end
function eff2blower(a,b)
if(b=0) then x=0 else x=1-a/b
eff2blower=x
end
function eff2furnace(a,b)
if(b=0) then x=0 else x=1-a/b
eff2furnace=x
end
function eff2diffu(a,b)
if(b=0) then x=0 else x=1-a/b
eff2diffu=x
end
function eff2house(a,b)
if(b=0) then x=0 else x=1-a/b
eff2house=x
end
function eff2pp(a,b)
if(b=0) then x=0 else x=1-a/b
eff2pp=x
end
Procedure MT(a,b,c,d:X,Y)
T=43
m=b/(a*(T-c))
if (m<d) and (d<>0) then

X=b/(a*d)+c;Y=d
else
X=T;Y=m
endif
end

Procedure T(a:X,Y)
if (a<21) then
X=21;Y=0.08
else
X=a;Y=0
endif
end
procedure Tx (a,b,c,d:T)
if (a=0)    then
T=d
else
T=(a-b)/a*c+b/a*d
endif
```

```
end
call Tx(m_dot_a_heating,m_dot_a_fresh,T_room,T_out:T_a_mix)
call T(T_out:T_room,m_dot_a_fresh)
call MT(cp_a,Q_dot_load,T_room,m_dot_a_fresh:T_a_supplied,m_dot_a_heating)
eff1pp=eff1pp(Q_dot_useful,Q_dot_supplied_pp)
eff1house=eff1house(Q_dot_useful,Q_dot_supplied_house)
eff2pp=eff2pp(X_dot_de_total,X_dot_supplied_pp)
eff2house=eff2house(X_dot_de_house,X_dot_supplied_house)
eff2diffu=eff2diffu(X_dot_de_diffu,X_dot_supplied_diffu)
eff2furnace=eff2furnace(X_dot_de_furnace,X_dot_supplied_furnace)
eff2blower=eff2blower(X_dot_de_blower,X_dot_supplied_blower)
FurnaceE=FurnaceE(IB,E_ng,E_elec)
FurnaceS=FurnaceS(IB,S_ng,S_elec)
FurnaceX=FurnaceX(IB,X_ng,X_elec)
RPLR=RPLR(PLR,RMIN)
FRAC=FRAC(RMIN,PLR)

"!System design parameters"
TK_room=(273+T_room) "[K]"
TK_o=(273+T_out) "[K]"
"TK_flame=2200 [K]"
cp_a=cp(air, T=0.5*(T_room+T_out)) "kJ/kg-K"
cp_a_o=cp(air,T=T_out)
rho_a=DENSITY(Air,T=T_a_mix,P=101.3)  "kg/m^3"
"m_dot_a_fresh=0.08 [kg/s]"
"T_a_supplied=43"

"!Furnace"
RMIN=0.1
PLR=(Q_dot_load+Q_dot_fresh)/CAP
E_ng=HIR_RPLR*CAP*FRAC/eta_gfurnace
E_elec=RPLR*CAP*FRAC/eta_efurnace
Q_dot_input_furnace=furnaceE
HIR_RPLR=0.0080472574+0.87564457*RPLR+0.29249943*RPLR^2-0.17624156*RPLR^3
CAP=16 [kW] "the design capacity of the furnace"
m_dot_a_mix=m_dot_a_heating
s_dot_a_in_furnace=entropy(air, T=T_a_mix,p=101.3)
s_dot_a_out_furnace=entropy(air,T=T_a_supplied,p=101.3)
S_dot_gen_furnace=FurnaceS
S_ng=m_dot_a_mix*(s_dot_a_out_furnace-s_dot_a_in_furnace)-Q_dot_input_furnace/TK_flame
+(Q_dot_input_furnace-Q_dot_diffu-Q_dot_fresh)/TK_o
S_elec=m_dot_a_mix*(s_dot_a_out_furnace-s_dot_a_in_furnace)
X_dot_de_furnace=TK_o*S_dot_gen_furnace
X_dot_supplied_furnace=FurnaceX
X_ng=Q_dot_input_furnace*(1-TK_o/TK_flame)
X_elec=Q_dot_input_furnace
eta_2_furnace=eff2furnace

"!Blower"
W_dot_blower=v_dot_blower*p_loss/(eta_mech*eta_comp)
v_dot_blower=m_dot_a_mix/rho_a
X_dot_de_blower=v_dot_blower*p_loss*((1/eta_comp)*((1/eta_mech)-1)+(TK_o/TK_room)*((1/et
a_comp)-1))
X_dot_supplied_blower=W_dot_blower
eta_2_blower=eff2blower
```

```
"!Mixing box"
Q_dot_fresh=m_dot_a_fresh*cp_a*(T_room-T_out)
S_dot_gen_mix=m_dot_a_mix*s_dot_a_mix-(m_dot_a_mix-m_dot_a_fresh)*s_dot_a_room-m_d
ot_a_fresh*s_dot_a_out
s_dot_a_mix=entropy(air, T=T_a_mix, p=101.3)
s_dot_a_room=entropy(air, T=T_room, p=101.3)
s_dot_a_out=entropy(air, T=T_out, p=101.3)
X_dot_de_mix=TK_o*S_dot_gen_mix

"!Room air"
S_dot_gen_room=Q_dot_load/TK_o
X_dot_de_room=TK_o*S_dot_gen_room

"!Diffusers"
Q_dot_diffu=Q_dot_load
s_dot_a_in_diffu=entropy(air, T=T_a_supplied,p=101.3)
s_dot_a_out_diffu=s_dot_a_room
S_dot_gen_diffu=m_dot_a_mix*(s_dot_a_out_diffu-s_dot_a_in_diffu)
X_dot_de_diffu=TK_o*s_dot_gen_diffu
X_dot_supplied_diffu=(1-TK_o/(273+T_a_supplied))*Q_dot_diffu
eta_2_diffu=eff2diffu

"!Power   transmission"
S_dot_gen_trans=W_dot_pp*(1-eta_trans)/TK_o
X_dot_de_trans=TK_o*S_dot_gen_trans
S_dot_gen_pp=S_dot_gen_gas+S_dot_gen_oil+S_dot_gen_coal+S_dot_gen_nuclear+S_dot_ge
n_hydro
S_dot_gen_gas=Q_dot_pp_gas*(1-eta_pp_gas)/TK_o-Q_dot_pp_gas/TK_flame
Q_dot_pp_gas=alpha_gas*W_dot_pp/eta_pp_gas
S_dot_gen_oil=Q_dot_pp_oil*(1-eta_pp_oil)/TK_o-Q_dot_pp_oil/TK_flame
Q_dot_pp_oil=alpha_oil*W_dot_pp/eta_pp_oil
S_dot_gen_coal=Q_dot_pp_coal*(1-eta_pp_coal)/TK_o-Q_dot_pp_coal/TK_flame
Q_dot_pp_coal=alpha_coal*W_dot_pp/eta_pp_coal
S_dot_gen_nuclear=Q_dot_pp_nuclear*(1-eta_pp_nuclear)/TK_o
Q_dot_pp_nuclear=alpha_nuclear*W_dot_pp/eta_pp_nuclear
S_dot_gen_hydro=Q_dot_pp_hydro*(1-eta_pp_hydro)/TK_o
Q_dot_pp_hydro=alpha_hydro*W_dot_pp/eta_pp_hydro
W_dot_pp=((1-IB)*Q_dot_input_furnace+W_dot_blower)/eta_trans
X_dot_de_pp=TK_o*S_dot_gen_pp

"!First law efficiencies at house level and plant level"
Q_dot_useful=Q_dot_load+Q_dot_fresh
Q_dot_supplied_house=Q_dot_input_furnace+W_dot_blower
Q_dot_supplied_pp=Q_dot_pp_gas+Q_dot_pp_oil+Q_dot_pp_coal+Q_dot_pp_nuclear+Q_dot_p
p_hydro+Q_dot_input_furnace*IB
eta_1_house=eff1house
eta_1_pp=eff1pp

"!Second law efficiencies at house level and plant level"
X_dot_de_house=X_dot_de_furnace+X_dot_de_blower+X_dot_de_mix+X_dot_de_diffu+X_dot_
de_exhaust+X_dot_de_room
X_dot_de_total=X_dot_de_furnace+X_dot_de_blower+X_dot_de_mix+X_dot_de_diffu+X_dot_de
_exhaust+X_dot_de_trans+X_dot_de_pp+X_dot_de_room
X_dot_supplied_house=X_dot_supplied_furnace+X_dot_supplied_blower
X_dot_supplied_pp=(Q_dot_pp_gas+Q_dot_pp_oil+Q_dot_pp_coal)*(1-TK_o/TK_flame)+Q_dot_
pp_nuclear+Q_dot_pp_hydro+X_dot_supplied_furnace*IB
```

```
eta_2_house=eff2house
eta_2_pp=eff2pp
$sumrow on
```