Exergy Analysis of Water Loop Heat Pump System in an Office Building

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Abstract

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HVAC systems have a significant contribution to the building energy demand and greenhouse gases emissions. The use of effective evaluation indicators and accurate analysis method are very important for improving the energy performance of HVAC systems. The second law of thermodynamics analysis is an appropriate approach to evaluate HVAC system performance.

This thesis presents the second law of thermodynamics analysis of a Water Loop Heat Pump (WLHP) system, applied to a commercial building located in Montreal. This system allows for the heat recovered in the core zone to be used partially in the winter for heating the perimeter zones. The analysis covers both peak design and annual operating conditions. The following equipment is included in the analysis: the water-to-air heat pumps, the boiler, the water circulating pumps, the fan and the heat ejector (e.g., cooling tower). Primary and secondary energy sources are considered, for instance in the case of the generation of electricity. Mathematical models developed in this study are implemented in the Engineering Equations Solver (EES) environment. The performance of the WLHP system is evaluated using indicators such as: the energy and exergy efficiency, the energy and exergy demand, the exergy lost, and the equivalent CO_2 emissions due to the system operation.

The results show that the exergy efficiency of the WLHP system has an annual average value of 2.8%. The annual average value of the Coefficient of Performance (COP) of the WLHP system is evaluated at 1.68. The major exergy destruction components of the WLHP system are the boiler, the heat pumps in core zone and the cooling tower.

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NOMENCLATURE

A	Area (m^2)
CAP	Capacity of the component (kW)
COP	Coefficient of performance
Cp	Specific heat (kJ/kg K)
$\dot{E}$	Electricity demand by the component or the WLHP system (kW)
E	Annual primary energy use in the generation of electricity (TWh/year)
EM_{co_2}	Off-site annual equivalent CO2 emissions (kt eq. CO_2/year)
ET_{co_2}	Environment tax due to the equivalent CO_2 emission per year (CAN$/yr)
EWT	Entering water temperature (°C)
H	Head pressure (kPa or Pa)
	Head pressure losses (kPa)
h	Enthalpy (kJ/kg)
L	Worst supply length for the WLHP system (m)
$\dot{m}$	Mass flow rate (kg/s)
ME	Mechanical efficiency
n	Total amount of hours during one year (hours)
N	Number of the component
$N_{ELECTRICAL}$	Electrical consumption per unit load of the cooling tower fan (kW/kW)
N_{floor}	Number of floors
N_{life}	Life cycle of the WLHP system (year)

N_{people}	Number of people
N_{use}	Usage fraction of heat pumps
P	Pressure loss factor (Pa/m)
	Pressure loss (kPa)
PLR	Part load ratio
$\dot{Q}$	Heat flow rate (kW)
$\dot{Q}'$	Modified loads (kW)
Rd	Relative density of water
s	Specific entropy (kJ/kg· K)
T	Temperature (°C or K)
T'	Modified temperature (°C)
T_{CO_2}	Environment tax ratio (CAN\$/ t eq. CO_2)
$\dot{V}$	Volume flow rate (m^3/s)
$\dot{X}$	Rate of exergy (kW)
$\dot{X}_D$	Rate of exergy destruction (kW)

Greek Symbol

α	Contribution ratio for the electricity mix
β	Equivalent CO_2 emissions ratio (kt eq. CO_2/TWh)
ρ	Density (kg/m^3)
Δ	Value difference
η	Energy efficiency

η_D	Exergy destruction ratio
$\eta_{X,}$	Exergy efficiency

Subscripts

0	Atmosphere or surrounding
actual	Actual value
air	Air
annual	Annual value
boiler	Boiler
c	Controller range
cooling	Cooling mode
	Cooling loads
D	Design condition
dry	Dry bulb
duct	Ducts of the WLHP system
fan	Fan for outside air
fresh	Outside air
gas	Natural gas-fired power plants
heating	Heating mode
	Heating loads
heatpump	Heat pumps
HP	Heat pumps

hydro	Hydro power plants
i	Zone i
	System component i
in	Entering the component
inside	Indoor
j	The j^{th} hour
lat	Latent thermal loads
leave	Leave the component
LF	Life cycle of the building
load	Space load covered by the heat pumps
loop	Water loop of the WLHP system
loopwater	Loop water in the WLHP system
lower	Lower set-point
makeup	Makeup water for the cooling tower
max	Maximum value
mix	Mixed
need	Needed
nuclear	Nuclear power plants
oil	Oil-fired power plants
out	Leaving the component
outdoor	Outdoor
Output	Output value by the WLHP system
overall	Overall WLHP system including transmission losses

pipe	Loop pipe of the WLHP system
prim	Peak load condition
pump	Circulation pump
R	Return water
s	Supply into the component
sens	Sensitive thermal loads
sup*ply*	Supply into the component or the system
system	WLHP system
theoretical	Theoretical value
total	Total
tower	Cooling tower
trans	Electricity transmission
upper	Upper set-point
useful	Useful exergy for the component or the system
water	Water
wet	Wet-bulb

CHAPTER 1

INTRODUCTION

Total energy consumption in North America grew by 31% from 1972 to 1997 (UNEP, 2001). In 1996, North America consumed 25% of total world primary energy consumption (UNEP, 2001). Canada and United States consumed nearly 25% of the world energy consumption (IEA, 2001). Quebec consumed about 21% of primary energy used in Canada (Redgwell C., 2004).

More than one third of the world's primary energy is used in buildings and most of energy is used to space heating and cooling (Schmidt D., 2004). The primary energy consumption in buildings in United States is about 36% of total consumption (Santamouris, 2001). Commercial buildings have one of the highest levels of energy consumption when compared with other building types, which varies between 100 to 1000 kWh per square meter per year (Burton, 2001) mainly for space cooling or heating and lighting.

A large amount of greenhouse gases, which are believed to have an impact on the global warming, have been released by the energy conversion and usage. Global mean surface temperature has increased by about 0.5 °C since the late 19th century and the sea level has risen 0.1-0.2 m over the past century (EPA, 2004). The signature of "Kyoto Protocol" has raised expectations that countries will undertake affordable and effective work to reduce the CO_2 emissions. Framework was created to measure the emissions of greenhouse gases (GHG). The protocol sets the target of reducing emissions and timetable. For instance, on average during the 2008-2012, emissions from Canada must be 6% lower than the 1990 level. For the countries in the European Union, it is 8% and for United States, it is 7% (UNFCCC, 1997).

The accurate analysis tools and evaluation indicators provide great help to enhance the energy performance of buildings through their design and operation. The second law analysis is an effective tool to estimate the energy performance of HVAC system, which account for a significant part of building energy use and related CO_2 emissions.

In this thesis, the second law of thermodynamics is used to analyze the energy performance of a water loop heat pump (WLHP) system in an office building. Chapter 2 presents the literature review about the topic. Chapter3 presents the mathematical model, based on the energy and exergy balances developed for each component of this system and for whole system including the power generating plant. Chapter 4 presents a case study of a WLHP system installed in an office building in Montreal. Chapter 5 presents the estimation of the greenhouse gas emissions. Chapter 6 presents the conclusions and recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Definition of Sustainability

The sustainability or sustainable development, as a well-known word now, was defined firstly by the former prime minister of Norway Giro Harlem Brundtland in the World Commission on Environment and Development in 1987. It was originally an ecological concept, reelecting “prudent behavior”, by a predator that avoids overexploiting its prey to ensure an “optimum sustained yield” (Bartelmus, 1994). At its most basic level, sustainable means "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987).

The concept of sustainability also implies a change in which the direction of technology development, the usage of natural resources, the style of our life, in order to meet both future and present needs. Generally, sustainability includes economic sustainability, social sustainability and ecological sustainability.

Today, sustainable development has become a very dominant theme all over the world. However, it is really difficult to obtain a clear and universal definition of sustainability because authors can define the sustainability from their own research fields, such as agriculture and urban development.

2.1.1 Sustainability and Engineering

Sustainable engineering is the application of all technical disciplines and arts toward greater efficiency and conservation of materials and energy resources, with emphasis on eliminating the use of non-renewable and hazardous substances. The progress of engineering provides available and effective technologies to achieve sustainable development. However, those advanced technologies raised many serious problems, which include acid rain, toxic waste and greenhouse effect, at the same time (Hartley, 1993). Traditional engineering technologies depend on and consume excessively natural resources. Traditional standards cannot evaluate the impact of technologies on sustainability. Even if a technology does not emit harmful substances at the point of use, some emissions and wastes may be associated with its manufacturing process (IAEA, 2005). For example, combustion of fossil fuels is responsible for urban air pollution, regional acidification and human-induced climate change. The use of nuclear power has attracted a number of concerns, such as the storage or disposal of high-level radioactive waste. The overuse of biomass in some developing countries contributes to desertification and loss of biodiversity. The design and evaluation of future technologies should ensure that they are entirely compatible with natural ecological and social systems, both in macro and micro aspects.

In engineering, the goal is to utilize energy as efficiently as possible while avoiding the impact on the environment. The energy is so important for modern society that the social and economic development is expected to stop without available energy. The use of energy has strong impact on every sector of the environment. The generation, transmission and use of energy may cause damage to the environment. Much of the current energy supply and use, still based, on limited resources of fossil fuels, is deemed to be environmentally unsustainable. There is no energy production or conversion technology without risk or without waste (IAEA, 2005).

More than one third of the world's primary energy is used in buildings (Schmidt, 2004). However, most of the energy is used in an unsustainable way, especially in the buildings construction and operation. The focus on energy efficiency and renewable energy in buildings, developed since the 1973 oil crisis (Newman, 1999) and on the "sustainable building" as a new concept is accepted by more and more people. Everyone has his own unique perspective on building sustainability, and some would agree that a sustainable building is also a "Green" building. A sustainable building refers to a structure that is designed, built, renovated, operated, or reused in an ecological and resource-efficient manner. It also results in the minimization of a structure ecological footprint, while maximizing its long-term social and economic contributions.

ASHRAE, in its position statement on building sustainability, "supports building sustainability as a means to provide a safe, healthy, comfortable indoor environment while simultaneously limiting the impact on the Earth's natural resources." (Building Sustainability and HVAC system, 2003)

2.1.2 Sustainability and Environment

Environmental sustainability refers to the long-term maintenance of valued environmental resources in an evolving human context (Environmental Sustainability

Index, 2005). Environmental sustainability is a fundamentally multi-dimensional concept, which includes natural resources, land and water resources, atmospheric and oceanic circulation and ecosystem, etc. Sustainability will be meaningless without talking about environment because it is the basis of our world existence and development.

The environmental sustainability could be termed as minimal and maximal environmental sustainability. The minimal environmental sustainability means future generations are guaranteed the avoidance of environmental catastrophe. The maximal environmental sustainability means future generations are left the opportunity to experience a level of environmental consumption at least equal to that of present generation (Gupta, 1997).

With technology development and industrialization, there are many environmental sustainability challenges, for instance, depletion of nonrenewable natural resource, water and air pollution, and destruction of ecosystems. Besides those problems, some challenges arise because the under-development and poverty-induced short-term thinking, such as lack of investment for renewable resources protection or pollution control. One of challenges, which would impact seriously on the sustainable development, is the global climate change. There are a lot of direct and indirect evidences to show that the global climate is becoming warm. For instance, the global mean surface temperatures have increased by about 0.5 °C since the late 19th century and the sea level has risen 0.1-0.2 m over the past century (EPA, 2004).

With respect to the land use, the sustainable concept recommends indicates using land and soil in such a way that the quality and multifunction of both are maintained or even improved thus leaving options for future generations (D 'Souza, 1998).

2.1.2 Sustainability and Economics and Social Science

Some researchers defined the sustainability from the economic aspect. Beckerman (1994) defined the sustainability as the non-declining utility of a representative member of society for millennia into the future. Calberg (1995) defined sustainability as the annualized equivalent of the present discounted value of consumption that the economy is capable of achieving.

The sustainability and economics impact on each other. The linkage between the natural resource utilization and the economic growth is the key for sustainability. Sustainability means that ecological and environmental goals are given roughly equivalent status, that they are used in the way that create much wider range and more value than are incorporated in market prices. Without sustainable development, the economy will not grow fast and for a long-term. For example, total U.S. economic impacts of the 1997-1998 El Niño, which is believed to be caused by the climate change, were estimated at about $25 billion, including storm damage, crop losses and important business variables like sales, revenues and employment (NOAA, 2005).

The notion of the social sustainability calls attention to the stability, quality of life and social cohesion in society. The social scientists always focus on such themes as eradicating absolute poverty and hunger, providing universal and basic social services, reducing economic and social disparities, increasing environmental quality, diminishing violence and armed conflict and stabilizing population when the sustainability of a society is researched.

For a specific city, sustainability would mean the potential to reach qualitatively a new level of socioeconomic, demographic and technological output which in the long run reinforces the foundations of the urban system.

2.2 Indicators of Sustainability

The sustainability remains an empty concept without practical indicators. An indicator helps understanding where you are, which way you are going and how far you are from where you want to be. A good indicator alerts about a problem before it gets too bad and helps recognize what needs to be done to avoid or eliminate the problem. Indicators play a major role in evaluating sustainability and will help monitor the progress of sustainable development.

This section discusses indicators of sustainability from three aspects: engineering, economics and social sciences.

2.2.1 Indicators and Engineering

Since the energy usage is so important for engineering, many international organizations have focused their efforts on developing some sets of indicators to measure and assess one or more aspects of sustainable engineering development. The United Nations started in 1995 to produce a set of indicators of energy evaluation (IAEA, 2005). The energy sustainability indicators include three parts: the annual energy use per capita, the share of consumption of renewable energy resources and the intensity of energy use.

The indicator of sustainability would not be the same in different engineering fields. For building science, sustainability indicators are needed to set targets and to measure the performance of the built environment. Decision-makers and policy-makers may use the indicators to evaluate economically viable and technically feasible strategies to improve the quality of life. Different actors in building processes may use indicators as guidelines and tools to improve current designs and to improve quality of construction. Indicators can be used for measuring the sustainability of building projects, the capability of different actors and the state of different regions or nations.

Leadership in Energy and Environmental Design (LEED), developed by the United States Green Building Council, is a design guideline and third-party certification tool (U. S. Green Building Council, 2003). LEED evaluates the building design or an existing building from five categories: (1) Sustainable Site with a maximum of 14 points; (2) Water Efficiency with a maximum of 5 points; (3) Energy & Atmosphere with a maximum of 17 points; (4) Materials & Resources with a maximum of 14 points; (5) Indoor Environmental Quality with a maximum of 15 points, and (6) Innovation & Design Process with a maximum of 5 points. Each category contains several indicators. Buildings are evaluated; and they received points for every indicator, up to the total available of 70 points. According to the number of points awarded, the building is associated to a certain level of performance: LEED certified with 26~32 points, Silver level with 33~38 points, Gold level with 39~51 points, and Platinum level with more than 52 points.

2.2.2 Indicators and Environment

In literature there is frequent reference to an indicator called “Strong Sustainability” (Hart, 2004). These indicator doses not consider the financial or other costs of attaining sustainability. It equates to what some call the ecological sustainability and the focus is primarily on the environment. In this case, the system quality is taken in terms of the physical measures of things (e.g. population, soil erosion).

Environmental Sustainability Index (2005) presented a set of indicators for the evaluation of environmental sustainability which include five core components: the environmental system, the reduction of the environmental stresses, the reduction of human vulnerability, the social and industrial capacity and global stewardship. These components totally contain 21 indicators, such as air quality, biodiversity, environmental health and greenhouse gas emission. These 21 indicators are considered to be the fundamental blocks of environmental sustainability, and they are aggregated to create the Environmental Sustainability Index (ESI). The equal weighting of 21 indicators is set because the simple aggregation is transparent and easy to understand. Moreover, when the 21 indicators are ranked, none stood out as being of substantially higher or lower importance than others.

2.2.2 Indicators and Economics and Social Science

The concept of sustainability is raised also by researchers in economics and social development. This indicator is always a combination of empirical data and theoretical analysis.

Hanley (1999) chose seven measures of the sustainability in Scotland: Green Net National Product, Genuine Savings, Ecological Footprint, Environmental Space, Net Primary Productivity, Index of Sustainable Economic Welfare and Genuine Progress Indicators.

The following indicators would contribute to appraise the social sustainable development from the aspect of poverty reduction: the level of the total fertility rate, the population growth, the energy use efficiency, the human capital formation, the local pollution and the sanitation and public health standards (Rao, 2000).

2.3 Second Law of Thermodynamics and HVAC Systems Analysis

In the traditional analysis, researchers often use the energy consumption and energy efficiency, based on the first law of thermodynamics, as indicators to evaluate the performance of buildings, HVAC systems and individual components. However, the first law of thermodynamics analysis can only reflect the quantity of energy used in a process. Both quality and quantity of energy used must be taken into account in order to achieve a full understanding of all essential aspects of energy usage.

2.3.1 Second Law of Thermodynamic and Entropy

The second law of thermodynamics has applications in many fields from biology, economics, philosophy to information technologies.

The concept of entropy was first introduced in 1850 by Clausius. In 1877, Ludwig Boltzmann formulated the alternative definition of entropy (Wikipedia, 2005). Entropy is the measure of the disorder or randomness of energy and matter in a system. According to the second law of thermodynamic, the total entropy of any isolated thermodynamic system increases approaching a maximum value over time. Entropy is not only used in thermodynamics, but also used in physical chemistry, information theory and quantum mechanics. Entropy application, for example, in physical chemistry is to predict whether or not a given chemical reaction can take place (Thompson, 2002).

2.3.2 Exergy

Exergy is an important concept introduced by the second law of thermodynamics. Exergy, also called available work, is the maximum theoretical work obtained from the system in a given environment. Exergy expresses the quality of the energy from different resources and in different environments. The term environment applies to some portion of surroundings (Moran, 1992). Unlike energy, the total amount of exergy is not conserved, except in an ideal process, but it could be destroyed because of heat transfer through boundaries and internal irreversibility. Exergy is destructed, and entropy is created in a process (Çengel, 2002).

In 1824, Carnot published a relation between heat and work which later resulted in the formulation of the second law of thermodynamics (Wall, 1986). In 1953, Rant suggested the name exergy and a general definition was given by Baehr in 1965.

The exergy analysis method utilizes both the first and second law of thermodynamics and pays special attention to the exergy (Kott, 1989). Exergy analysis method avoids the shortcomings of first law of thermodynamics analysis by identifying work lost or improvement potential in a specific component or process, for instance, the adiabatic throttling process (Çengel, 2002). Exergy analysis method also could determine the location, cause and true magnitude of energy waste. Such information can be used to design new energy efficient systems and improve the energy performance of existing systems. When exergy concept is combined with principles of engineering economy, the analysis method called exergoeconomics (Kreith, 2000).

2.3.3 Applications to Buildings and HVAC System Design and Analysis

Hepbasli A. (2005) analyzed the exergy performance of main components of a ground source heat pump. The highest exergy loss, of more than 56% of energy input, occurs in the compressor. The second largest exergy loss is due to the condenser because of the large temperature difference of refrigerant between entering and leaving conditions. The third largest exergy loss is located in the capillary tube because of pressure drop of refrigerant. According to his research, engineers should focus on these key components of heat pumps in order to improve the exergy performance.

Asada and Takeda (2002) used exergy to analyze the effect of outdoors shading on a room with ceiling radiant cooling system. By comparing with a room without shading, they concluded that the cool radiation exergy emitted by the ceiling radiant panel surface is increased, and the cool exergy consumption of the panel is reduced in the room with shading. Since the cooling water was obtained from a well, the water pump consumes between 30 to 56 times more exergy than the ceiling radiant panel.

Bridges (2001) analyzes the refrigerator and air conditioner in terms of exergy. In the refrigerator system, the compressor contributes to the most exergy destruction. The potential improvement is estimated to be in heat exchangers. In the case of air conditioner system, the exergy efficiency with wet-evaporator operation is greater than in the case of extracting heat from dry air only.

Badescu (2001) analyzed a solar-assisted heat pump for heating system by the second law of thermodynamics. The research showed that the heat pump system can be driven by solar energy only, if appropriate electrical energy storage is available. The most part of exergy losses occur during compression 37% of total exergy loss and condensation 39.5%.

Nishikawa et al. (1999) extended the exergy analysis method to the evaluation of effects of shading and natural ventilation on the heat storage of building envelopes. They calculated the cooling exergy could be obtained from the concrete wall in the daytime of hot season, under a given environment with combination of shading and natural ventilation.

2.4 Water Loop Heat Pump (WLHP) system

2.4.1 Description of WLHP system

The WLHP system was first presented in 1960s (Pietsch, 1990). Generally, a WLHP system contains five main components which are: the water-to-air heat pumps, the secondary heat source, the heat rejector, the circulating pump, and the fan for circulating the ventilation air. The WLHP system can be applied in a single-zone or multiple-zone buildings. Any number of heat pumps may be installed in the WLHP system, connected by a water loop piping system. The operating mode of heat pumps in different zones could be different, that is some heat pumps installed on the perimeter zones can work in heating mode (in winter), while those installed in core zones can work in cooling mode. Heat pumps in cooling mode cool the supply air and reject the heat to the water loop through their condensers. Excess heat gathered by the water loop is rejected to outside through the heat rejector (i.e. cooling tower). Heat pumps in heating mode extract heat from the water loop through their evaporators. The heat required to maintain the temperature of the water loop is supplied by a secondary heat source (i.e. electrical boiler). Thus, the system recovers and redistributes heat.

There is a fan to provide necessary ventilation outside air for indoor air quality requirements. The outside air is mixed with return air from the zone before entering the heat pumps.

The water in the water loop system is driven by the circulating pump. The water temperature should be kept at a constant value or be maintained in an acceptable operation range, which traditionally is from 16 °C to 32 °C (ASHRAE, 1997). However, wider operation range is becoming common because it reduces the operating costs of the secondary heat source and heat rejector.

In this study, in each zone there are water-to-air heat pumps. The electrical boiler is used as the secondary heat source, and the cooling tower with constant speed fan is used as a heat rejector. One constant speed circulating pump and one supply fan are selected.

2.4.2 Advantage and disadvantage of the WLHP system

The WLHP system is applied in many types of buildings. Comparing with the central air-to-air system, the WLHP system has following advantages:

- WLHP systems allow for simultaneous heating and cooling by multiple separate and distinct units, and thus increase individual comfort. Furthermore, recovering heat from cooled areas and recycling it into other areas adds to the system efficiency (Energy Star, 2005).

- Efficiency of water-to-air and water-to-water units are generally higher than air-to-air systems, where a COP of 3.8 to 4.0 is not uncommon. High efficiency water-source heat pumps may have a COP as high as 4.4 (Energy Star, 2005).
- Heat pumps have a longer service life than the air-cooled equipment (ASHRAE, 1997).
- Energy usage for providing comfortable thermal environment can be metered for each tenant (ASHRAE, 1997).
- Total life-cycle cost of this system frequently compares favorably to that of central systems when considering installed cost, operating costs, and system life (ASHRAE, 1997).
- The water in the WLHP system can come from wells, lakes or underground, which are used as heat sink or heat source, with a more constant temperature than the outside air temperature (Binggeli, 2003).

Comparing with individual air conditioners, the WLHP system has following advantages (ASHRAE, 1997):

- The WLHP system gives the opportunity for recovering heat from interior zones and/or waste heat and by storing excess heat from daytime.
- The wall penetrations are not needed to provide for the rejection of heat from air-cooled condensers.
- Noise levels can be lower than those of air-cooled equipment because condenser fans are eliminated and the compression ratio is lower.

However, the WLHP system has some disadvantages during installation and operation:

- Initial cost may be higher than use multiple unitary HVAC equipment (ASHRAE, 1997).
- The reduced airflow can cause the heat pump to overheat and cut out. Therefore, periodic filter maintenance is imperative (ASHRAE, 1997).
- Equipment cost is expensive for using free energy sources such as solar energy or geothermal energy, compared with the secondary heating source or heat rejector.

Zmeureanu (2000) presented the optimization of a geothermal WLHP system in a large office building located in Montreal by two different approaches: the nonlinear mathematical programming and the genetic algorithm. He found the genetic algorithm is more efficient than the nonlinear mathematical programming in finding an optimum solution when optimizing a jagged objective function. The reason is that the genetic algorithm explores the whole space of possibilities and quickly finds out the most promising regions, while the nonlinear programming cannot move away from local optima because of the shape of the objective function.

2.5 Objectives

The first objective of this research is to apply the second law analysis to a WLHP system and to evaluate the energy and exergy performance.

The second objective is to estimate two indicators of the sustainability performance by: the exergy efficiency and the greenhouse gas (GHG) emissions, of the WLHP system.

CHAPTER 3

MATHEMATICAL MODEL OF WATER LOOP HEAT PUMP SYSTEM

The HVAC system evaluated in this study is a closed water loop heat pump (WLHP) system, which is installed in an office building with five floors, and one core zone and four perimeter zones per floor. All heat pumps are connected by a water loop piping system. The outdoor air is distributed into the building through a duct system. In this study, the water temperature (EWT) entering heat pumps has a constant value (35°C). At this stage, the constant speed pump is used. One electrical boiler is selected as the secondary heat supplier, which works when the EWT is less than the set point value of 35°C or the lower set point temperature. One cooling tower is used as the heat rejector when the EWT is greater than the set point value of 35°C or the upper set point temperature.

The mathematical model covers the following main components of the WLHP: the heat pumps, the water loop, the outdoor air fan, the secondary heat source equipment, the heat rejector and the circulating pump.

The hourly heating/cooling loads of each zone are assumed to be known and therefore they are an input to the model. The heating/cooling loads are obtained from the simulation of an office building in Montreal by using the DOE-2 program (Zmeureanu, 1995). The system is assumed to be able to satisfy the heating/cooling loads of each zone.

Figure 3.1 shows the overall flowchart of the system and Figure 3.2 shows, as an example, the reversed-connection of four heat pumps in zone no.1 (core zone).

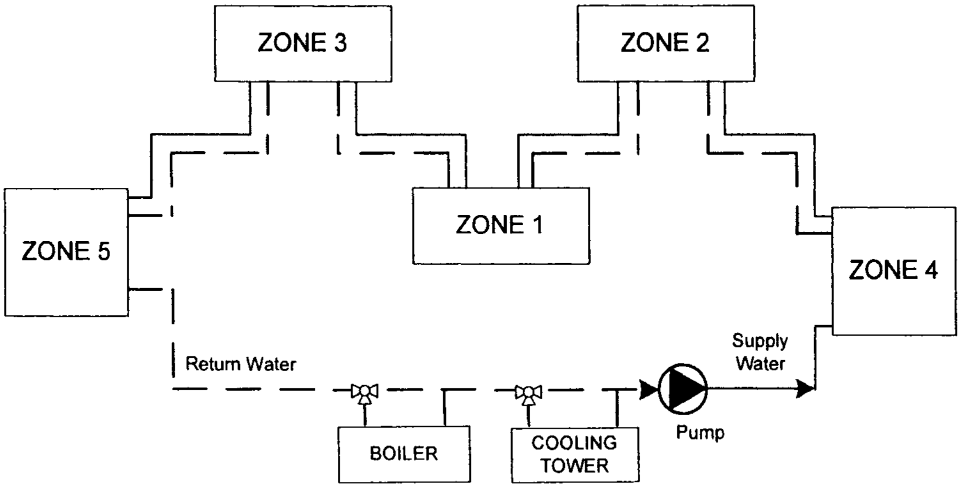

Figure 3.1 Diagram of the WHLP system

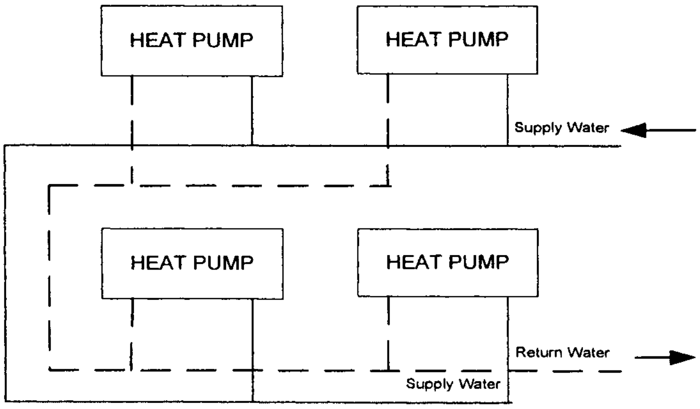

Figure 3.2 Reversed-connection of heat pumps in Core Zone

Section 3.1 presents the energy balance of each component, the coefficient of performance (COP) of the WLHP system and the coefficient of performance (COP) of the overall system including the electricity generation and transmission losses. Section 3.2 presents the exergy balance of each component, the exergy efficiency of the WLHP system and the overall exergy efficiency including the electricity generation and transmission losses.

3.1 Energy Balance

Mathematical model of the WLHP system was developed during this study, and then implemented in the Engineering Equation Solver (EES) environment (F-Chart Software, 2005).

3.1.1 Outdoor air

In this study, the outdoor air volume brought into the building is constant. The volume of outdoor air that is supplied into the building depends on the occupant density of the building. The number of people in each zone is calculated as follows:

$$N_{people,i} = A_i / D \tag{3.1}$$

where

$N_{people,i}$ is the number of people in zone i;

A_i is the floor area of zone i, m^2;

D is the occupant density, m^2/person; the occupant density of an office building is 25 m^2/person (National Research Council Canada, 1998).

The total volumetric flow rate of outdoor air that is transferred into the zone i is given by:

$$\dot{V}_{fresh,i} = N_{people,i} \times \dot{V}_{need} \tag{3.2}$$

where

$\dot{V}_{fresh,i}$ is the outdoor air flow rate supplied into zone i, m^3/s;

$\dot{V}_{need}$ is the volume of outdoor air per person, m^3/s*person; in this study, the $\dot{V}_{need}$ is 0.012 m^3/s*person (National Research Council Canada, 1998).

The total volumetric flow rate of outdoor air brought into the building is given by:

$$\dot{V}_{fresh,total} = N_{floor} \times \sum_{1}^{5} \dot{V}_{fresh,i} \tag{3.3}$$

where

$\dot{V}_{fresh,total}$ is the total outdoor air flow rate supplied into all zones of five floors, m^3/s;

N_{floor} is the number of floors, in this study, $N_{floor} = 5$.

The outdoor air is supplied at each heat pump by the fan, where it is mixed with the return air from the corresponding zone. The outdoor air will absorb heat from the outdoor air fan. The heat absorbed by the outdoor air is equal to the electrical energy that is input to the fan. The temperature of outdoor air, after the supply fan is calculated as follows.

$$T_{air,\mathrm{out}} = \frac{\dot{E}_{fan}}{\dot{V}_{fresh,total} \times Cp_{air} \times \rho_{air}} - 273.5 + T_{air,outdoor,dry} \tag{3.4}$$

where

$T_{air,\mathrm{out}}$ is the outdoor air temperature after the supply fan, °C;

$\dot{E}_{fan}$ is the electric input to the outdoor air fan, kW;

ρ_{air} is the air density, kg/m^3;

C_{pair} is the specific heat of air before the supply fan, kJ/kg K;

$T_{air,outdoor,dry}$ is the dry-bulb temperature of outdoor air, °C;

The electric demand of fan used to circulate the outdoor air is calculated by the following formula (Metric Conversion Handbook, 1984):

$$\dot{E}_{fan} = \frac{\dot{V}_{fresh,total} \times H_{fan}}{ME \times 1000} \tag{3.5}$$

where

H_{fan} is the fan head pressure, Pa; the pressure loss on the air side is assumed to be 800 Pa (ASHRAE, Handbook, 1997);

ME is the mechanical efficiency for the fan, dimensionless; it is assumed equal to 0.65 (Kuts, 1998).

The actual mechanical efficiency of fans and pumps in a system is a function of fluid flow rate and total head loss. The mechanical efficiency could be obtained from the curve provided by manufacturer. Here, we assume the average mechanical efficiency of pumps and fans as 0.65 (Kuts, 1998).

$$H_{fan} = L_{duct} \times \Delta P_{duct} + \Delta P_{HP} \tag{3.6}$$

where

L_{duct} is the worst supply duct length of the WLHP system, m;

ΔP_{duct} is the average pressure loss factor due to the friction and the duct diameter change in the duct, Pa/m; $\Delta P_{duct} = 6 Pa/m$;

ΔP_{HP} is the airflow resistance due to one heat pumps' coils, Pa.

The round duct is assumed to be used in WLHP system for circulating the ventilation into heat pumps. The maximum length of supply duct is calculated as 50 m. The average pressure loss factor, P_{duct}, is selected through the Friction Chart (ASHRAE, 2001) based on the air flow rate. The pressure loss through one heat pump is assumed as 500 Pa (IBK, 2004). Hence, the fan head pressure is calculated as 800 Pa.

3.1.2 Heat Pump

The required number of heat pumps in a zone is calculated through an iterative process. The initial number of heat pumps is calculated at peak heating and cooling loads.

In heating mode:

$$N_{heating,i,prim} = \text{int}[|\dot{Q}_{\max,heating,i}| / CAP_{heating,i} + 1] \tag{3.7}$$

In cooling mode:

$$N_{cooling,i,prim} = \text{int}[\dot{Q}_{\max,cooling,i} / CAP_{cooling,i} + 1] \tag{3.8}$$

where

$N_{heating,i,prim}$ is the initial number of the heat pumps needed in zone i at peak heating load;

$N_{cooling,i,prim}$ is the initial number of the heat pumps needed in zone i at peak cooling load;

$\dot{Q}_{\max,\,heating,i}$ is the peak heating load of zone i, kW; this value is considered to be negative;

$\dot{Q}_{\max,\,cooling,i}$ is the peak cooling load of zone i, kW; this value is considered to be positive;

$\mathrm{CAP}_{\mathrm{heating},\,\mathrm{i}}$ is the selected capacity of each heat pump in zone i, in heating mode, kW;

$\mathrm{CAP}_{\mathrm{cooling},\,\mathrm{i}}$ is the selected capacity of each heat pump in zone i, in cooling mode, kW.

For each zone, the number of heat pumps is selected in such a way to satisfy the worst condition of either heating or cooling:

$$N_{i,prim} = \max(N_{cooling,i,prim}, N_{heating,i,prim}) \tag{3.9}$$

where

$N_{i,prim}$ is the initial design number of the heat pumps for the zone i.

The maximum thermal load which can be satisfied by the heat pumps can be calculated as follows:

In heating mode:

$$\dot{Q}_{peak,heating,HP} = -N_{i,prim} \times CAP_{heating,HP} \tag{3.10}$$

In cooling mode:

$$\dot{Q}_{peak,cooling,HP} = N_{i,prim} \times CAP_{cooling,HP} \tag{3.11}$$

where

$\dot{Q}_{peak,heating,HP}$ is the maximum heating capacity of heat pumps in zone i, kW; this value is considered to be negative;

$\dot{Q}_{peak,cooling,HP}$ is the maximum cooling capacity of heat pumps in zone i, kW; this value is considered to be positive;

$CAP_{heating,HP}$ is the selected capacity of each heat pump, in heating mode, kW;

$CAP_{cooling,HP}$ is the selected capacity of each heat pump, in cooling mode, kW;

The temperature of mixture between the outside and return air is calculated based on the initial number of heat pumps:

$$T_{air,mix} = \frac{\dot{V}_{fresh,i}}{N_{i,prim} \times \dot{V}_{air,HP}} \times T_{air,out} + \frac{N_{i,prim} \times \dot{V}_{air,HP} - \dot{V}_{fresh,i}}{N_{i,prim} \times \dot{V}_{air,HP}} \times T_{inside} \qquad (3.12)$$

where

$T_{air,mix}$ is the mixed air temperature entering each heat pump, °C;

$\dot{V}_{air,HP}$ is the selected air flow rate for one heat pump, m^3/s;

T_{inside} is the inside air temperature, °C; in this study, $T_{inside} = 23°C$.

The design air temperature supplied by each heat pump is calculated as follows:

In heating mode:

$$T_{air,s,D} = T_{air,mix} - \frac{\dot{Q}_{peak,heating,HP}}{N_{i.prim} \times \dot{V}_{air,HP} \times \rho_{air} \times Cp_{air}} \qquad (3.13)$$

In cooling mode:

$$T_{air,s,D} = T_{air,mix} - \frac{\dot{Q}_{peak,cooling,HP}}{N_{i,prim} \times \dot{V}_{air,HP} \times \rho_{air} \times Cp_{air}} \tag{3.14}$$

where

$T_{air,s,D}$ is the design supply air temperature, °C;

The design thermal load that can be covered by heat pumps in a zone can be calculated as follows:

In heating mode:

$$\dot{Q}_{load,heating,D,i} = N_{i,prim} \times \dot{V}_{air,HP} \times \rho_{air} \times Cp_{air} \times (T_{inside} - T_{air,s,D}) \tag{3.15}$$

In cooling mode:

$$\dot{Q}_{load,cooling,D,i} = N_{i,prim} \times \dot{V}_{air,HP} \times \rho_{air} \times Cp_{air} \times (T_{inside} - T_{air,s,D}) \tag{3.16}$$

where

$\dot{Q}_{load,heating,D,i}$ is the design space heating load covered by all heat pumps in zone i, kW; this value is considered to be negative;

$\dot{Q}_{load,cooling,D,i}$ is the design space cooling load covered by all heat pumps in zone i, kW; this value is considered to be positive.

The difference between the design space thermal load and peak space thermal load that are from original input data is calculated as follows:

In the heating mode:

$$\Delta\dot{Q}_{heating,i,j} = \left|\dot{Q}_{load,heating,D,i,j}\right| - \left|\dot{Q}_{heating,i,j}\right| \tag{3.17}$$

In the cooling mode:

$$\Delta\dot{Q}_{cooling,i,j} = \left|\dot{Q}_{load,cooling,D,i,j}\right| - \left|\dot{Q}_{cooling,i,j}\right| \tag{3.18}$$

where

$\Delta\dot{Q}_{heating,i,j}$ is the difference between the absolute value of the design heating load and the absolute value of the peak space heating load in the zone i on the jth hour, kW;

$\Delta\dot{Q}_{cooling,i,j}$ is the difference between the absolute value of the design cooling load and the absolute value of the peak space cooling load in the zone i on the jth hour, kW;

$\dot{Q}_{heating,i,j}$ is the space heating load, in the zone i on the jth hour, kW;

$\dot{Q}_{cooling,i,j}$ is the space cooling load, in the zone i on the jth hour, kW.

If $\Delta\dot{Q}_{heating,i,j}$ or $\Delta\dot{Q}_{cooling,i,j}$ is less than zero, it means that the heat pumps in the zone can not satisfy the thermal requirement. The design number of the heat pumps, $N_{i,prim}$, should be increased, for instance, from 10 heat pumps to 11 heat pumps. Formulas (3.12) to (3.16) are used again, and conditions (3.17) and (3.18) are verified. The iterative process continues until results from formulas (3.17) and (3.18) are greater than zero.

The fraction of an hour that each heat pump in used is calculated as follows:

In heating mode

$$N_{use,heating,i,j} = \frac{\dot{Q}_{load,heating,i,j}}{CAP_{heating,HP} \times N_{i,HP}} \tag{3.19}$$

In cooling mode

$$N_{use,cooling,i,j} = \frac{\dot{Q}_{load,cooling,i,j}}{CAP_{cooling,HP} \times N_{i,HP}} \tag{3.20}$$

where

$N_{i,HP}$ is the number of heat pumps in zone i;

$N_{use,\,heating,\,i,\,j}$ is the usage fraction of heat pumps in heating mode on the jth hour in zone i;

$N_{use,\,cooling,\,i,\,j}$ is the usage fraction of heat pumps in cooling mode in the jth hour in zone i.

The heat transferred by heat pumps out of the water loop in heating mode is calculated as follows:

$$\dot{Q}_{loop,\,heating,\,i,j} = \dot{Q}_{load,\,heating,i,\,j} \times (1 - 1 / COP_{heating}) \tag{3.21}$$

The heat transferred by heat pumps into the water loop in cooling mode is calculated as follows:

$$\dot{Q}_{loop,\,cooling,\,i,\,j} = \dot{Q}_{load,\,cooling,i,\,j} \times (1 + 1 / COP_{cooling}) \tag{3.22}$$

where

$\dot{Q}_{loop,\,heating,\,i,\,j}$ is the heat flow rate transferred from the water loop system when heat pumps are in heating mode, kW, in the jth hour for zone i, this value is considered to be negative;

$\dot{Q}_{loop,\,cooling,\,i,\,j}$ is the heat flow rate transferred into the water loop system when heat pumps are in cooling mode, kW, in the jth hour for zone i, this value is considered to be positive;

$COP_{heating}$ is the coefficient of performance of heat pump in heating mode;

$COP_{cooling}$ is the coefficient of performance of heat pump in cooling mode.

For the whole WLHP system, the net heat transferred into/from the water loop in the j^{th} hour is calculated by the following formula:

$$\dot{Q}_{loop,\,total,\,j} = \sum_{1}^{5} \dot{Q}_{loop,\,i,\,j} \tag{3.23}$$

where

$\dot{Q}_{loop,\,total,\,j}$ is the net heat transferred into/from the water loop by all heat pumps installed on one floor in the j^{th} hour, kW;

$\dot{Q}_{loop,\,i,\,j}$ is heat transferred into/from water loop by all heat pumps of zone i in the j^{th} hour, kW.

In heating mode,

$$\dot{Q}_{loop,\,i,\,j} = \dot{Q}_{loop,\,heating,\,i,\,j} \tag{3.24}$$

In cooling mode,

$$\dot{Q}_{loop,\,i,\,j} = \dot{Q}_{loop,\,cooling,\,i,\,j} \tag{3.25}$$

In the j^{th} hour, the total electric demand of all heat pumps installed in the building is calculated by the following formula:

$$\dot{E}_{heatpump,\,total,\,j} = n_{floor} \times [\sum_{1}^{Nheating}(\dot{E}_{input,heatpump,heating} \times N_{use,\,heating,\,i,\,j}) + \sum_{1}^{Ncooling}(\dot{E}_{input,heatpump,cooling} \times N_{use,\,cooling,\,i,\,j})] \tag{3.26}$$

where

$\dot{E}_{heatpump,\,total,\,j}$ is the electricity demands of all heat pumps installed in the five floors in the jth hour, kW

$\dot{E}_{input,\,heatpump,\,heating}$ is the electrical demand of one heat pump that is in heating mode, kW;

$\dot{E}_{input,\,heatpump,\,cooling}$ is the electrical demand of one heat pump that is in cooling mode, kW;

$N_{heating}$ is the number of heat pumps that are operating in heating mode on one floor;

$N_{cooling}$ is the number of heat pumps that are operating in cooling mode on one floor.

The largest horizontal heat pump of this manufacturer (IBK, 2004), the model VH654, has the maximum cooling capacity of 6.48 kW and the corresponding electrical input of 2.59 kW, which gives a COP of 2.50. The maximum heating capacity of the same model is 5.11 kW and the corresponding electrical input is 1.22 kW, which give a COP of 4.19. The supply airflow rate is 0.42 m^3/s. The water flow rate is 0.23 l/s. The performance data corresponds to the case when every heat pump is supplied with water at the 35°C (EWT=35 °C) (Table 3.1). The performance of other models of heat pumps from the same manufacturer is presented in the Appendix A.

Table 3.1 Performance Data of selected Heat Pump Model VH645 (IBK, 2004)

Total Cooling Output (kW)	6.48
Total Electrical Input (kW)	2.59
Total Heating Output (kW)	5.11
Total Electrical Input (kW)	1.22
Airflow (m^3/s)	0.42
Water Flow Rate (l/s)	0.23

All performance data given at EWT 35°C, EAT 24°C, 50%RH Cooling, EAT 19°C Heating.

3.1.3 Circulating Pump

The electric demand of the circulating pump is calculated as follows (Metric Conversion Handbook, 1984):

$$\dot{E}_{pump} = N_{floor} \times \dot{V}_{total} \times H_{pump} \times Rd / ME \tag{3.27}$$

where

$\dot{E}_{pump}$ is the electric demand of the pump, kW;

$\dot{V}_{total}$ is the total water flow rate corresponding to all heat pumps installed on one floor, m^3/s;

H_{pump} is the pump head pressure, kPa;

Rd is the relative density of water; in SI unit, Rd is 1.00;

ME is the mechanical efficiency of pump, dimensionless; it is selected as 0.65 (Kuts, 1998).

$$\dot{V}_{total} = \sum_{1}^{5} (\dot{V}_{water,\,heatpump} \times N_{HP,i}) \tag{3.28}$$

where

$\dot{V}_{water,\,heatpump}$ is the water flow rate through one heat pump, m^3/s.

The pipe length of worst circulation loop in the WLHP system is estimated at 70 m. The velocity of water in pipes is 1.2 m/s. The general range of pipe friction loss for design of hydraulic system is between 100 to 400 Pa/m of pipe. A value of 250 Pa/m represents the mean to which the system is designed (ASHRAE, 2001). Fitting losses are calculated by considering an additional length of pipes of about 60% (ASHRAE, 2001). The pressure loss in the heat pump coil is 5 kPa per heat pump (IBK, 2004). Hence, the pump head pressure to cover the worst circulation loop is calculated as follows:

$$H_{pump} = H_{pipe} + H_{fitting} + H_{HP} \tag{3.29}$$

where

H_{pipe} is the pressure losses in the pipes, kPa;

$H_{fitting}$ is the pressure losses due to the fittings in the water loop, kPa;

H_{HP} is the pressure losses due to one heat pump coil, kPa. H_{HP} = 5 kPa.

$$H_{pipe} = \frac{L_{pipe} \times P_{pipe}}{1000} \tag{3.30}$$

where

L_{pipe} is the worst pipe length of the WLHP system, m; L_{pipe} = 200 m;

P_{pipe} is the pressure loss factor due to friction in pipe, Pa/m; $P_{pipe} = 250\, Pa/m$.

$$H_{fitting} = 0.6 \times H_{pipe} \tag{3.31}$$

Hence, H_{pump} is equal to 85 kPa.

3.1.4 Boiler and Cooling Tower

The return water temperature, T_R, of the whole WLHP system is calculated by the following formula:

$$T_{R,j} = EWT + \frac{\dot{Q}_{loop,total,j}}{\rho_{water} \times \dot{V}_{total} \times Cp_{water}} \tag{3.32}$$

where

ρ_{water} is the water density, kg/m^3;

Cp is the specific heat of water, kJ/kg K;

EWT is the entering water temperature at each heat pump, °C;

$T_{R,j}$ is the return water temperature for the whole WLHP system in the jth hour, °C;

$\dot{Q}_{loop,total,j}$ is the net heat transferred into/from the water loop in the jth hour, kW.

In this system, the secondary heat source is an electrical boiler and the heat rejector is a cooling tower. When the return water temperature, T_R, is between the upper (T_{upper}) and lower (T_{lower}) set-point temperatures, there is no need for heat to be supplied or to be removed from the water loop. If T_R is greater than the upper set-point temperature, the cooling tower rejects the extra heat from the water loop. If T_R is less than the lower set-point temperature, the boiler supplies heat into the water loop.

The heat rejected by the cooling tower from the water loop is calculated as follows:

$$\dot{Q}_{tower,j} = N_{floor} \times \rho_{water} \times \dot{V}_{total} \times Cp_{water} \times (T_{upper} - T_{R,j}) \tag{3.33}$$

where

$\dot{Q}_{tower,j}$ is the heat transferred from the water loop by the cooling tower the j^th^ hour, kW;

T_{upper} is the upper set-point temperature, °C.

The heat added by the boiler to the water loop is calculated as follows:

$$\dot{Q}_{boiler,j} = N_{floor} \times \rho_{water} \times \dot{V}_{total} \times Cp_{water} \times (T_{lower} - T_{R,j}) \tag{3.34}$$

where

$\dot{Q}_{boiler,j}$ is the heat supplied by boiler the j^{th} hour, kW;

T_{lower} is the lower set-point temperature, °C.

Since the information from the manufacturer's catalogue is based on a constant entering water temperature (EWT= 35 °C), T_{lower} and T_{upper} are set as follows.

$$T_{upper} = EWT + \Delta T_c \tag{3.35}$$

$$T_{lower} = EWT - \Delta T_c \tag{3.36}$$

where

ΔT_c is the controller range, °C; ΔT_c is assumed as 0.5 °C.

The boiler capacity, CAP_{boiler}, is the maximum value of the boiler load calculated in the (3.34), increased by 10% as it is recommended by(ASHRAE, 1989):

$$CAP_{boiler} = \max(\dot{Q}_{boiler,1}, \cdots, \dot{Q}_{boiler,j}) \times 1.1 \tag{3.37}$$

where

CAP_{boiler} is the boiler capacity, kW.

In a similar way, the capacity of the cooling tower, CAP_{tower}, is the maximum value of the cooling tower load calculated in the (3.33), increased by 10% (ASHRAE, 1989):

$$CAP_{tower} = \max(\dot{Q}_{tower,1}, \cdots, \dot{Q}_{tower,j}) \times 1.1 \tag{3.38}$$

where

CAP_{tower} is the capacity of the cooling tower, kW.

The electrical demand of the electrical boiler is calculated as follows (BLAST, 1991):

$$\dot{E}_{boiler,j} = \frac{\dot{Q}_{boiler,j}}{\eta_{actual,j}} \tag{3.39}$$

where

$\dot{E}_{boiler,j}$ is the electric demand of the boiler in the j^{th} hour, kW;

$\eta_{actual,j}$ is the actual efficiency of the boiler in the j^{th} hour; the following formula applies:

$$\frac{\eta_{actual,j}}{\eta_{theoretical}} = 0.563 + 0.921 PLR_{boiler,j} - 0.518 PLR_{boiler,j}^2 \tag{3.40}$$

where

$\eta_{theoretical}$ is the theoretical efficiency of the boiler; $\eta_{theoretical}$ at full load is 0.9, according to the information from the manufacturer (Carrier Corporation, 2004);

$PLR_{boiler,j}$ is the part load ratio of the boiler in the j^{th} hour.

$$PLR_{boiler,j} = \frac{\dot{Q}_{boiler,j}}{CAP_{boiler}} \tag{3.41}$$

where

$\dot{Q}_{boiler,j}$ is the boiler load in the j^{th} hour, kW.

The electric demand of the cooling tower is calculated as follows (BLAST, 1991):

$$\dot{E}_{tower} = \dot{Q}_{tower,j} \times N_{ELECTRICAL} \tag{3.42}$$

where

$\dot{E}_{tower,j}$ is the electricity demand of the cooling tower in the j^{th} hour, kW;

$N_{ELECTRICAL}$ is the fan electrical consumption per unit load of the cooling tower.

$$N_{ELECTRICAL} = \frac{\dot{E}_{tower,fan}}{CAP_{tower}} \tag{3.43}$$

where

$\dot{E}_{tower,fan}$ is the electrical input of the fan of the cooling tower, kW; $\dot{E}_{tower,fan}$ is a constant value when the type of the cooling tower is selected.

The design outdoor dry bulb temperature is 39.22°C and the design outside wet bulb temperature is 25.6°C. The cooling tower model VXT-40 is selected in this study, based on information from the manufacturer (Baltimore Aircoil, 1983). The electric input fan of the cooling tower, $\dot{E}_{tower,\,fan}$, is 2.24 kW. The electrical demand of the circulating pump to the cooling tower is zero because the water loop is directly connected to the cooling tower.

3.1.5 Coefficient of Performance of the WLHP system

The coefficient of performance (COP) of the whole WLHP system is calculated as follows:

$$COP_{system,\,j} = \frac{\dot{Q}_{Output,\,j}}{\dot{E}_{system,\,input,\,j}} \tag{3.44}$$

where

$COP_{system,\,j}$ is the coefficient of performance of the whole system in the j^{th} hour;

$\dot{Q}_{Output,\,j}$ is total heating and cooling loads including the load for ventilation air, which are satisfied by heat pumps in the j^{th} hour, kW;

$\dot{E}_{system,\,input,\,j}$ is the total electric demand to the system in the j^{th} hour, kW.

$$\dot{Q}_{Output,\,j} = \sum_{1}^{5} \left| \dot{Q}_{heating,j} \right| + \sum_{1}^{5} \dot{Q}_{cooling,j} \tag{3.45}$$

where

$\sum_{1}^{5} \dot{Q}_{heating,\,j}$ is the space heating load as input from the DOE-2 program of all zones in five floors, in the j^{th} hour, kW;

$\sum_{1}^{5}\dot{Q}_{cooling,j}$ is the space cooling load as input from the DOE-2 program of all zones in five floors, in the j th hour, kW.

$$\dot{E}_{system,\,input,\,j} = \dot{E}_{heatpump,\,total,\,j} + \dot{E}_{fan} + \dot{E}_{pump} + \dot{E}_{boiler,\,j} + \dot{E}_{tower,\,j} \tag{3.46}$$

3.1.6 Overall Coefficient of Performance

When the efficiency of electricity generation and transmission losses are taken into account, the overall COP is calculated as follows:

$$COP_{overall,\,j} = \frac{\dot{Q}_{Output,\,j}}{\dot{E}_{system,\,input,\,j} \times \eta_{overall}} \tag{3.47}$$

where

$COP_{overall,\,j}$ is the overall COP, in the j th hour;

$\eta_{overall}$ is the overall power plant efficiency, including transmission losses.

The overall power plant efficiency is calculated as follows:

$$\eta_{overall} = \frac{1}{\eta_{trans}} \times \left(\frac{\alpha_{hydro}}{\eta_{hydro}} + \frac{\alpha_{gas}}{\eta_{gas}} + \frac{\alpha_{oil}}{\eta_{oil}} + \frac{\alpha_{nuclear}}{\eta_{nuclear}}\right) \tag{3.48}$$

where

η_{trans} is the overall efficiency of electricity transmission;

η_{hydro} is the overall efficiency of hydro power plants;

α_{hydro} is the contribution of hydro power plants to the electricity mix;

η_{gas} is the overall efficiency of natural gas-fired power plants;

η_{oil} is the overall efficiency of oil-fired power plants;

$\eta_{nuclear}$ is the overall efficiency of nuclear power plants;

α_{gas} is the contribution of natural gas-fired power plants to the electricity mix;

α_{oil} is the contribution of oil-fired power plants to the electricity mix;

$\alpha_{nuclear}$ is the contribution of nuclear power plants to the electricity mix.

In Quebec, there are four types of power plants. They are hydro, natural gas-fired, oil-fired and nuclear power plants. Every type of power plant has different overall efficiencies. (Wu, 2004):

Table 3.2 Contribution of different power plants to the generation of electricity in Quebec

	Overall efficiency	Contribution
Hydro power plant	80%	96.7%
Natural gas fired power plant	43.1%	1.1%
Oil fired power plant	33%	1.1%
Nuclear power plant	30%	1.1%
Transmission lines	86%	

3.2 Exergy Balance

In this study, the whole WLHP system and each component are analyzed as a steady flow thermodynamics system (Çengel, 2002). The kinetic and potential energies are negligible. The exergy analysis includes the following main components of the WLHP system: the heat pumps, the outdoor air fan, the secondary heat source equipment, the heat rejector and the circulating pump.

3.2.1 Heat Pump

The components of the exergy balance for one heat pump are presented in the Figure 3.3, when the heat pump operates in heating mode and in Figure 3.4 when it operates in cooling mode.

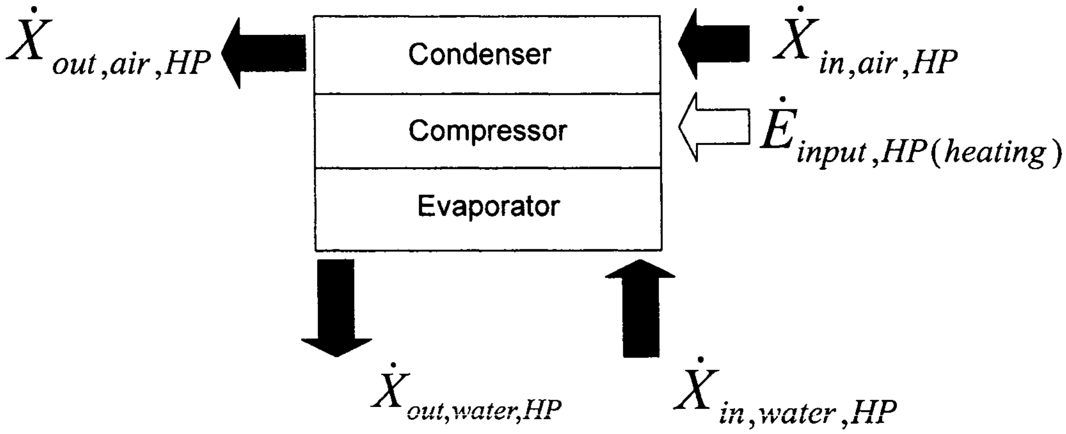

Figure 3.3 Exergy balance of one heat pump in heating mode

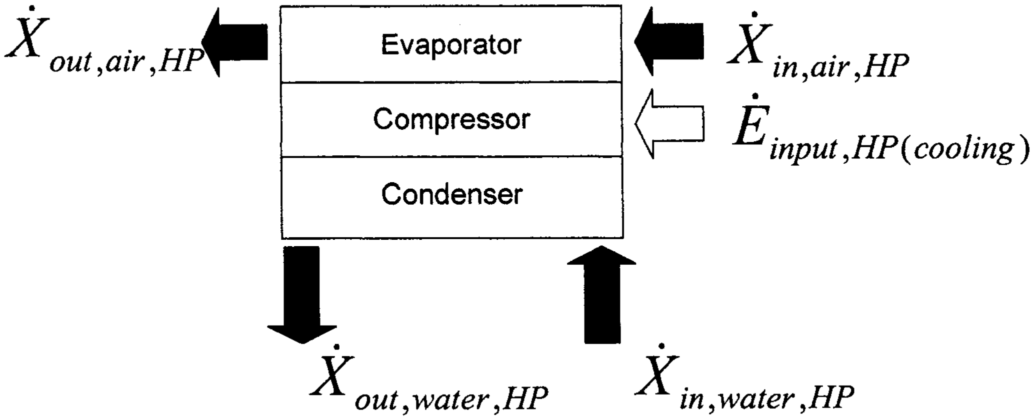

Figure 3.4 Exergy balance of one heat pump in cooling mode

The exergy balance equation is written as follows:

$$\dot{X}_{in,air,HP} - \dot{X}_{out,air,HP} + \dot{X}_{in,water,HP} - \dot{X}_{out,water,HP} + \dot{E}_{input,HP} - \dot{X}_{D,HP} = 0 \tag{3.49}$$

The exergy efficiency of each heat pump installed in one zone is calculated as follows:

$$\eta_{X,\,heatpump} = \frac{\left|\dot{X}_{out,air,HP} - \dot{X}_{in,air,HP}\right|}{\dot{X}_{supply,\,HP}} \tag{3.50}$$

where

$\eta_{X,\,heatpump}$ is the exergy efficiency of one heat pump;

$\dot{X}_{in,air,HP}$ is the exergy transferred by the entering air to one heat pump, kW;

$\dot{X}_{out,air,HP}$ is the exergy transferred by the leaving air from one heat pump, kW;

$\dot{X}_{in,water,HP}$ is the exergy transferred by the entering water to one heat pump, kW;

$\dot{X}_{out,water,HP}$ is the exergy transferred by the leaving water from one heat pump, kW;

$\dot{E}_{input,HP}$ is the electric demand of one heat pump, kW;

$\dot{X}_{D,HP}$ is the exergy destruction of one heat pump, kW;

$\dot{X}_{supply,HP}$ is the exergy supplied to one heat pump, kW.

By considering that all heat pumps installed in one zone are identical and operate under the same conditions, the exergy flows for one heat pump is written as follows:

$$\dot{X}_{in,air,HP} = \dot{m}_{in,air,HP} \times [(h_{in,air,HP} - h_0) - T_0 \times (s_{in,air,HP} - s_0)] \tag{3.51}$$

$$\dot{X}_{out,air,HP} = \dot{m}_{out,air,HP} \times [(h_{out,air,HP} - h_0) - T_0 \times (s_{out,air,HP} - s_0)] \tag{3.52}$$

$$h_{in,air} = \frac{\dot{m}_{fresh} \times h_{fresh} + (\dot{m}_{in,air,HP} - \dot{m}_{fresh}) \times h_{return,air}}{\dot{m}_{in,air,HP}} \tag{3.53}$$

$$\dot{m}_{fresh} = \frac{\dot{V}_{fresh,i} \times \rho_{air}}{N_{HP,i}} \tag{3.54}$$

In heating mode:

$$\dot{m}_{in,air,HP} = \dot{m}_{out,air,HP} = N_{use,\,heating,\,i,\,j} \times \dot{V}_{air,HP} \times \rho_{air} \tag{3.55}$$

$$h_{out,air} = \frac{\dot{m}_{in,air,HP} \times h_{air,\,design} + \dot{Q}_{load,\,heating,\,j}}{\dot{m}_{in,air,HP}} \tag{3.56}$$

$$\dot{X}_{supply,HP} = \dot{E}_{input,heating,HP} \tag{3.57}$$

In cooling mode:

$$\dot{m}_{in,air,HP} = \dot{m}_{out,air,HP} = N_{use,cooling,i,j} \times \dot{V}_{air,HP} \times \rho_{air} \tag{3.58}$$

$$h_{out,air,HP} = \frac{\dot{m}_{in,air,HP} \times h_{air,inside} - \dot{Q}_{load,cooling,j}}{\dot{m}_{in,air,HP}} \tag{3.59}$$

$$\dot{X}_{supply,HP} = \dot{E}_{input,cooling,HP} \tag{3.60}$$

where

$N_{HP,i}$ is the number of heat pumps in zone i;

$\dot{m}_{in,air,HP}$ is the air mass flow rate entering one heat pumps, kg/s;

$\dot{m}_{out,air,HP}$ is the air mass flow rate leaving one heat pumps, kg/s;

$\dot{m}_{fresh}$ is the outside air mass flow rate entering one heat pumps, kg/s;

$\dot{V}_{air,\ HP}$ is the air flow rate supplied by one heat pump, m^3/s; in this study, a constant value of 0.42 m^3/s is used, from the manufacturer catalogues (Table 3.1);

ρ_{air} is the air density at the indoor temperature of 296 K, kg/ m^3;

T_0 is the reference temperature, K; in this study, T_0 is equal to outside air temperature;

$h_{in,air,HP}$ is the enthalpy of the air entering heat pumps, kJ/kg;

$h_{out,air,HP}$ is the enthalpy of the air leaving heat pumps, kJ/kg;

h_0 is the enthalpy of outside air, kJ/kg; it is calculated at T_0;

$h_{air,inside}$ is the enthalpy of indoor air, kJ/kg; it is calculated at the inside temperature, T_{inside}, and the inside relative humidity, 50%;

$s_{in,air,HP}$ is the entropy of air entering heat pumps, kJ/kg K;

$s_{out,air,HP}$ is the entropy of air leaving heat pumps, kJ/kg K;

s_0 is the entropy of outside air, kJ/kg K, it is used as reference entropy calculated at T_0.

3.2.2 Boiler

The components of the exergy balance for the electric boiler are shown in Figure 3.5:

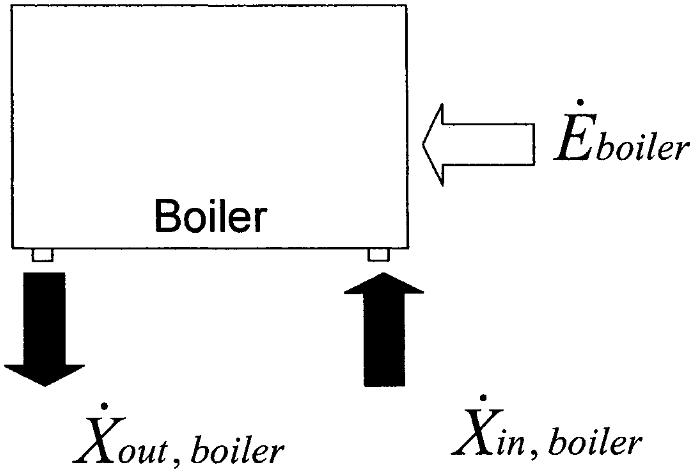

Figure 3.5 Exergy balance of the boiler

The exergy balance equation is written as follows:

$$\dot{X}_{in,\,boiler} - \dot{X}_{out,\,boiler} + \dot{X}_{supply,\,boiler} - \dot{X}_{D,\,boiler} = 0 \tag{3.61}$$

The exergy efficiency of the boiler is calculated as follows:

$$\eta_{X,\,boiler} = \frac{\dot{X}_{out,\,boiler} - \dot{X}_{in,\,boiler}}{\dot{X}_{supply,\,boiler}} \tag{3.62}$$

where

$\eta_{X,\,boiler}$ is the exergy efficiency of the boiler;

$\dot{X}_{out,\,boiler}$ is the exergy transferred from the boiler by water, kW;

$\dot{X}_{in,\,boiler}$ is the exergy transferred into the boiler by water, kW;

$\dot{X}_{\sup ply,\,boiler}$ is the exergy supplied into the boiler, kW.

$$\dot{X}_{out,\,boiler} = \dot{m}_{loopwater} \times [(h_{out,boiler} - h_0) - T_0 \times (s_{out,boiler} - s_0)] \tag{3.63}$$

where

$\dot{m}_{loopwater}$ is the water mass flow rate in the system, kg/s;

$h_{out,boiler}$ is the enthalpy of the water leaving the boiler to heat pumps, kJ/kg; it is calculated at T=35°C;

$s_{out,boiler}$ is the entropy of the water leaving the boiler to heat pumps, kJ/kg; it is calculated at T=35°C;

$$\dot{m}_{loopwater} = \rho_{water} \times \dot{V}_{total} \times N_{floor} \tag{3.64}$$

$\dot{V}_{loopwater}$ is the volume flow rate of water in the system, m^3/s;

ρ_{water} is the density of water at the entering heat pumps, kg/ m^3, it is calculated at T=35°C;

$$\dot{X}_{in,\,boiler} = \dot{m}_{loopwater} \times [(h_{in,boiler} - h_0) - T_0 \times (s_{in,boiler} - s_0)] \tag{3.65}$$

$h_{in,boiler}$ is the enthalpy of the water entering the boiler, corresponding with the return water temperature, kJ/kg;

$s_{in,boiler}$ is the entropy of the water entering the boiler, corresponding with the return water temperature, kJ/kg·K.

$$\dot{X}_{supply,\,boiler} = \dot{E}_{boiler} \tag{3.66}$$

$\dot{E}_{boiler}$ is the energy demand of the boiler, kW;

3.2.3 Cooling Tower

The components of the exergy balance of the cooling tower are presented in Figure 3.6:

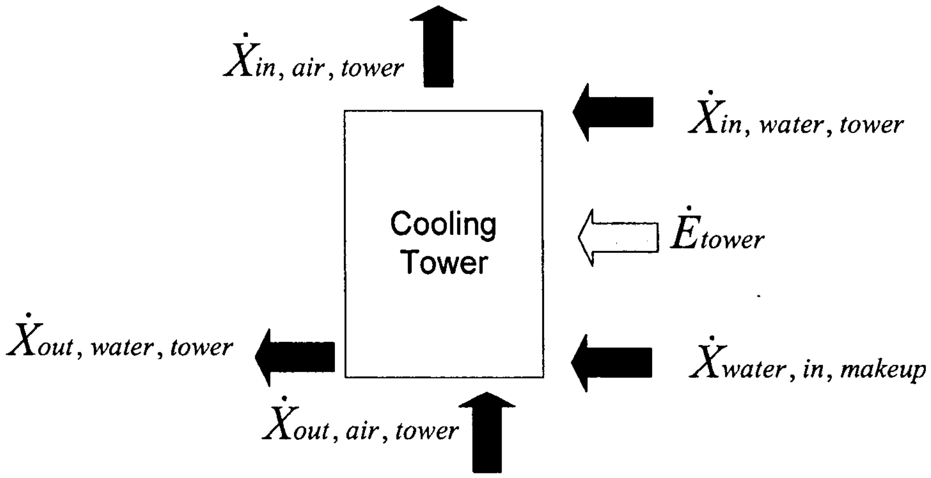

Figure 3.6 Exergy balance of the cooling tower

The exergy balance of the cooling tower is calculated as follows:

$$\dot{X}_{in,water,tower} - \dot{X}_{out,water,tower} + \dot{E}_{tower} + \dot{X}_{in,air,tower} - \dot{X}_{out,air,tower} - \dot{X}_{D,tower} + \dot{X}_{water,in,makeup} - \dot{X}_{water,out,makeup} = 0 \tag{3.67}$$

The exergy efficiency of the boiler is calculated as follows:

$$\eta_{X,\ tower} = \frac{\dot{X}_{useful,tower}}{\dot{X}_{supply,\ tower}} \tag{3.68}$$

where

$\dot{X}_D$ is the exergy destruction of the cooling tower, kW;

$\eta_{X,\ tower}$ is the exergy efficiency of the cooling tower;

$\dot{X}_{out,\ water,\ tower}$ is the exergy transferred from the cooling tower through water, kW;

$\dot{X}_{in,\ water,\ tower}$ is the exergy transferred to the cooling tower through water, kW;

$\dot{X}_{water,in,makeup}$ is the exergy transferred to the cooling tower through makeup water, kW;

$\dot{X}_{water,out,makeup}$ is the exergy transferred from the cooling tower through makeup water, kW;

$\dot{X}_{in,\ air,\ tower}$ is the exergy transferred to the cooling tower through air, kW;

$\dot{X}_{out,\ air,\ tower}$ is the exergy transferred from the cooling tower through air, kW;

$\dot{X}_{useful,tower}$ is the useful exergy transferred within the cooling tower, kW;

$\dot{X}_{supply,\ tower}$ is the exergy supplied to the cooling tower, kW;

$\dot{E}_{tower}$ is the electricity demand for the fan of the cooling tower, kW.

$$\dot{X}_{out,\ water,\ tower} = \dot{m}_{loopwater} \times [(h_{out,water,tower} - h_0) - T_0 \times (s_{out,water,tower} - s_0)] \qquad (3.69)$$

where

$h_{out,water,tower}$ is the enthalpy of the water leaving the cooling tower to heat pumps, kJ/kg; it is calculated at T=35°C;

$s_{out,\ water,\ tower}$ is the entropy of the water leaving the cooling tower to heat pumps , kJ/kg·K; it is calculated at T=35°C;

$\dot{m}_{loopwater,\ out,\ tower}$ is the water mass flow rate that leaves the cooling tower, kg/s.

$$\dot{X}_{in,water,tower} = \dot{m}_{loopwate} \times [(h_{in,water,tower} - h_0) - T_0 \times (s_{in,water,tower} - s_0)] \qquad (3.70)$$

where

$\dot{m}_{loopwater,\ in,\ tower}$ is the water mass flow rate that enters the cooling tower, kg/s;

$h_{water,in,tower}$ is the enthalpy of the water supplied into the cooling tower, kJ/kg, it is calculated at the return water temperature;

$s_{in,water,tower}$ is the entropy of the water supplied into the cooling tower, kJ/kg·K, it is calculated at the return water temperature.

$$\dot{X}_{water,in,makeup} = \dot{m}_{water,makeup} \times [(h_{water,in,makeup} - h_0) - T_0 \times (s_{water,in,makeup} - s_0)] \qquad (3.71)$$

where

$\dot{m}_{makeupwaeter,in}$ is the water mass flow rate make up of the cooling tower, kg/s;

$h_{water,in,makeup}$ is the enthalpy of the make up water, kJ/kg, it is calculated at T=10°C;

$s_{waeter,in,makeup}$ is the entropy of the make up water, kJ/kg·K, it is calculated at T=10°C.

$$\dot{X}_{water,out,makeup} = \dot{m}_{water,makeup} \times [(h_{water,out,makeup} - h_0) - T_0 \times (s_{water,out,makeup} - s_0)] \qquad (3.72)$$

where

$\dot{m}_{makeupwaeter,in}$ is the make up water mass flow rate for the cooling tower, kg/s;

$h_{water,out,makeup}$ is the enthalpy of the lost water, kJ/kg, it is calculated at air temperature leaving the cooling tower, $T_{leave,air,tower}$;

$s_{water,out,makeup}$ is the entropy of the lost water, kJ/kg·K, it is calculated at air temperature leaving the cooling tower.

In this study, the mass ratio of the make up water to the loop water entering the cooling tower is assumed as 0.05:1 (ASHRAE, 2001).

$$\dot{m}_{water,makeup} = 0.05 \times \dot{m}_{loopwater} \qquad (3.73)$$

$$\dot{X}_{in,air,tower} = \dot{m}_{in,air,tower} \times [(h_{in,air,tower} - h_0) - T_0 \times (s_{in,air,tower} - s_0)] \tag{3.74}$$

where

$\dot{m}_{,in,air,tower}$ is the air mass flow rate entering the cooling tower, kg/s;

$h_{in,air,tower}$ is the enthalpy of the air entering the cooling tower, kJ/kg, it is calculated at the outside temperature;

$s_{in,air,tower}$ is the entropy of the air entering the cooling tower, kJ/kg·K, it is calculated at the outside temperature.

$$\dot{X}_{out,air,tower} = \dot{m}_{out,air,tower} \times [(h_{out,air,tower} - h_0) - T_0 \times (s_{out,air,tower} - s_0)] \tag{3.75}$$

where

$\dot{m}_{,out,air,tower}$ is the air mass flow rate leaving the cooling tower, kg/s;

$h_{out,air,tower}$ is the enthalpy of the air leaving the cooling tower, kJ/kg, it is calculated at the relative humidity of 0.95;

$s_{out,air,tower}$ is the entropy of the air leaving the cooling tower, kJ/kg·K, it is calculated at the relative humidity of 0.95.

$$\dot{m}_{in,air,tower} = \dot{m}_{out,air,tower} \tag{3.76}$$

$$\dot{X}_{supply,tower} = \dot{X}_{water,in,makeup} - \dot{X}_{water,out,makeup} + \dot{X}_{in,air,tower} - \dot{X}_{out,air,tower} + \dot{E}_{tower} \tag{3.77}$$

$$\dot{X}_{useful,\,tower} = \dot{X}_{in,\,water,\,tower} - \dot{X}_{out,\,water,\,tower} \tag{3.78}$$

3.2.4 Circulating Pump

The components of the exergy balance for the pump are shown in Figure 3.7:

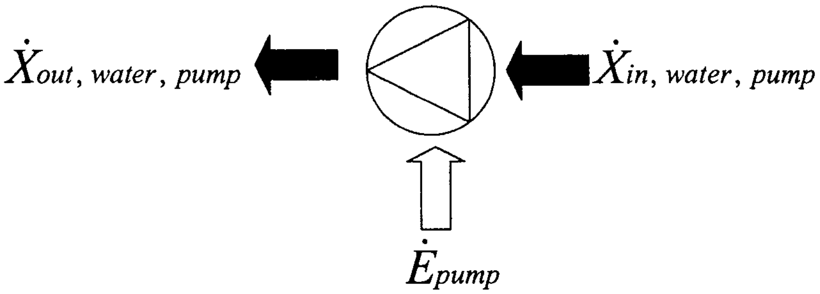

Figure 3.7 Exergy balance of the circulating pump

The exergy balance of the pump is written as follows:

$$\dot{E}_{pump} - \dot{X}_{out,\,water,\,pump} + \dot{X}_{in,\,water,\,pump} - \dot{X}_{D,\,pump} = 0 \tag{3.79}$$

The exergy efficiency of the circulating pump is calculated as follows:

$$\eta_{X,\,pump} = \frac{\dot{X}_{out,\,water,\,pump} - \dot{X}_{in,\,water,\,pump}}{\dot{X}_{supply,\,pump}} \tag{3.80}$$

where

$\eta_{X,\,pump}$ is the exergy efficiency of the pump;

$\dot{X}_{out,\,water,\,pump}$ is the exergy transferred from the pump through the water, kW;

$\dot{X}_{in,\,water,\,pump}$ is the exergy transferred to the pump through the water, kW;

$\dot{E}_{pump}$ is the electric demand of the pump, kW;

$\dot{X}_{supply,\,pump}$ is the exergy supplied into the pump, kW.

$$\dot{X}_{out,\,water,\,pump} - \dot{X}_{in,\,water,\,pump} = \dot{m}_{loopwater} \times [(h_{out,water,pump} - h_{in,water,pump}) \\ - T_0 \times (s_{out,water,pump} - s_{in,water,pump})] \tag{3.81}$$

where

$h_{out,water,pump}$ is the enthalpy of the water leaving the pump, kJ/kg, corresponding to the leaving water temperature, $T_{water,\,out}$, and leaving water pressure, $P_{water,\,out}$;

$h_{in,water,pump}$ is the enthalpy of the water entering the pump, kJ/kg, corresponding to the entering water temperature, $T_{water,\,in}$, and water pressure, $P_{water,\,in}$;

$s_{out,water,pump}$ is the entropy of the water at the outlet of the pump, corresponding to the water temperature and pressure leaving the pump, kJ/kg·K;

$s_{in,water,pump}$ is the entropy of the water entering the pump, corresponding to the water temperature and pressure entering the pump, kJ/kg·K.

The water pressure entering the pump is calculated as follows:

$$P_{in,\,water} = P_0 + \frac{V_{water}^2 \times \rho_{water}}{2 \times 10^3} \tag{3.82}$$

where

$P_{in,\,water}$ is the water pressure at the inlet of the pump, kPa;

P_0 is the atmosphere pressure, kPa, in this study, it is a constant value, 101 kPa;

V_{water} is the water velocity at the inlet of the pump, m/s, in this study, it is assumed as 1.2 m/s.

The water pressure leaving the circulating pump is calculated as follows:

$$P_{out,water} = P_{in,water} + H_{pump} \tag{3.83}$$

where

$P_{out,\ water}$ is the water pressure at the outlet of the pump, kPa;

H_{pump} is the head pressure of water for this system, kPa.

The water temperature leaving the pump is calculated as follows:

$$T_{out,water} = \Delta T + T_{in,water} \tag{3.84}$$

where

ΔT is the water temperature difference across the circulating pump, °C, in this study, ΔT=0°C (National Research Council Canada, 1998);

$T_{in,water}$ is the water temperature entering the circulating pump, °C;

$T_{out,water}$ is the water temperature leaving the circulating pump, °C.

$$\dot{X}_{\mathrm{supply},\ pump} = \dot{E}_{pump} \tag{3.85}$$

3.2.5 Fan for outside air

The components of the exergy balance of the fan that is used to circulate the outside air are presented in Figure 3.8:

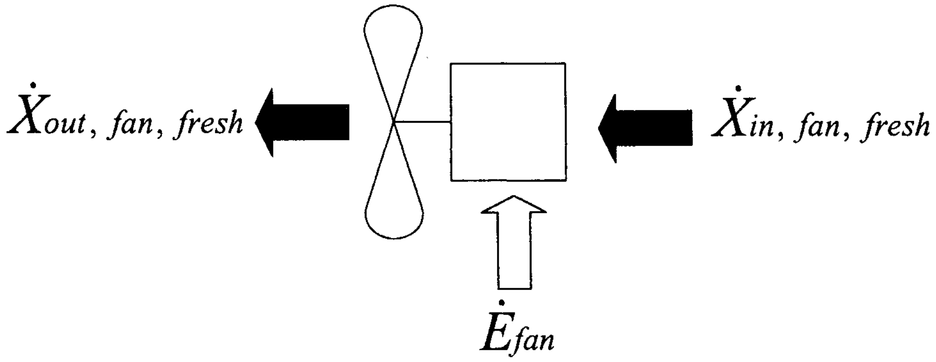

Figure 3.8 Exergy balance of the outside air fan

The exergy balance of the outside air fan is written as follows:

$$\dot{X}_{in, fan, fresh} + \dot{E}_{fan} - \dot{X}_{out, fan, fresh} - \dot{X}_{D, fan} = 0 \tag{3.86}$$

The exergy efficiency of the fan to supply the outside air is calculated as follows:

$$\eta_{X, fan, fresh} = \frac{\dot{X}_{out, fan, fresh} - \dot{X}_{in, fan, fresh}}{\dot{X}_{supply, fan, fresh}} \tag{3.87}$$

where

$\eta_{X, fan, fresh}$ is the exergy efficiency of the fan;

$\dot{X}_{out, fan, fresh}$ is the exergy transferred from the fan through the air, kW;

$\dot{X}_{in, fan, fresh}$ is the exergy transferred to the fan through the air, kW;

$\dot{E}_{fan}$ is the electric demand to the fan, kW;

$\dot{X}_{supply,\,fan\,,fresh}$ is the exergy supplied to the fan, kW.

$$\dot{X}_{out,\,fan,\,fresh} = \dot{m}_{fresh,\,total} \times [(h_{fresh,out} - h_0) - T_0 \times (s_{fresh,out} - s_0)] \tag{3.88}$$

where

$\dot{m}_{fresh,\,total}$ is the mass flow rate of the outside air supplied into the building, kg/s;

$h_{fresh,\,out}$ is the enthalpy of the air leaving the fan, corresponding to the air temperature after the fan, and at a pressure that is higher by 5.8 kPa, calculated in section 3.1.1, than the atmospheric pressure, kJ/kg;

$s_{fresh,out}$ is the entropy of the air leaving the fan, corresponding to the air temperature after passed the fan and the increased pressure, kJ/kg·K;

$$\dot{m}_{fresh,\,total} = \dot{V}_{fresh,\,total} \times \rho_{air} \tag{3.89}$$

where

$\dot{V}_{fresh,\,total}$ is the total outdoor air flow rate supplied into zone 1 to 5, m^3/s;

$$\dot{X}_{in,\,fan,\,fresh} = \dot{m}_{fresh,\,total} \times [(h_{in,fresh} - h_0) - T_0 \times (s_{in,fresh} - s_0)] \tag{3.90}$$

where

$h_{in,fresh}$ is the enthalpy of the air entering the fan, corresponding to the outside air temperature, kJ/kg;

$s_{in,fresh}$ is the entropy of the air entering the fan, corresponding to the outside air temperature, kJ/kg·K.

$$\dot{X}_{\text{supply}, fan} = \dot{E}_{fan} \tag{3.91}$$

3.2.6 The exergy efficiency of the WLHP system

The exergy efficiency of the whole system is calculated as follows:

$$\eta_{X, system} = \frac{\dot{X}_{useful,system}}{\dot{X}_{\sup ply,system}} \tag{3.92}$$

where

$\eta_{X\ system}$ is the exergy efficiency of the WLHP system;

$\dot{X}_{useful,system}$ is the useful exergy for the WLHP system, kW;

$\dot{X}_{\sup ply,system}$ is the exergy supply to all components of the WLHP system, kW.

$$\dot{X}_{useful,system} = \left| \dot{m}_{out,air,HP} \times [(h_{leave,air,HP} - h_{air,inside}) - T_0 \times (s_{leave,air,HP} - s_{air,inside})] \right| \tag{3.93}$$

where

$h_{leave,air,HP}$ is the air enthalpy leaving heat pumps, kJ/kg;

$s_{leave,air,HP}$ is the air entropy leaving heat pumps, kJ/kg·K;

$h_{air,inside}$ is the inside air enthalpy, kJ/kg; it is calculated as the constant inside air temperature, 23°C and the constant relative humidity, 50%;

$s_{air,inside}$ is the inside air entropy, kJ/kg·K; it is calculated as the constant inside air temperature, 23°C and the constant relative humidity, 50%.

$$\dot{X}_{\sup ply,system} = \dot{E}_{heatpump,total} + \dot{E}_{fan} + \dot{E}_{boiler} + \dot{E}_{pump} + \dot{E}_{tower} \tag{3.94}$$

where

$\dot{E}_{heatpump,total}$ is the electricity demand of all heat pumps, which were installed on five floors, kW.

3.2.7 The exergy efficiency of the overall system

When the efficiency of electricity generation and transmission losses is taken into account, the exergy efficiency of the overall system is calculated as follows:

$$\eta_{X,overall} = \frac{\dot{X}_{useful,system}}{(\dot{X}_{\sup ply,system} / \eta_{overall})} \tag{3.95}$$

where

$\eta_{X,overall}$ is the overall exergy efficiency of the WLHP system;

$\eta_{overall}$ is the overall power plant efficiency that includes transmission losses.

3.2.8 The exergy destruction distribution for the components of the WLHP system

The contribution of each component to the total exergy destruction in the WLHP system is calculated as follows:

$$\eta_{D,,i} = \frac{\dot{X}_{D,i}}{\sum \dot{X}_{D,i}} \tag{3.96}$$

Where

$\eta_{D,,i}$ is the exergy destruction ratio for one component such as heat pumps and boiler;

$\dot{X}_{D,i}$ is the exergy destruction by one component of WLHP system, kW.

The exergy destruction due to heat pumps in the zone is calculated as follows:

$$\dot{X}_{D,HP} = \dot{X}_{in,air,HP} - \dot{X}_{out,air,HP} + \dot{X}_{in,water,HP} - \dot{X}_{out,water,HP} + \dot{E}_{input,HP} \tag{3.97}$$

The exergy destruction due to the boiler is calculated as follows:

$$\dot{X}_{D,boiler} = \dot{X}_{in,boiler} - \dot{X}_{out,boiler} + \dot{E}_{boiler} \tag{3.98}$$

The exergy destruction due to the cooling tower is calculated as follows:

$$\dot{X}_{D,tower} = \dot{X}_{water,in,makeup} - \dot{X}_{water,out,makeup} + \dot{E}_{tower} + \dot{X}_{in,\,air,\,tower} - \dot{X}_{out,\,air,\,tower} \tag{3.99}$$

The exergy destruction due to the circulating pump is calculated as follows:

$$\dot{X}_{D,pump} = \dot{E}_{pump} - \dot{X}_{out,water,pump} + \dot{X}_{in,water,pump} \tag{3.100}$$

The exergy destruction due to the fan is calculated as follows:

$$\dot{X}_{D,fan} = \dot{X}_{in,fan\,,fresh} + \dot{E}_{fan} - \dot{X}_{out,fan\,,fresh} \tag{3.101}$$

CHAPTER 4

CASE STUDY

This chapter presents the energy performance of a WLHP system installed in an office building in Montreal. The thermal loads of an existing building were simulated using the DOE program (Zmeureanu, 1995) and input to the EES program. The equations, programmed in the EES program in which the decimal of results places six, are solved by Newton's method (F-Chart Software, 2005). The results are obtained using the mathematical model presented in chapter 3.

4.1 Energy efficiency of the WLHP system

4.1.1 Heating and cooling loads

This section presents the heating and cooling loads of each zone of a typical floor, as obtained from the hourly simulation with DOE program (Zmeureanu, 1995). In Table 4.1, Table 4.2 and Table 4.3, the maximum hourly thermal loads in every month are presents as "Peak Load" and the total heating and cooling loads during one month are presented as "Monthly Load" ("C" stands for cooling and "H" stands for heating).

Table 4.1 Monthly Loads of Core & North zone

	Core Zone				North Zone			
	Peak Load (kW)		Monthly Load ($\times10^5$ kWh)		Peak Load (kW)		Monthly Load ($\times10^5$ kWh)	
	C	H	C	H	C	H	C	H
Jan	12.69	0.00	121.00	0.00	0.00	7.21	0.00	49.10
Feb	12.69	0.00	106.00	0.00	0.00	7.53	0.00	46.60
Mar	12.69	0.00	115.00	0.00	3.86	6.08	2.93	25.30
Apr	12.69	0.00	112.00	0.00	4.85	3.60	12.20	6.39
May	12.69	0.00	124.00	0.00	7.72	1.23	36.40	0.39
Jun	12.69	0.00	109.00	0.00	10.21	1.84	44.00	0.29
Jul	12.69	0.00	115.00	0.00	8.87	0.00	55.40	0.00
Aug	12.69	0.00	121.00	0.00	7.14	0.04	48.90	0.0014
Sep	12.69	0.00	106.00	0.00	5.69	1.89	22.00	1.07
Oct	12.69	0.00	121.00	0.00	3.24	3.51	5.13	9.71
Nov	12.69	0.00	112.00	0.00	1.51	5.12	0.570	22.30
Dec	12.69	0.00	118.00	0.00	0.00	8.40	0.40	39.20
Total			1380.00	0.00			228.00	200.00

Table 4.2 Monthly Loads of East & South Zone

	East Zone				South Zone			
	Peak Load (kW)		Monthly Load ($\times10^5$ kWh)		Peak Load (kW)		Monthly Load ($\times10^5$ kWh)	
	C	H	C	H	C	H	C	H
Jan	5.98	7.26	4.55	28.20	6.62	6.19	4.51	33.70
Feb	8.04	6.68	6.78	28.00	8.31	6.20	6.73	31.20
Mar	10.17	5.70	14.70	16.40	11.54	4.85	17.40	18.30
Apr	9.32	3.50	18.00	4.61	9.74	2.98	21.60	5.62
May	8.77	1.21	37.70	0.33	10.31	1.08	46.70	0.66
Jun	8.87	1.88	39.60	0.27	9.35	1.61	47.80	0.42
Jul	8.58	0.00	51.90	0.00	9.90	0.00	60.60	0.00
Aug	10.10	0.47	52.40	0.00	11.01	0.50	64.30	0.017
Sep	9.55	2.01	31.20	0.57	11.33	1.85	37.70	0.94
Oct	7.65	3.36	15.70	6.05	8.38	2.98	20.40	6.80
Nov	5.76	5.23	6.29	12.90	7.52	4.44	10.10	14.10
Dec	8.00	7.85	4.65	21.30	8.40	6.74	5.65	24.20
Total			283.00	119.00			343.00	136.00

Table 4.3 Monthly Loads of West Zone

	West Zone			
	Peak Load (kW)		Monthly Load ($\times10^5$ kWh)	
	C	**H**	**C**	**H**
Jan	0.00	6.19	0.00	41.80
Feb	0.00	6.20	0.00	39.30
Mar	2.49	4.85	2.24	20.30
Apr	4.14	2.98	9.61	5.54
May	5.52	1.08	30.00	0.63
Jun	6.82	1.61	37.30	0.34
Jul	6.71	0.00	44.50	0.00
Aug	5.71	0.50	40.30	0.022
Sep	4.56	1.85	17.80	1.06
Oct	2.72	2.98	4.22	8.17
Nov	1.29	4.44	0.48	18.60
Dec	0.00	6.74	0.00	29.70
Total			186.00	166.00

Figure 4.1 shows the peak heating and cooling load of the north zone. Total building heating loads are 0.62×10^8 kWh, and total cooling loads are 2.42×10^8 kWh. The heat pumps in the north zone work in the both heating and cooling modes in order to keep the indoor air temperature around the set point value.

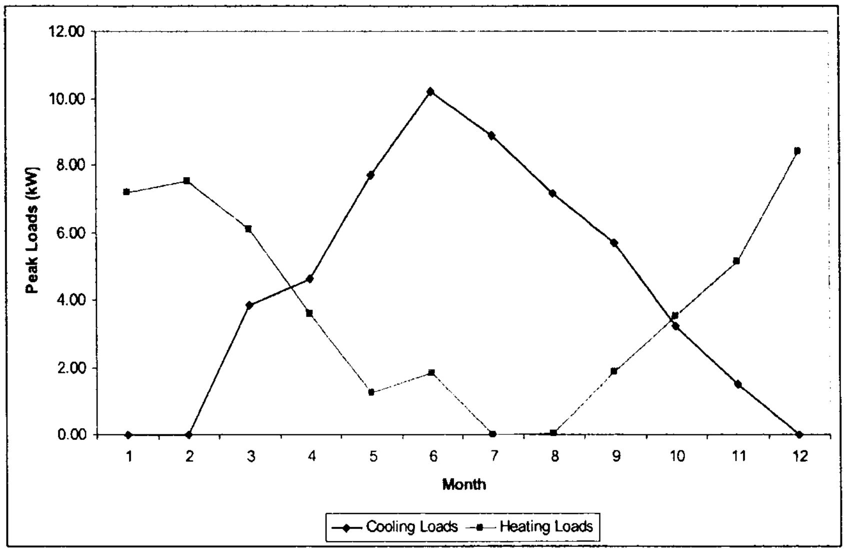

Figure 4.1 Monthly peak heating and cooling loads of the North zone

Figure 4.2 shows the monthly heating and cooling loads of the north zone.

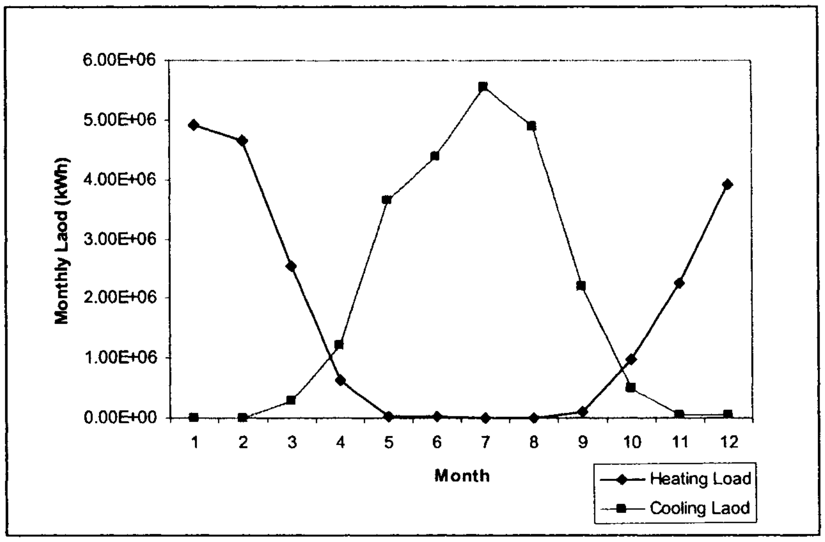

Figure 4.2 Monthly thermal loads of the North zone

Table 4.4 presents the hourly thermal loads of the each zone on the selected day, Jan 21st.

Table 4.4 Hourly Thermal Loads on Jan 21st (kW)

	Core Zone		North Zone		East Zone		South Zone		West Zone	
	C	H	C	H	C	H	C	H	C	H
8:00	5.77	0.00	0.00	2.69	0.00	2.26	0.00	2.82	0.00	2.41
9:00	10.08	0.00	0.00	1.79	0.00	1.53	0.00	1.92	0.00	1.66
10:00	11.30	0.00	0.00	1.41	0.00	1.21	0.00	1.51	0.00	1.33
11:00	11.79	0.00	0.00	1.09	0.00	0.93	0.00	1.12	0.00	1.04
12:00	12.11	0.00	0.00	0.82	0.00	0.68	0.00	0.80	0.00	0.80
13:00	12.33	0.00	0.00	0.55	0.00	0.43	0.00	0.50	0.00	0.55
14:00	12.48	0.00	0.00	0.41	0.00	0.30	0.00	0.35	0.00	0.42
15:00	12.58	0.00	0.00	0.41	0.00	0.30	0.00	0.36	0.00	0.41
16:00	12.65	0.00	0.00	0.51	0.00	0.41	0.00	0.48	0.00	0.49
17:00	12.69	0.00	0.00	0.66	0.00	0.57	0.00	0.64	0.00	0.62
18:00	10.50	0.00	0.00	1.17	0.00	0.99	0.00	1.14	0.00	1.01
19:00	9.25	0.00	0.00	1.44	0.00	1.22	0.00	1.39	0.00	1.22
20:00	8.80	0.00	0.00	1.50	0.00	1.28	0.00	1.45	0.00	1.26
21:00	8.40	0.00	0.00	1.68	0.00	1.42	0.00	1.63	0.00	1.41
22:00	7.32	0.00	0.00	1.99	0.00	1.69	0.00	1.97	0.00	1.69
23:00	5.86	0.00	0.00	2.31	0.00	1.95	0.00	2.28	0.00	1.95
Total	163.91	0.00	0.00	2.66	0.00	2.25	0.00	2.63	0.00	2.23

Figure 4.3 presents the hourly thermal load of the North zone on Jan 21st.

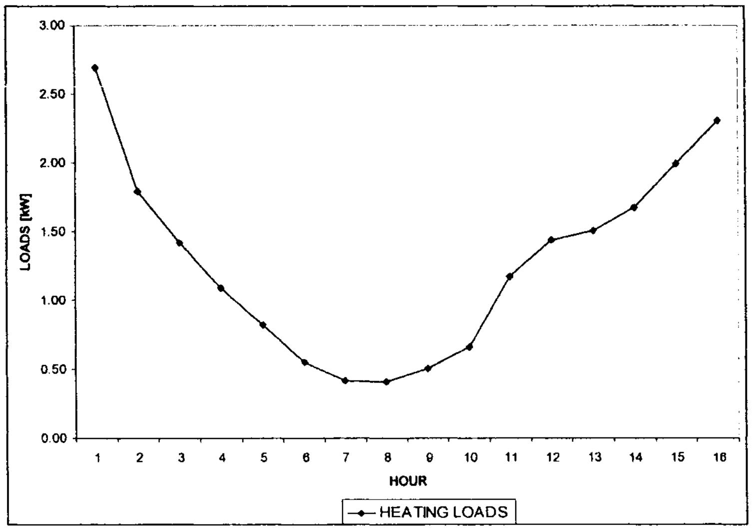

Figure 4.3 Hourly thermal load of North zone on January 21st

Table 4.5 presents the hourly thermal loads of each zone on the selected day, Jul 21st.

Table 4.5 Hourly Thermal Loads on Jul 21st (kW)

	Core Zone		North Zone		East Zone		South Zone		West Zone	
	C	H	C	H	C	H	C	H	C	H
8:00	5.27	0.00	1.25	0.00	1.04	0.00	1.37	0.00	1.15	0.00
9:00	5.33	0.00	1.65	0.00	1.37	0.00	1.86	0.00	1.52	0.00
10:00	5.36	0.00	2.42	0.00	2.02	0.00	2.97	0.00	2.23	0.00
11:00	5.39	0.00	2.86	0.00	2.41	0.00	3.44	0.00	2.55	0.00
12:00	5.41	0.00	3.53	0.00	3.12	0.00	4.46	0.00	3.07	0.00
13:00	5.42	0.00	4.09	0.00	4.04	0.00	4.94	0.00	3.50	0.00
14:00	5.43	0.00	4.59	0.00	5.38	0.00	5.13	0.00	3.82	0.00
15:00	5.43	0.00	4.68	0.00	6.47	0.00	4.84	0.00	3.72	0.00
16:00	5.44	0.00	5.05	0.00	6.82	0.00	4.35	0.00	3.41	0.00
17:00	4.98	0.00	5.72	0.00	6.63	0.00	3.77	0.00	3.00	0.00
18:00	4.80	0.00	5.87	0.00	5.73	0.00	2.99	0.00	2.39	0.00
19:00	4.76	0.00	4.95	0.00	4.28	0.00	2.14	0.00	1.71	0.00
20:00	4.73	0.00	3.31	0.00	2.82	0.00	1.34	0.00	1.06	0.00
21:00	4.71	0.00	2.13	0.00	1.81	0.00	0.80	0.00	0.63	0.00
22:00	4.69	0.00	1.39	0.00	1.18	0.00	0.49	0.00	0.37	0.00
23:00	4.68	0.00	0.81	0.00	0.69	0.00	0.20	0.00	0.14	0.00
Total	81.82	0.00	54.31	0.00	55.81	0.00	45.10	0.00	34.27	0.00

Figure 4.4 presents the thermal load of the North zone on Jul 21st.

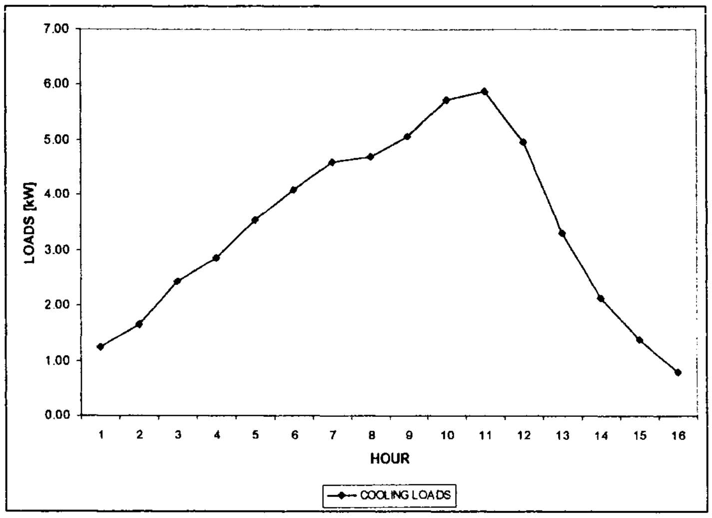

Figure 4.4 Thermal load of North zone on July 21st

Thermal loads affect the energy and exergy efficiency of components of the WLHP system. Comparing the coil load of heat pumps and the space thermal load in one floor (Figure 4.5), it is noticed the impact of ventilation air on the heating loads of WLHP system.

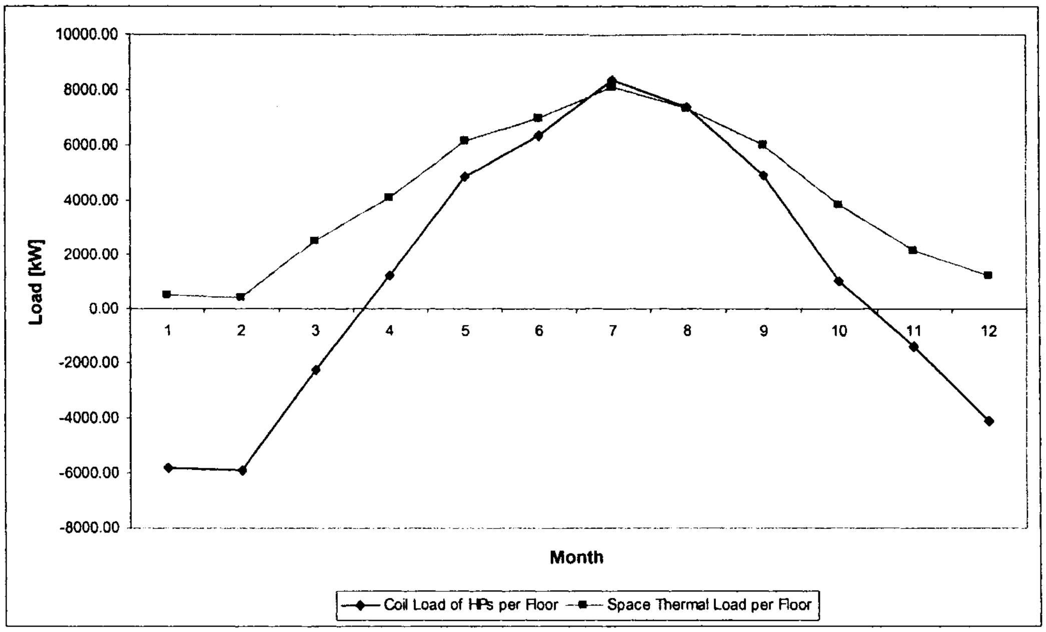

Figure 4.5 Comparison of coil load of heat pumps vs. space thermal load per floor

4.1.2 Capacity of each component of the WLHP system

The required capacity and the electric demand of each component of the WLHP system are presented in Table 4.6.

Table 4.6 Capacity and electric energy demand of components of the WLHP system

Component	Number	Max capacity (kW)	Max electric demand (kW)
Heat Pump	11(per floor)	6.48 (Cooling)	2.59 (Cooling)
		5.11 (Heating)	1.22 (Heating)
Boiler	1	213	243.5
Cooling Tower	1	322.8	2.03
Pump	1	-	6.28
Fan	1	-	5.02

4.1.3 Energy efficiency of the WLHP system

The cooling tower, the boiler, the circulating pump and the fan for outside air are selected in such a way to satisfy the demand for heating and cooling of the whole building. Table 4.7 presents the monthly coefficient of performance of the WLHP system (COP_{WLHP}) and that of system including the efficiency of electricity generation and transmission losses ($COP_{overall}$). Table 4.8 and Table 4.9 present the daily COP of the WLHP system and the COP of the overall system in the January and July.

From the calculation results, the COP of WLHP system is much lower in cold season than that in warm season because the space thermal loads impact on the COP of WLHP system. Comparing the space thermal loads and the COP of system, it is noticed that the COP of system increases with the space thermal loads increasing from February to July and the COP of system decreases with the space thermal loads decreasing from August to January. Both of them reach their maximum value in July.

Table 4.7 Monthly COP of the WHLP system and of the overall system

	COP_{WLHP}	$COP_{overall}$
Jan	1.04	0.68
Feb	0.94	0.63
Mar	1.33	0.87
Apr	1.72	1.14
May	2.08	1.37
Jun	2.11	1.39
Jul	2.22	1.46
Aug	2.20	1.45
Sep	2.05	1.35
Oct	1.73	1.14
Nov	1.55	1.02
Dec	1.24	0.82
Annual Average	1.68	1.11

Table 4.8 Daily COP of the WHLP system and of the overall system in January and July

	January		July	
	COP_{WLHP}	$COP_{overall}$	COP_{WLHP}	$COP_{overall}$
1	0.86	0.57	2.14	1.41
2	0.84	0.55	2.24	1.48
3	0.78	0.51	2.20	1.45
4	1.85	1.22	2.19	1.44
5	0.78	0.51	2.27	1.49
6	0.80	0.74	2.27	1.50
7	0.80	0.53	2.28	1.50
8	0.80	0.53	2.27	1.50
9	0.78	0.52	2.27	1.50
10	0.83	0.55	2.26	1.49
11	0.79	0.52	2.15	1.42
12	1.09	0.83	2.20	1.45
13	1.09	0.72	2.21	1.46
14	1.03	0.68	2.26	1.49
15	0.84	0.56	2.25	1.48
16	1.71	1.13	2.08	1.37
17	1.61	1.06	2.18	1.44
18	1.70	1.12	2.26	1.49
19	0.85	0.56	2.25	1.48
20	0.80	0.53	2.10	1.38
21	0.80	0.53	2.10	1.38
22	0.83	0.55	2.24	1.48
23	0.85	0.56	2.26	1.49
Daily Average	1.00	0.68	2.21	1.46

Table 4.9 Hourly COP for the WHLP system and Overall system on January 21st and July 21st

	January 21st		July 21st	
	COP_{WLHP}	$COP_{overall}$	COP_{WLHP}	$COP_{overall}$
8:00	0.73	0.48	1.96	1.29
9:00	1.13	0.75	2.02	1.33
10:00	1.66	1.09	2.12	1.40
11:00	2.42	1.60	2.15	1.42
12:00	2.70	1.78	2.20	1.45
13:00	2.60	1.71	2.24	1.47
14:00	2.55	1.68	2.26	1.49
15:00	2.55	1.68	2.26	1.49
16:00	2.58	1.70	2.26	1.49
17:00	2.63	1.73	2.25	1.49
18:00	1.59	1.05	2.22	1.47
19:00	1.06	0.70	2.16	1.42
20:00	0.95	0.63	2.03	1.34
21:00	0.87	0.58	1.87	1.23
22:00	0.71	0.47	1.71	1.13
23:00	0.71	0.47	1.60	1.05
Hourly Average	1.71	1.13	2.08	1.37

Figure 4.5 presents the monthly COP of the WLHP system and the overall system. Figure 4.6 presents the daily COP of the WLHP system in the January vs. July. Figure 4.7 presents the daily COP of the overall system in January vs. July. Figure 4.8 presents the hourly COP of the WLHP system on the January 21st vs. July 21st.

Based on the monthly average results (Table 4.7), the system COP varies greatly during one year, in which the highest COP is about twice of the lowest one. According to the Figure 4.7, the system COP in July throttles in more narrow range than the system COP in January because the change of thermal loads, especially the heating loads, impact on the system COP more greatly in cold days than in warm days. The daily average COP in January is only about half of the daily average COP in July, and the hourly system COP on January 21st is about 82% of the hourly system COP on July 21st. In the Figure 4.8, it is noticed that the heating loads impact on the system COP by the solar radiation in the cold day, while such affection is milder.

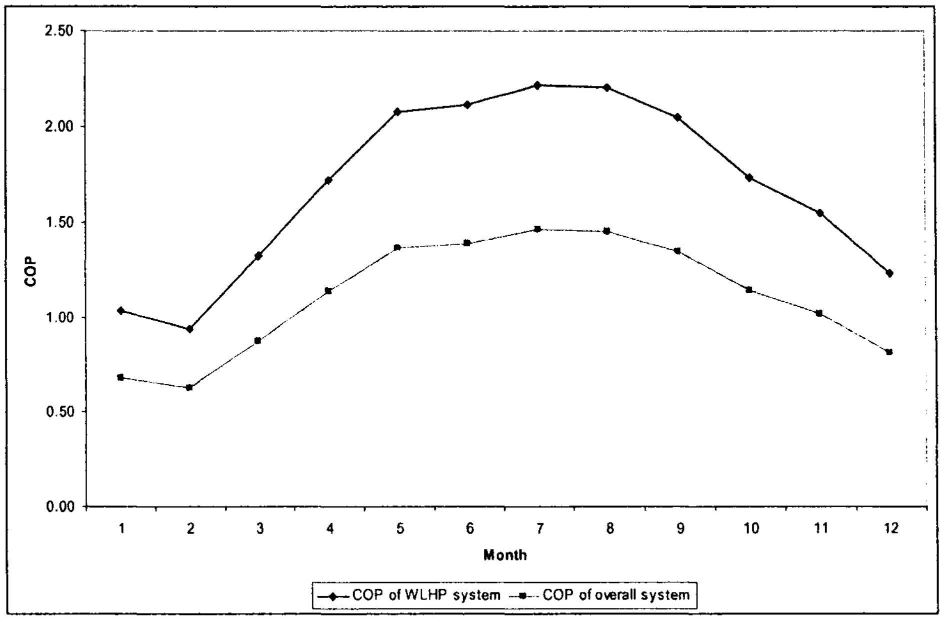

Figure 4.6 Monthly COP of the WLHP system and the overall system

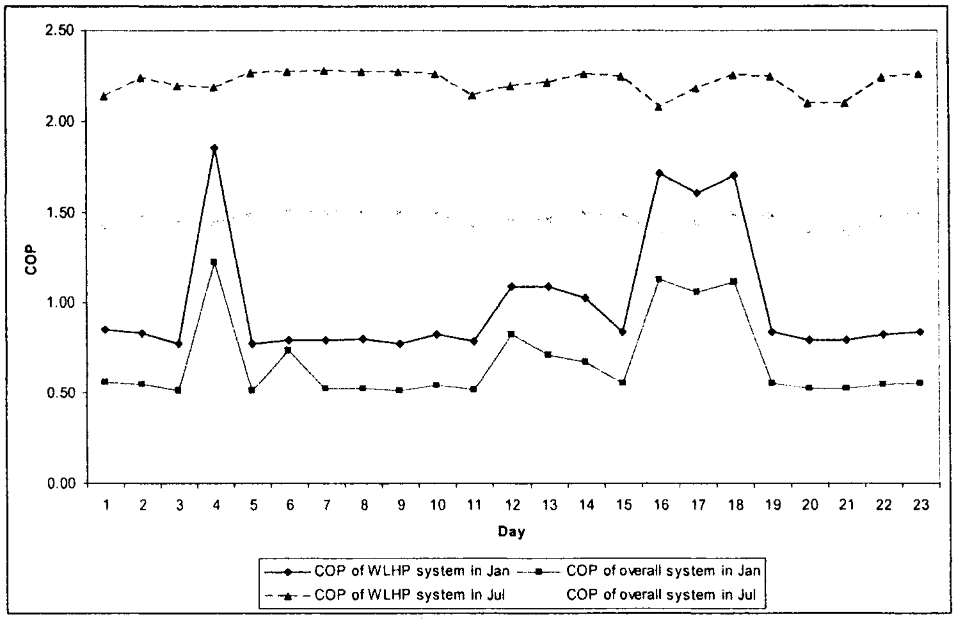

Figure 4.7 Daily COP of the WLHP system and overall COP in January vs. July

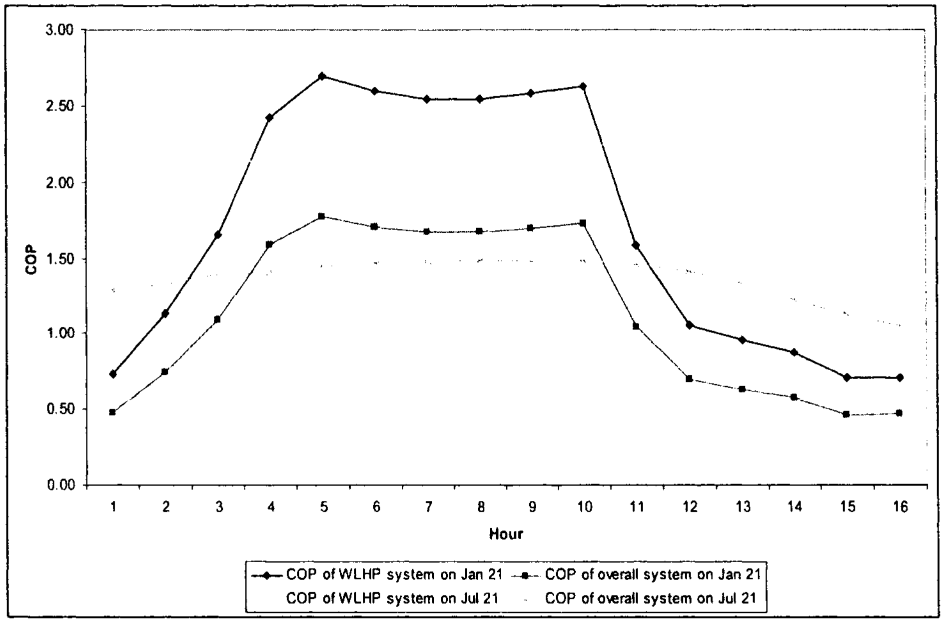

Figure 4.8 Hourly COP of the WLHP system and overall COP

on the January 21st vs. July 21st

4.2 Exergy efficiency of the WLHP system

This section presents the average exergy efficiency of each component and of the WLHP system during one-year operation in terms of month period, day period and hour period. January and July are selected as analysis months, and January 21st and the July 21st are selected as analysis days.

4.2.1 Monthly average exergy efficiency of components of the WLHP system

Table 4.10 presents the exergy efficiency of the heat pumps in the zone from 1 to 5. Table 4.11 presents the exergy efficiency of other components of the system, including the boiler, the fan for outside air and the pump, the WLHP system and the overall system.

Compared with the COP of the heat pump, the exergy efficiency of heat pumps is much lower. In the warm season, the heat pumps works under higher exergy efficiency than in the cold season. The exergy efficiency of heat pumps installed in the core zone with annual average of 7.25%, which work in cooling mode throughout the year, is higher than the exergy efficiency of heat pumps of perimeter zones with maximum annual average of 5.18%, which change between heating and cooling modes throughout the year. The exergy efficiency for the boiler, which reaches the maximum value of 5.07% in February, is affected by the space heating loads and the return water temperature. According to section 3.2.2, the available work provided by the boiler in the warm season is lower than the available work provided by the boiler in cold season because the space heating loads in warm season is lower than in cold season and the return water temperature is closer to the set loop water temperature, 35°C, in the warm season. The exergy efficiency of the cooling tower depends on the outside air condition besides the return water temperature. Compared with the return water temperature, the exergy efficiency of cooling tower more depends on the variation of outside air temperature and humidity. The exergy efficiency of the fan increases with the temperature and humidity of outside air raise and the exergy efficiency of the circulating pump contain about 64.5% throughout the year. On the contrary, the WLHP system obtains higher exergy efficiency in the cold season than in the warm season. For example, in December, January and February, the average exergy efficiency for WLHP system is 3.34%, however, it is 1.88% in June, July and August. The reason is that the available work provided by the system becomes lower when the surrounding condition close to the inside condition, which is assumed as a constant condition, based on the WLHP system exergy efficiency calculation in sections 3.2.6 and 3.2.7.

Table 4.10 Monthly average exergy efficiency (%) of heat pumps in each zone

	HP in Core Zone	HP in North Zone	HP in East Zone	HP in South Zone	HP in West Zone
Jan	3.84	2.98	2.49	2.80	2.67
Feb	3.50	2.65	2.64	2.74	2.37
Mar	3.98	3.15	3.89	4.41	2.59
Apr	6.31	2.58	3.20	3.85	2.09
May	9.25	4.63	5.02	6.43	3.77
Jun	10.83	6.27	5.67	7.18	5.30
Jul	11.88	7.97	7.42	8.98	6.23
Aug	12.09	6.72	7.28	9.33	5.40
Sep	9.54	3.48	5.08	6.39	2.80
Oct	6.54	2.28	3.02	3.64	1.91
Nov	5.03	3.35	2.58	3.10	2.83
Dec	4.24	3.53	2.89	3.36	2.99
Annual Average	7.25	4.13	4.26	5.18	3.41

Table 4.11 Monthly average exergy efficiency (%) of the boiler, the fan, the circulating pump, the cooling tower and the WLHP system

	Boiler	Cooling Tower	Pump	Fan	WLHP system	Overall System
Jan	4.11	0.52	64.42	63.66	3.19	2.10
Feb	5.07	0.25	64.33	61.93	3.43	2.26
Mar	1.80	6.96	64.55	66.57	3.19	2.11
Apr	0.34	16.77	64.73	67.04	3.67	2.42
May	0.01	34.86	64.91	69.21	2.18	1.44
Jun	0.01	33.41	64.99	70.44	1.86	1.22
Jul	0.00	32.53	65.09	71.73	1.94	1.28
Aug	0.00	33.37	65.07	71.47	1.84	1.21
Sep	0.03	27.96	64.94	69.78	2.24	1.48
Oct	0.31	14.00	64.76	67.32	3.43	2.26
Nov	0.89	4.39	64.66	66.08	3.39	2.24
Dec	2.82	2.45	64.52	64.64	3.40	2.24
Annual Average	1.28	17.29	64.75	67.49	2.81	1.85

Figure 4.9 presents the monthly exergy efficiency of heat pumps in the north zone. The monthly exergy efficiencies for other components of WLHP system, including the boiler, the cooling tower, the circulating pump and the fan, are presented in Figures 4.10, 4.11, 4.12 and 4.13, respectively. The monthly exergy efficiency of the WLHP system and the monthly exergy efficiency of the overall system are presented in Figure 4.14.

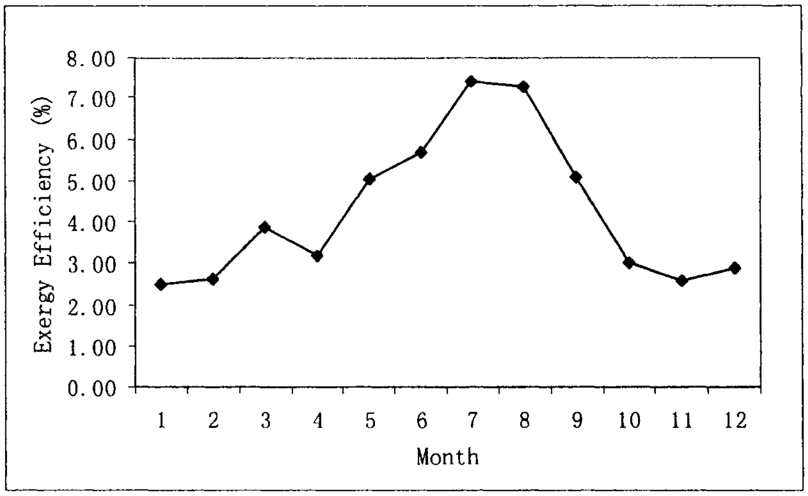

Figure 4.9 Monthly exergy efficiency of heat pumps in North zone

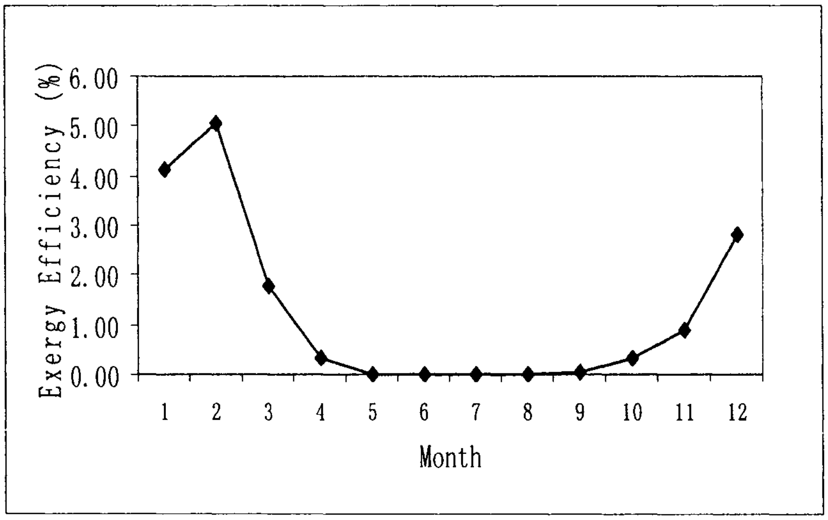

Figure 4.10 Monthly exergy efficiency of the boiler

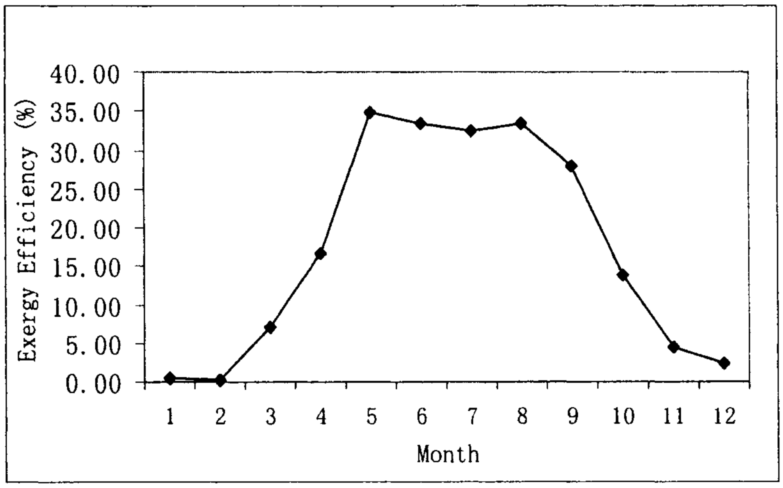

Figure 4.11 Monthly exergy efficiency of the cooling tower

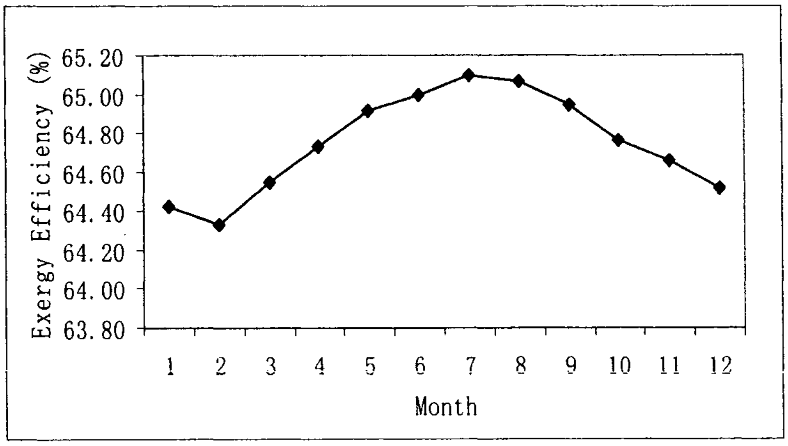

Figure 4.12 Monthly exergy efficiency of the circulating pump

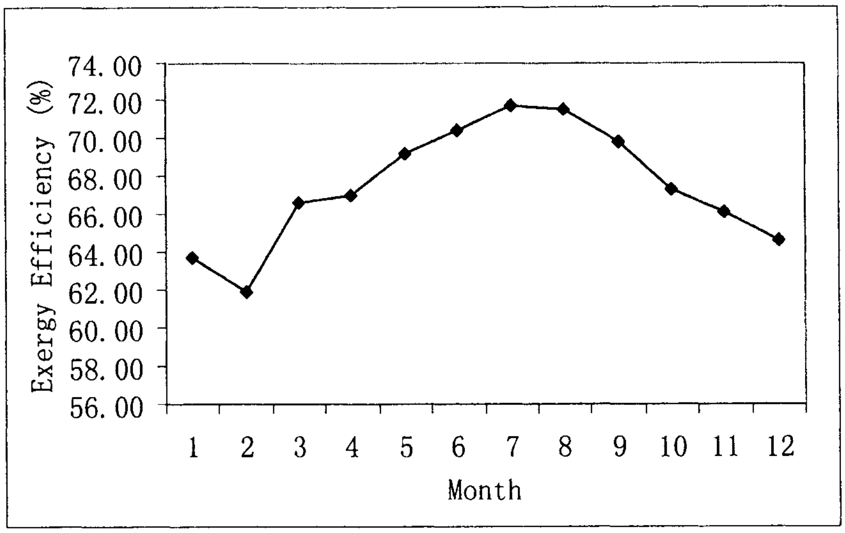

Figure 4.13 Monthly exergy efficiency of the fan

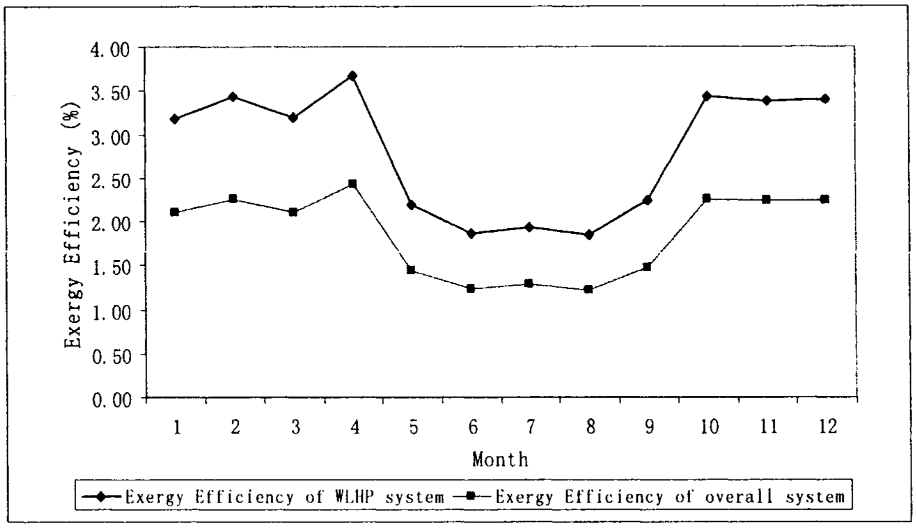

Figure 4.14 Monthly exergy efficiency of WLHP system and of the overall system

4.2.2 Daily average exergy efficiency of components of the WLHP system in January and July

Table 4.12 presents the daily average exergy efficiency of heat pumps in January. Operation during weekends is not simulated. Table 4.13 presents the daily average exergy efficiency of other components and the WLHP system in January. Table 4.14 and 4.15 present the exergy efficiency of the same components and of the WLHP system in July. The table does not contain weekends during the months of January and July.

The exergy efficiency of heat pumps varies depending on the operation mode and the surroundings condition. For example, for heat pumps in perimeter zone, the average exergy efficiency in July is almost 2.8 time of that in January. For heat pumps in core zone, where the space thermal loads is nearly constant and which operate in cooling mode throughout the year, the average exergy efficiency increases about 210% with the outside condition changing from January to July. The daily exergy efficiency and the operation time of the boiler become smaller because the heating loads become lower. The daily exergy efficiency for the cooling tower is impacted by both the return water temperature and the outside air condition, such as temperature or humidity. The daily exergy efficiency for the circulating pump changes little because the return water temperature throttle in a narrow range and the daily exergy efficiency for the fan varies because of the outside air condition change. The daily average exergy efficiency values for WLHP system and overall system in January is higher of about 64% than that in July and the system exergy efficiency enlarges with the space thermal loads reducing.

Table 4.12 Daily average exergy efficiency (%) of the heat pumps in each zone in the January

	HP in Core Zone	HP in North Zone	HP in East Zone	HP in South Zone	HP in West Zone
1	5.84	2.59	2.64	2.85	2.70
2	2.52	2.54	2.70	1.88	2.34
3	1.76	3.49	2.90	3.16	3.07
4	5.98	3.14	2.62	3.09	2.66
5	3.49	4.77	3.96	4.69	4.17
6	3.34	3.60	2.60	2.78	3.11
7	2.94	2.06	1.64	1.96	1.97
8	3.05	2.01	1.67	2.02	1.92
9	2.32	2.94	2.00	2.13	2.63
10	5.28	3.76	2.54	3.48	3.53
11	2.35	3.17	2.62	3.14	2.78
12	3.10	3.77	2.67	2.65	3.22
13	4.11	3.96	3.34	3.78	3.32
14	2.30	2.79	3.32	3.74	2.55
15	6.01	2.32	2.09	2.23	2.32
16	5.56	3.28	2.75	3.27	2.83
17	5.58	3.38	2.44	2.76	2.81
18	5.44	3.18	2.60	2.77	2.69
19	2.38	3.56	2.29	2.79	3.09
20	4.85	4.08	3.73	4.72	3.67
21	2.38	2.60	2.28	2.40	2.42
22	4.08	0.39	0.61	0.73	0.37
23	3.61	1.15	1.30	1.29	1.21
Daily Average	3.84	2.98	2.49	2.80	2.67

Table 4.13 Daily average exergy efficiency (%) of other components and of the WLHP system in the January

	Boiler	Cooling Tower	Pump	Fan	WLHP system	Overall System
1	8.18	0.00	64.37	62.09	4.57	3.01
2	4.66	0.00	64.30	61.57	2.93	1.93
3	3.68	0.00	64.40	62.82	1.42	0.94
4	0.36	2.25	64.68	66.39	4.04	2.66
5	3.58	0.00	64.58	64.85	1.51	1.00
6	2.10	0.00	64.47	63.70	2.46	1.62
7	5.97	0.00	64.27	61.14	3.29	2.17
8	6.15	0.00	64.26	61.06	3.28	2.17
9	4.14	0.00	64.33	62.02	2.15	1.42
10	5.92	0.00	64.43	62.92	3.35	2.21
11	3.95	0.00	64.37	62.47	1.58	1.04
12	1.70	1.01	64.51	64.23	2.75	1.81
13	1.63	0.00	64.55	64.74	1.87	1.23
14	3.89	0.00	64.31	61.84	3.46	2.28
15	7.21	0.00	64.32	61.61	4.42	2.91
16	0.55	1.94	64.65	66.05	3.71	2.45
17	0.63	4.06	64.65	65.95	3.80	2.51
18	0.55	2.81	64.65	65.94	4.17	2.75
19	3.31	0.00	64.40	62.79	1.99	1.31
20	3.65	0.00	64.46	63.43	3.53	2.33
21	5.64	0.00	64.32	61.73	2.69	1.78
22	8.48	0.00	64.15	74.38	5.58	3.68
23	8.55	0.00	64.22	60.49	4.73	3.12
Daily Average	4.11	0.52	64.42	63.66	3.19	2.10

Table 4.14 Daily average exergy efficiency (%) of heat pumps in each zone in July

	HP in Core Zone	HP in North Zone	HP in East Zone	HP in South Zone	HP in West Zone
1	5.27	6.41	5.77	7.54	5.37
2	13.79	7.96	7.39	9.35	6.57
3	13.10	6.61	5.47	6.59	5.04
4	6.31	6.46	6.19	8.11	5.72
5	14.60	9.00	8.12	10.42	7.87
6	8.65	8.46	8.16	11.96	8.58
7	15.16	10.80	9.51	10.10	7.57
8	14.72	10.53	9.30	11.22	7.64
9	14.68	9.57	8.62	10.65	7.18
10	14.45	10.28	9.32	7.81	5.93
11	5.86	6.08	5.93	7.95	5.02
12	12.28	7.67	6.94	8.58	5.98
13	12.90	8.26	7.64	8.51	5.90
14	14.11	9.25	8.39	9.54	7.03
15	14.27	8.32	7.81	9.19	6.60
16	5.64	5.95	6.23	4.87	3.57
17	12.70	7.16	6.90	7.24	4.78
18	13.82	8.02	7.53	11.84	7.50
19	13.66	7.25	7.31	10.58	6.64
20	13.46	6.79	6.40	9.09	6.32
21	5.76	5.72	5.41	4.76	3.47
22	13.74	8.11	7.82	9.46	6.24
23	14.31	8.67	8.47	11.19	6.71
Daily Average	11.88	7.97	7.42	8.98	6.23

Table 4.15 Daily average exergy efficiency (%) of other components and of the WLHP system in the July

	Boiler	Pump	Cooling Tower	Fan	WLHP system	Overall System
1	0	27.99	65.03	70.79	1.54	1.02
2	0	36.70	65.09	71.52	1.84	1.21
3	0	34.50	65.03	71.25	1.29	0.85
4	0	25.26	65.10	71.70	1.75	1.15
5	0	33.01	65.14	72.36	2.24	1.48
6	0	16.34	65.26	73.92	3.68	2.42
7	0	30.47	65.17	72.97	2.21	1.46
8	0	33.52	65.16	72.39	2.88	1.90
9	0	32.59	65.15	72.38	2.49	1.64
10	0	32.32	65.13	72.24	2.06	1.36
11	0	25.55	65.07	71.26	1.77	1.17
12	0	43.67	64.99	70.34	1.17	0.77
13	0	40.85	65.03	70.87	1.45	0.96
14	0	36.21	65.12	71.81	2.31	1.52
15	0	33.36	65.13	71.99	2.07	1.37
16	0	21.36	65.06	71.35	1.94	1.28
17	0	37.79	65.02	70.76	1.38	0.91
18	0	39.05	65.08	71.68	1.79	1.18
19	0	38.62	65.09	71.40	1.74	1.14
20	0	35.52	65.06	71.40	1.54	1.02
21	0	21.47	65.06	71.51	1.81	1.19
22	0	37.03	65.08	71.68	1.51	0.99
23	0	35.01	65.12	72.14	2.09	1.38
Daily Average	0	32.53	65.09	71.73	1.94	1.28

The comparison of daily average exergy efficiency of heat pumps in North zone in the January and July is presented in Figure 4.15. The daily exergy efficiency of other components, including the boiler, the cooling tower, the circulating pump and the fan in January and July, are presented in Figures 4.16, 4.17, 4.18 and 4.19, respectively. The comparison of the daily WLHP system exergy efficiency and overall system exergy efficiency is presented in Figure 4.20.

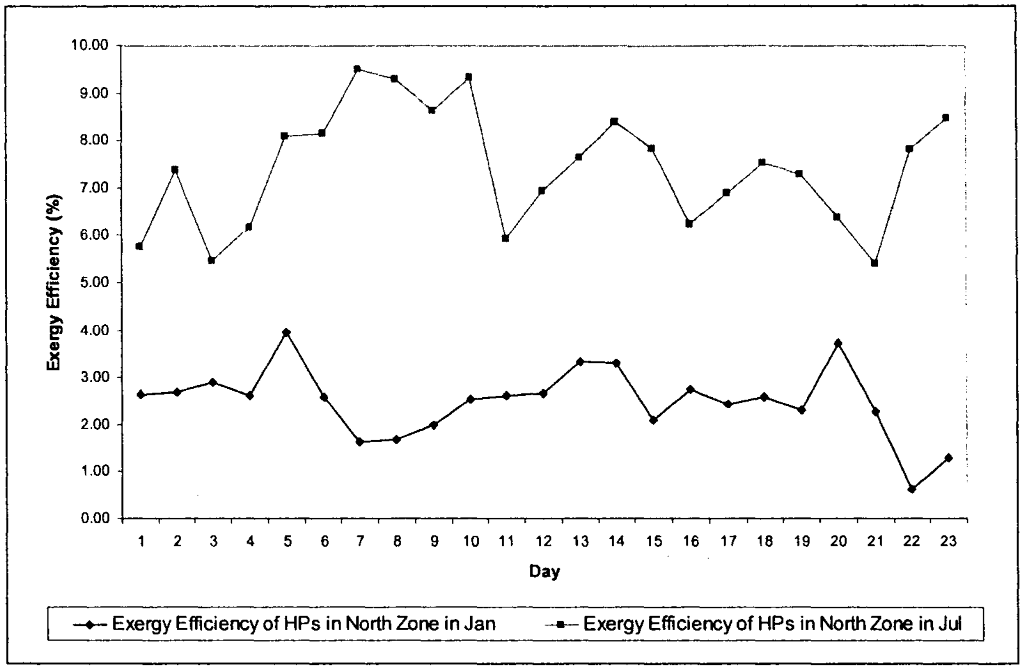

Figure 4.15 Daily exergy efficiency of heat pumps in north zone in January vs. July

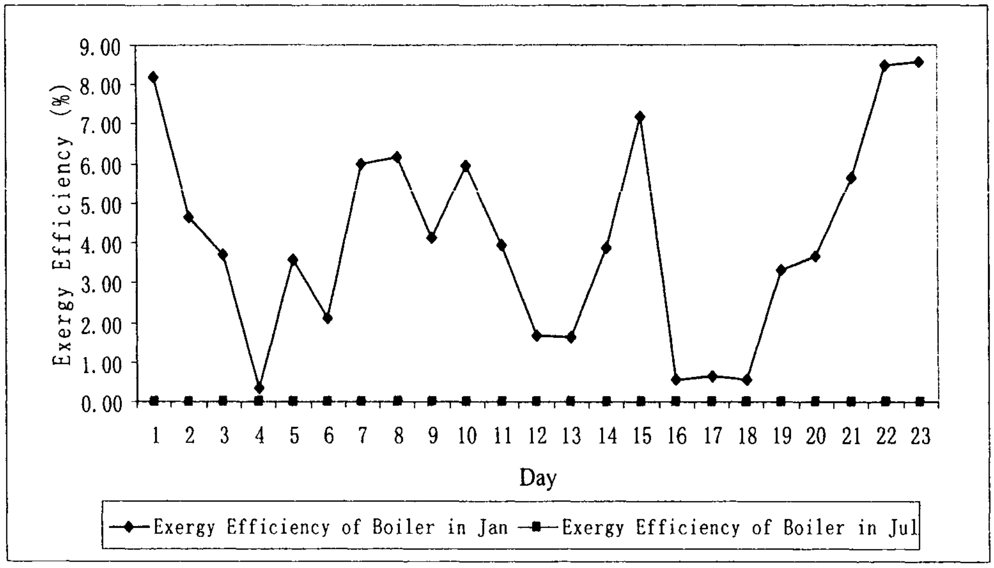

Figure 4.16 Daily exergy efficiency of the boiler in January vs. July

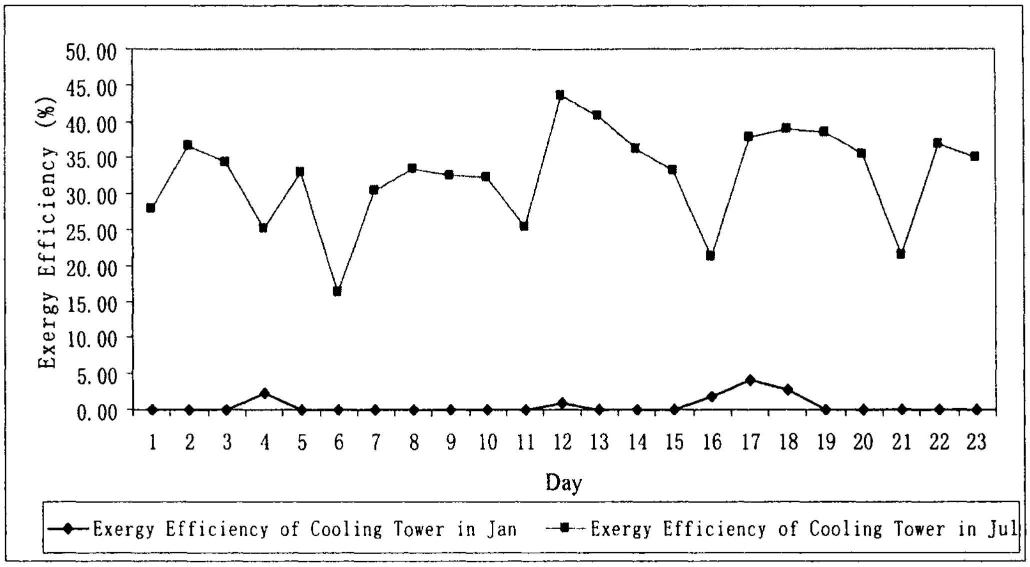

Figure 4.17 Daily exergy efficiency of the cooling tower in January vs. July

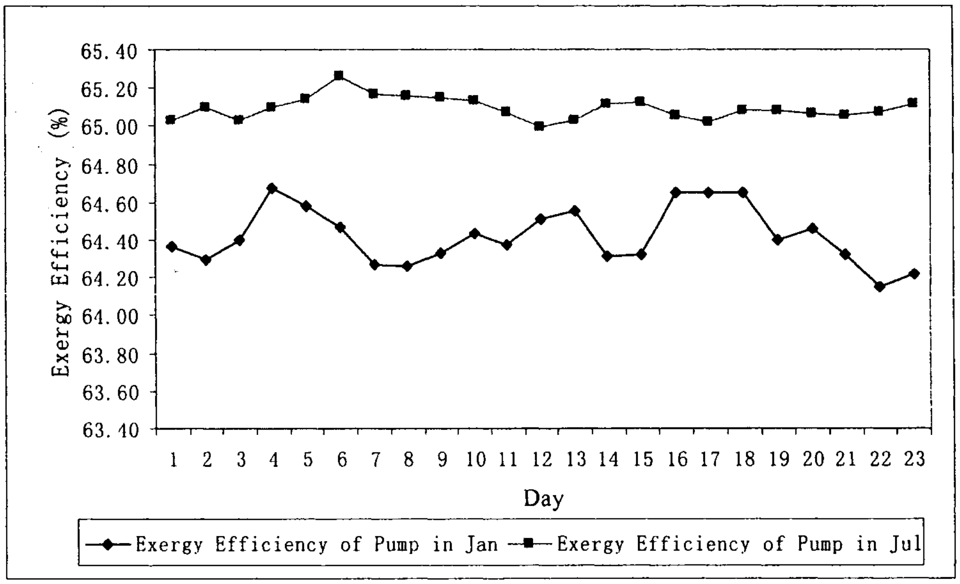

Figure 4.18 Daily exergy efficiency of the circulating pump in January vs. July

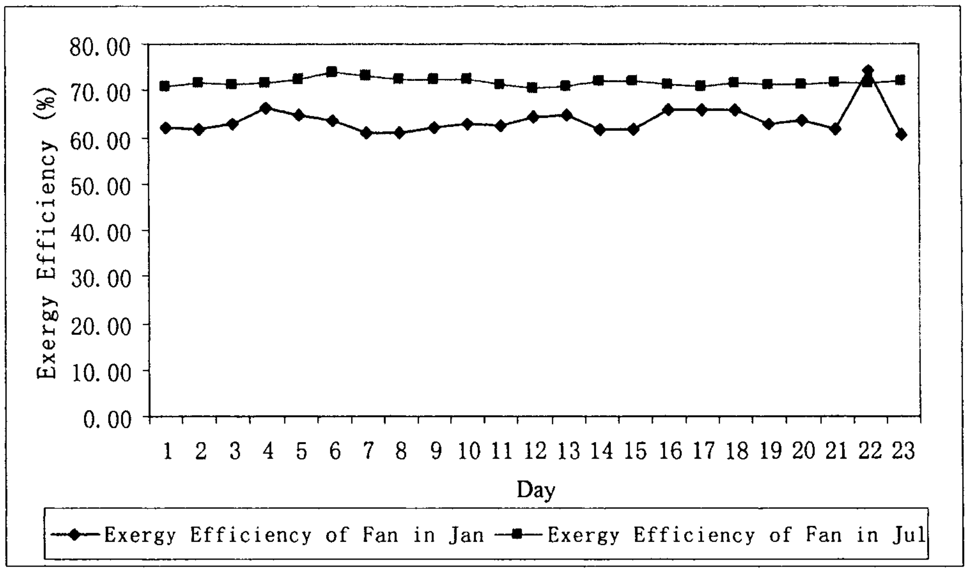

Figure 4.19 Daily exergy efficiency of the fan in January vs. July

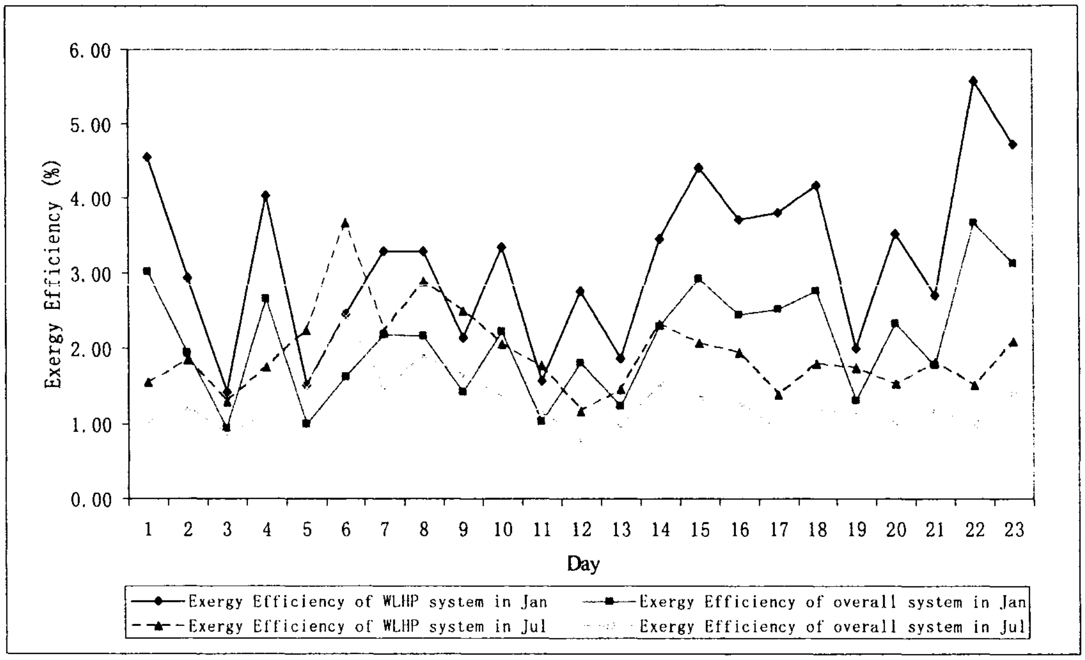

Figure 4.20 Daily WLHP system exergy efficiency and overall system exergy efficiency in January vs. July

4.2.3 Hourly average exergy efficiency of components of the WLHP system on January 21st and July 21st

Table 4.16 and 4.17 present the hourly exergy efficiency of each components and the WLHP system on the selected day, Jan 21st. Table 4.18 and 4.19 present the hourly exergy efficiency of each components and the WLHP system on the selected day, Jul 21st. Those tables only present the results of the work hour, 8:00 to 23:00.

According to the Tables 4.16 and 4.18, it is not same that the exergy efficiency trends for heat pumps in heating mode and cooling mode. For instance, for the heat pumps in North zone in heating mode, the exergy efficiency will decrease when the heating loads reduce and the outside temperature rises. While in cooling mode, the exergy efficiency will increase when the cooling loads and the outside temperature rise. The maximum exergy efficiency for the cooling tower appears around the noon of the selected days both in January and July. The average exergy efficiency for the circulating pump and fan keep relative stable values, with about 65% and 68%, both on Jan 21st and Jul 21st. The hourly average exergy efficiency of WLHP system on January 21st is greater of about 91% than that in July 21st. Based on the Figure 4.26, the space thermal loads impact on the system exergy efficiency on both cold and warm day and they influence the system exergy efficiency of cold day, January 21st, more strongly than that of warm day, July 21st.

Table 4.16 Hourly exergy efficiency (%) of heat pumps on Jan 21st

	HP in Core Zone	HP in North Zone	HP in East Zone	HP in South Zone	HP in West Zone
8:00	1.53	4.65	3.97	4.75	4.10
9:00	4.58	3.84	3.26	3.96	3.39
10:00	6.57	3.46	2.93	3.56	3.06
11:00	7.39	3.12	2.62	3.15	2.74
12:00	7.95	2.82	2.34	2.80	2.47
13:00	8.61	2.50	2.03	2.44	2.18
14:00	8.87	2.34	1.87	2.26	2.02
15:00	9.04	2.34	1.88	2.28	2.01
16:00	9.16	2.46	2.01	2.42	2.11
17:00	9.23	2.64	2.20	2.61	2.26
18:00	5.54	3.21	2.70	3.17	2.72
19:00	3.54	3.50	2.95	3.44	2.95
20:00	2.85	3.56	3.01	3.51	3.00
21:00	2.24	3.74	3.17	3.69	3.15
22:00	0.35	4.03	3.43	4.00	3.42
23:00	1.44	4.32	3.68	4.30	3.68
Hourly Average	5.56	3.28	2.75	3.27	2.83

Table 4.17 Hourly exergy efficiency (%) of other components and of the WLHP system on Jan 21st

	Boiler	Cooling Tower	Pump	Fan	WLHP system	Overall System
8:00	2.08	0	64.66	65.97	0.53	0.35
9:00	0.68	0	64.65	65.97	1.29	0.85
10:00	0.27	0	64.65	65.97	2.91	1.92
11:00	0.05	0	64.64	65.97	5.21	3.43
12:00	0	1.86	64.64	65.97	6.66	4.39
13:00	0	4.97	64.65	66.12	7.12	4.70
14:00	0	6.26	64.65	66.12	7.42	4.89
15:00	0	6.53	64.65	66.12	7.47	4.93
16:00	0	6.10	64.65	66.12	7.37	4.86
17:00	0	5.27	64.65	66.12	7.18	4.73
18:00	0.24	0	64.66	66.12	2.79	1.84
19:00	0.60	0	64.66	66.12	1.27	0.84
20:00	0.72	0	64.66	66.12	0.97	0.64
21:00	0.89	0	64.66	66.12	0.68	0.45
22:00	1.40	0	64.66	65.97	0.12	0.08
23:00	1.81	0	64.66	65.97	0.38	0.25
Hourly Average	0.55	1.94	64.65	66.05	3.71	2.45

Table 4.18 Hourly exergy efficiency (%) of heat pumps on Jul 21st

	HP in Core Zone	HP in North Zone	HP in East Zone	HP in South Zone	HP in West Zone
8:00	5.46	1.83	1.51	2.04	1.69
9:00	5.54	2.53	2.08	2.91	2.33
10:00	5.80	3.97	3.27	4.99	3.64
11:00	5.84	4.78	3.97	5.91	4.24
12:00	6.45	6.19	5.38	8.05	5.29
13:00	7.06	7.37	7.23	9.12	6.16
14:00	7.61	8.43	10.00	9.56	6.81
15:00	7.45	8.61	12.42	8.94	6.61
16:00	7.43	9.38	13.22	7.92	6.02
17:00	6.66	10.81	12.80	6.76	5.23
18:00	5.66	11.12	10.78	5.13	4.01
19:00	4.79	9.02	7.63	3.41	2.68
20:00	3.90	5.49	4.60	1.78	1.38
21:00	3.65	3.17	2.68	0.79	0.59
22:00	3.63	1.81	1.54	0.27	0.17
23:00	3.40	0.74	0.64	0.32	0.32
Hourly Average	5.64	5.95	6.23	4.87	3.57

Table 4.19 Hourly exergy efficiency (%) of other components and of the WLHP system on the Jul 21st

	Boiler	Cooling Tower	Pump	Fan	WLHP system	Overall System
8:00	0	13.21	65.04	71.04	2.23	1.47
9:00	0	15.80	65.03	71.04	2.03	1.34
10:00	0	20.67	65.04	71.22	1.66	1.09
11:00	0	23.24	65.04	71.22	1.46	0.96
12:00	0	26.16	65.08	71.62	1.14	0.75
13:00	0	26.99	65.11	72.10	1.58	1.04
14:00	0	26.99	65.15	72.51	2.17	1.43
15:00	0	28.95	65.14	72.40	2.28	1.50
16:00	0	29.18	65.14	72.32	2.34	1.54
17:00	0	28.89	65.12	72.21	2.26	1.49
18:00	0	29.38	65.07	71.62	1.73	1.14
19:00	0	25.65	65.03	71.04	1.26	0.83
20:00	0	18.60	64.98	70.46	1.79	1.18
21:00	0	12.72	64.97	70.35	2.18	1.44
22:00	0	9.19	64.98	70.28	2.37	1.56
23:00	0	6.17	64.97	70.17	2.64	1.74
Hourly Average	0.00	21.36	65.06	71.35	1.94	1.28

The hourly exergy efficiency for heat pumps in north zone in Jan 21st and Jul 21st is presented in Figure 4.20. The comparisons of hourly exergy efficiency of other components, including the boiler, the cooling tower, the circulating pump and the fan, on selected days are presented in Figure 4.21, 4.22, 4.23 and 4.24, respectively. The comparison of hourly exergy efficiencies for WLHP system and overall system on selected day is presented in Figure 4.25.

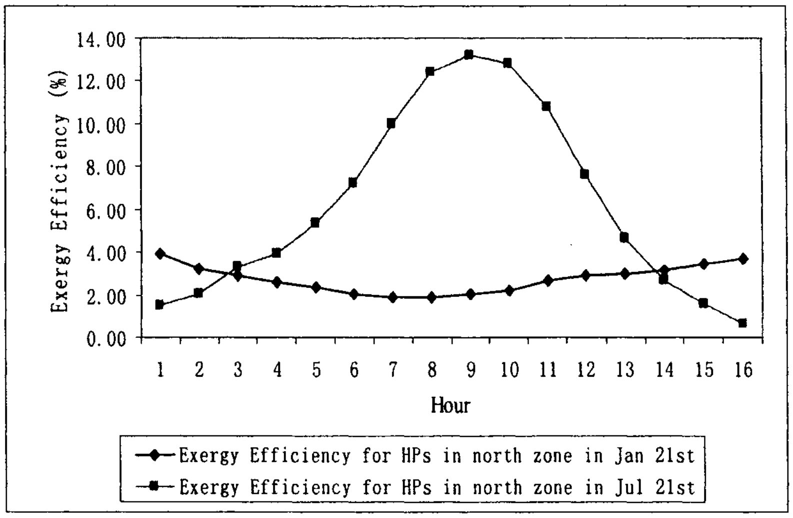

Figure 4.21 Hourly exergy efficiency of heat pumps in North zone on Jan 21st and Jul 21st

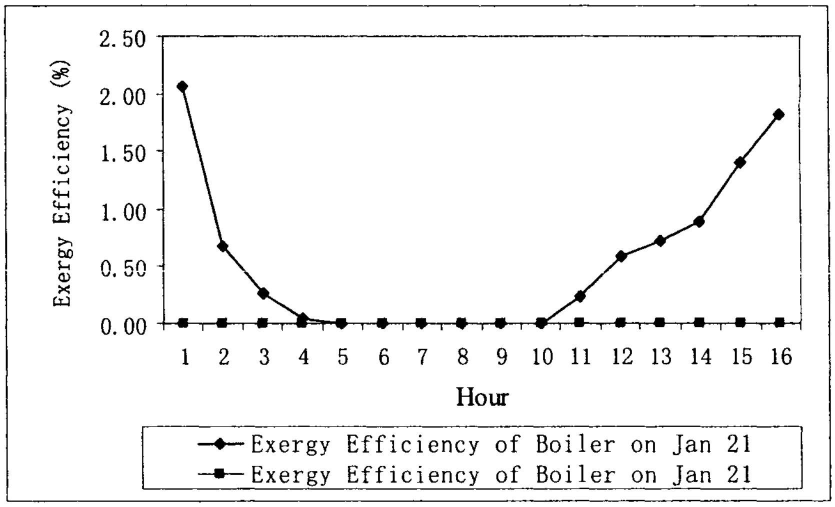

Figure 4.22 Hourly exergy efficiency of the boiler on Jan 21st vs. Jul 21st

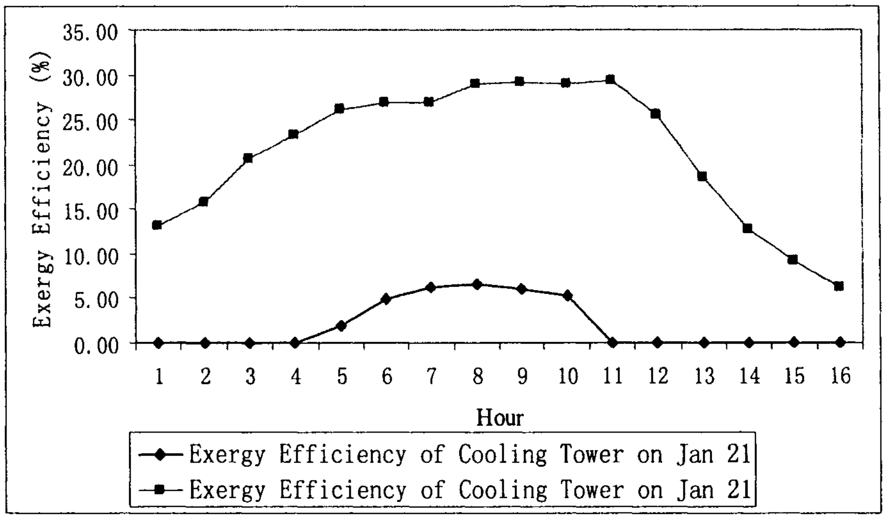

Figure 4.23 Hourly exergy efficiency of the cooling tower on Jan 21st vs. Jul 21st

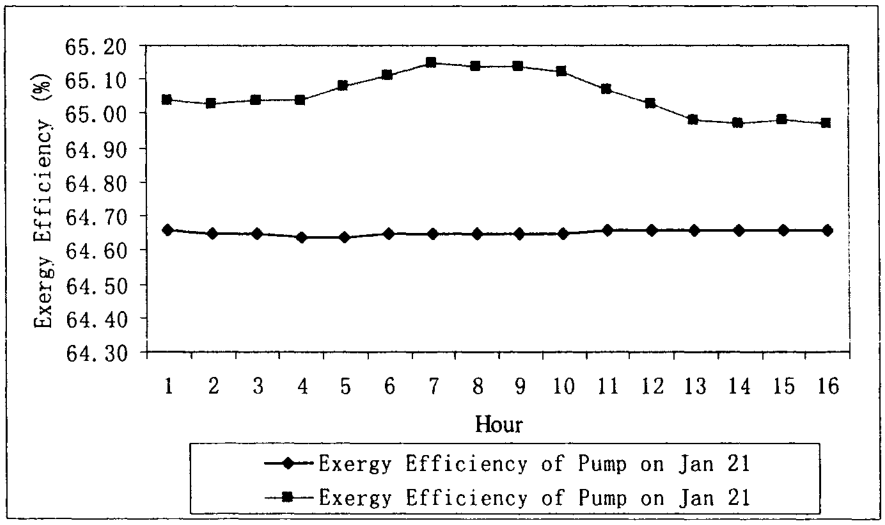

Figure 4.24 Hourly exergy efficiency of the circulating pump on Jan 21st vs. Jul 21st

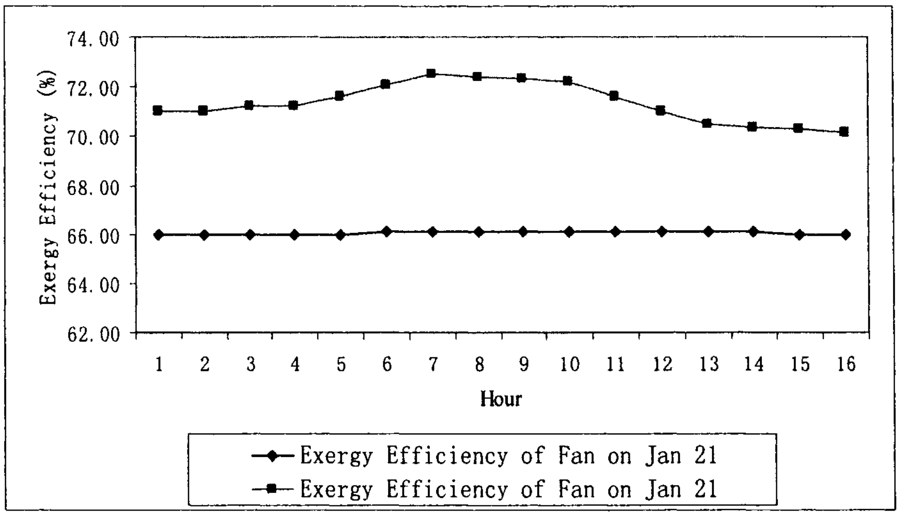

Figure 4.25 Hourly exergy efficiency of the fan on Jan 21st vs. Jul 21st

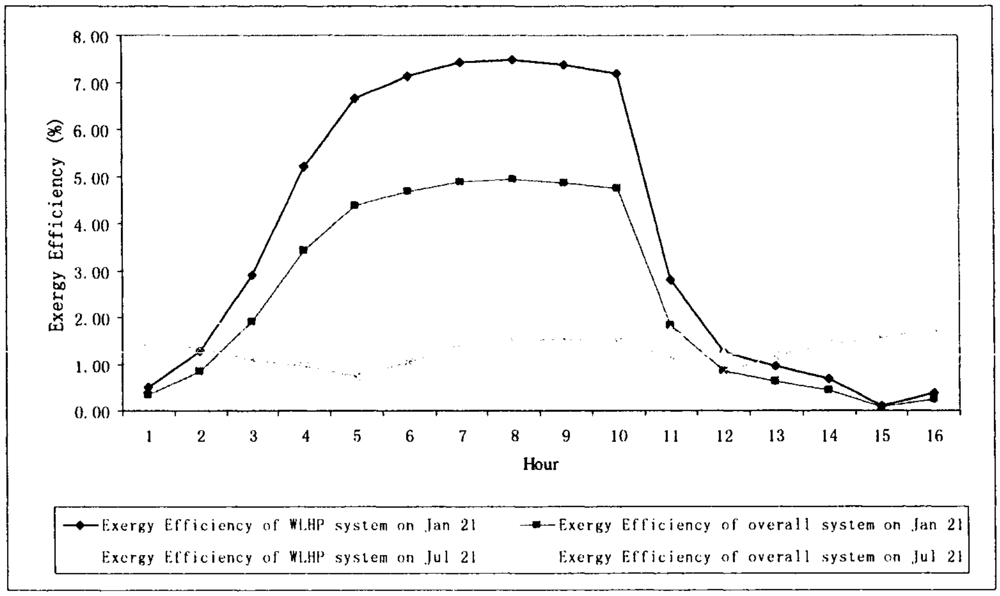

Figure 4.26 Hourly exergy efficiency of the WLHP system and the overall system on Jan 21st vs. Jul 21st

4.3 Exergy destruction of components of the WLHP system

The exergy destructions by components of the WLHP system are calculated and compared in order to locate the equipment that needs improvements or replacement with new technologies to enhance the exergy performance. Table 4.20 and 4.21 presents the monthly average contribution of each component to the exergy destruction in the WLHP system. There are two months selected to compare the contribution exergy destruction to each component, which is January and July. Table 4.22 and 4.23 present the daily average exergy destruction distribution for each component of the WLHP system in January. Tables 4.24 and 4.25 present the daily average contribution to the exergy destruction of each component of the WLHP system, in July.

According to the comparison, the most exergy is consumed by the boiler, heat pumps in the core zone and the cooling tower. The exergy destruction contribution to the boiler is 35.86%, to the heat pumps in the core zone is 15.96% and to the cooling tower is 14.66%. In cold days, the boiler has the highest contribution to the exergy destruction of about 93%, which the exergy destruction by other components, such as heat pumps, could almost be neglected. The exergy is destructed in July mainly by the cooling tower and the heat pumps in the core zone, whose exergy destruction ratios are about 30.5% and 20.7%, respectively.

Table 4.20 Monthly average contributions (%) to the exergy destruction of heat pumps in each zone

	HP in Core Zone	HP in North Zone	HP in East Zone	HP in South Zone	HP in West Zone
Jan	4.11	2.24	1.49	1.62	1.87
Feb	1.23	2.05	1.76	1.55	1.73
Mar	7.73	3.20	4.63	4.63	2.49
Apr	19.64	4.09	5.77	6.44	3.18
May	22.24	7.14	7.14	8.95	6.07
Jun	21.60	8.21	7.27	8.72	7.13
Jul	20.66	9.84	8.88	9.93	7.75
Aug	21.88	8.64	8.79	10.02	6.95
Sep	24.45	5.69	7.81	9.18	4.65
Oct	22.01	3.33	5.38	5.96	2.78
Nov	15.58	4.31	3.02	3.57	3.57
Dec	8.03	3.34	2.39	2.78	2.80
Annual Average	15.76	5.17	5.36	6.11	4.25

Table 4.21 Monthly average contributions (%) to the exergy destruction of the boiler, the cooling tower, the circulating pump and the fan

	Boiler	Cooling Tower	Pump	Fan
Jan	83.99	0.30	1.61	2.78
Feb	88.77	0.12	0.98	1.81
Mar	62.50	5.26	3.53	6.03
Apr	28.44	13.78	7.09	11.57
May	3.33	27.85	6.78	10.49
Jun	2.88	29.77	5.76	8.65
Jul	0.00	32.20	4.41	6.33
Aug	0.00	32.13	4.73	6.85
Sep	5.75	24.97	6.93	10.56
Oct	31.13	11.66	6.78	10.96
Nov	52.64	3.26	5.28	8.77
Dec	71.27	1.57	2.89	4.93
Annual Average	35.89	15.24	4.73	7.48

Table 4.22 Daily average contribution (%) exergy destruction of heat pumps in each zone in January

	HP in Core Zone	HP in North Zone	HP in East Zone	HP in South Zone	HP in West Zone
1	1.11	1.31	0.84	1.17	1.07
2	1.12	1.31	0.84	1.16	1.07
3	1.10	1.32	0.84	1.14	1.07
4	1.07	1.33	0.85	1.10	1.08
5	1.03	1.35	0.85	1.04	1.10
6	0.99	1.38	0.85	0.98	1.12
7	0.93	1.42	0.83	0.94	1.16
8	0.86	1.49	0.85	0.88	1.21
9	0.80	1.58	0.97	0.85	1.29
10	0.72	1.65	1.06	0.85	1.35
11	0.66	1.68	1.04	0.85	1.37
12	0.62	1.68	1.01	0.84	1.38
13	0.59	1.68	1.00	0.84	1.38
14	0.57	1.68	0.99	0.83	1.38
15	0.55	1.68	0.98	0.83	1.38
16	0.54	1.68	0.98	0.83	1.38
17	0.55	1.67	0.97	0.82	1.38
18	0.54	1.67	0.97	0.82	1.38
19	0.53	1.66	0.96	0.84	1.38
20	0.51	1.66	0.95	0.87	1.37
21	0.49	1.65	0.95	0.91	1.36
22	0.47	1.63	0.95	0.94	1.35
23	0.47	1.60	0.97	0.97	1.33
Daily Average	0.73	1.56	0.93	0.93	1.28

Table 4.23 Daily average contribution (%) exergy destruction of the boiler, the circulating pump, the cooling tower and the fan in January

	Boiler	Pump	Cooling Tower	Fan
1	93.49	0.35	0	0.66
2	93.49	0.35	0	0.66
3	93.50	0.36	0	0.67
4	93.52	0.37	0	0.69
5	93.54	0.38	0	0.71
6	93.55	0.40	0	0.74
7	93.52	0.42	0	0.79
8	93.38	0.46	0	0.87
9	93.03	0.51	0	0.96
10	92.76	0.55	0	1.04
11	92.75	0.58	0	1.09
12	92.77	0.59	0	1.11
13	92.79	0.60	0	1.12
14	92.81	0.60	0	1.13
15	92.82	0.61	0	1.14
16	92.83	0.61	0	1.15
17	92.84	0.61	0	1.15
18	92.85	0.62	0	1.16
19	92.85	0.62	0	1.16
20	92.86	0.62	0	1.16
21	92.86	0.62	0	1.17
22	92.87	0.62	0	1.16
23	92.90	0.61	0	1.15
Daily Average	93.07	0.52	0	0.99

Table 4.24 Daily average contribution (%) exergy destruction of heat pumps in each zone in the July

	HP in Core Zone	HP in North Zone	HP in East Zone	HP in South Zone	HP in West Zone
1	16.20	11.16	9.48	11.73	9.30
2	16.98	11.50	9.76	11.18	8.47
3	17.55	11.81	10.02	10.56	7.84
4	17.96	11.96	10.16	10.03	7.47
5	18.31	12.01	10.20	9.60	7.21
6	18.61	12.00	10.18	9.23	7.01
7	18.90	11.95	10.10	8.94	6.85
8	19.16	11.88	9.95	8.71	6.72
9	19.40	11.79	9.73	8.54	6.61
10	19.64	11.65	9.45	8.43	6.55
11	19.95	11.41	9.17	8.42	6.56
12	20.37	11.05	8.90	8.51	6.64
13	20.85	10.56	8.67	8.63	6.75
14	21.33	10.03	8.44	8.78	6.88
15	21.70	9.55	8.26	8.98	7.05
16	21.89	9.20	8.18	9.23	7.27
17	21.86	8.99	8.20	9.61	7.59
18	22.26	8.99	8.20	9.45	7.36
19	22.59	9.01	8.21	9.30	7.22
20	22.83	9.03	8.22	9.16	7.14
21	22.97	9.05	8.23	9.04	7.10
22	23.07	9.06	8.23	8.93	7.07
23	23.12	9.06	8.20	8.85	7.05
Daily Average	20.33	10.55	9.05	9.30	7.20

Table 4.25 Daily average contributions (%) to the exergy destruction of the boiler, the circulating pump, the cooling tower and the fan in July

	Boiler	Pump	Cooling Tower	Fan
1	0	5.96	27.40	8.77
2	0	5.83	27.72	8.56
3	0	5.67	28.23	8.32
4	0	5.54	28.77	8.11
5	0	5.42	29.31	7.93
6	0	5.31	29.89	7.76
7	0	5.20	30.46	7.60
8	0	5.10	31.03	7.44
9	0	5.00	31.63	7.30
10	0	4.91	32.22	7.16
11	0	4.84	32.59	7.06
12	0	4.79	32.77	6.98
13	0	4.74	32.90	6.90
14	0	4.64	33.15	6.76
15	0	4.48	33.46	6.51
16	0	4.30	33.71	6.23
17	0	3.97	34.05	5.72
18	0	4.07	33.79	5.87
19	0	4.14	33.55	5.99
20	0	4.19	33.36	6.07
21	0	4.23	33.24	6.14
22	0	4.26	33.18	6.19
23	0	4.29	33.20	6.23
Daily Average	0	4.82	31.72	7.03

Figure 4.27 presents the comparison of the annual contribution to the exergy destruction of each component of WLHP system. Figure 4.28 presents the daily average contribution to the exergy destruction of each component of WLHP system, in January. Figure 4.29 presents daily average contribution to the exergy destruction of each component of WLHP system, in July.

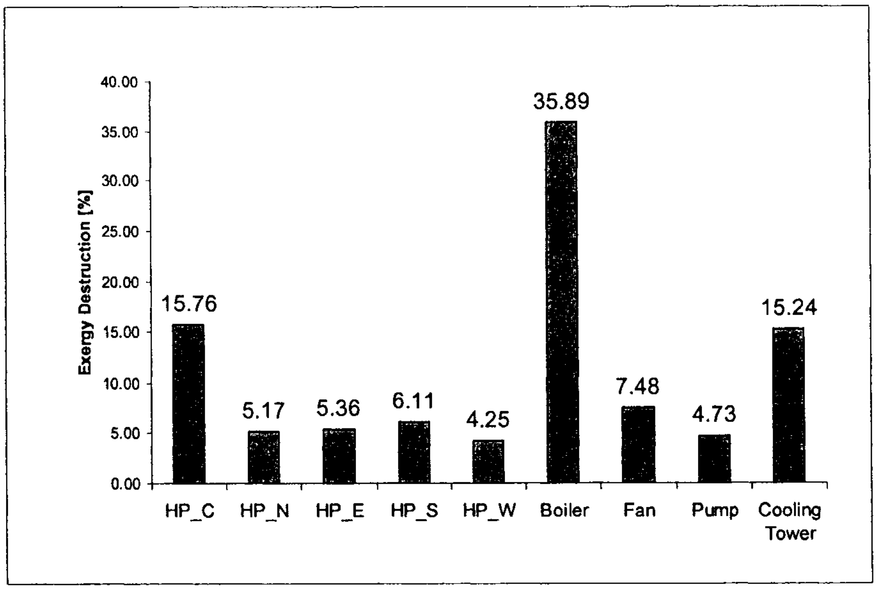

Figure 4.27 Annual contributions to the exergy destruction to each component of the WLHP system

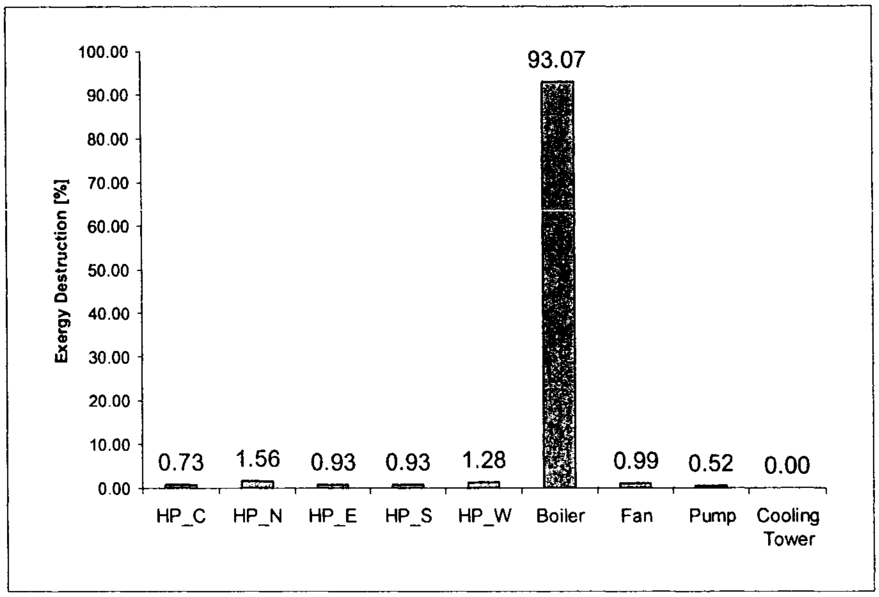

Figure 4.28 Daily exergy destruction distributions for each component of the WLHP system in January

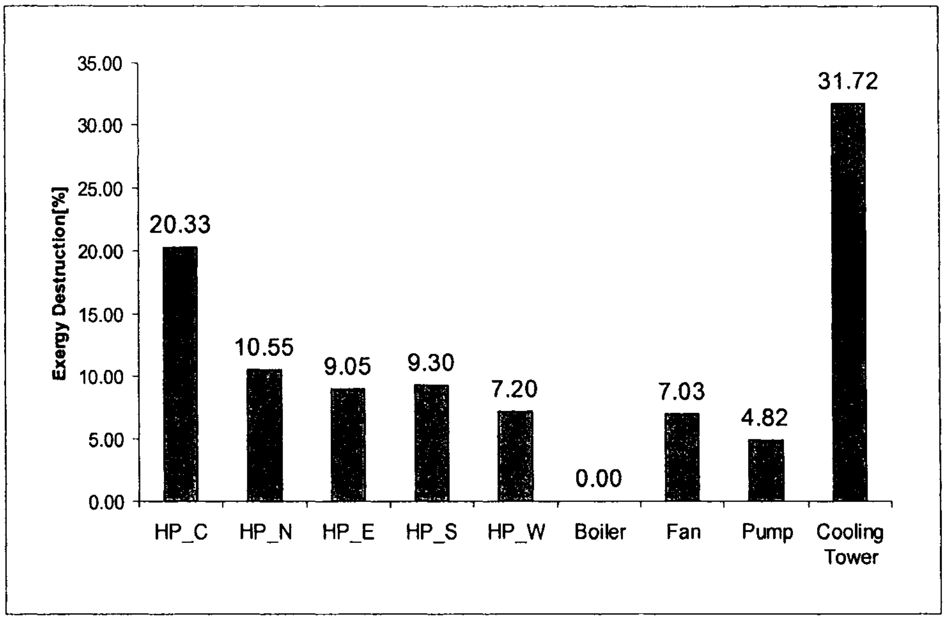

Figure 4.29 Daily average contributions to the exergy destruction of each component of the WLHP system, in July

CHAPTER 5

EQUIVALENT CO_2 EMISSIONS CORRESPONDING TO ENERGY USE AND SUSTAINABILITY PERFORMANCE OF THE WLHP SYSTEM

The greenhouse gases (GHG), including carbon dioxide (CO_2), methane (CH_4) and nitrous oxides (NO_X), are believed to impact on the global climate. Most GHG are released during the use of fossil fuels, such as petroleum, natural gas and coal in factories, buildings, electricity power plants, transportation etc. Except for water vapor, CO_2 from combustion of fossil fuels is the largest single source of anthropogenic GHG emissions, accounting for about 80% in the United States and 87% in Canada during the past 50 years (Gentzis, 2000). In Canada, the government ratified the Kyoto Protocol on April 29, 1998, with the reduction target of equivalent CO2 emissions of 6% below 1990 levels over the years 2008~2012 (Gentzis, 2000). Hence, the reduction of the equivalent CO_2 emissions is the substantial action for mitigating the global climate change. The equivalent CO_2 emissions are used as an important indicator to estimate the impact on the global climate change by the HVAC system. The evaluation of equivalent CO_2 emissions due to the annual energy use by the WLHP system for operation is presented in this chapter.

5.1 Annual equivalent CO2 emissions due to the electricity generation

In this study, the energy used by the WLHP system is electricity generated by the power plants, which use hydro, heavy oil, natural gas and nuclear power, because this case study uses an office building located in Montreal. The annual equivalent CO2 emissions are calculated as follows (Gagnon, 2002):

$$EM_{co_2} = \beta_{hydro} \times E_{hydro} + \beta_{oil} \times E_{oil} + \beta_{gas} \times E_{gas} + \beta_{nuclear} \times E_{nuclear} \quad (5.1)$$

where

EM_{co_2} is the off-site annual equivalent CO2 emissions, kt eq. CO_2/year;

β_{hydro} is the equivalent CO_2 emissions due to the use of hydro for the generation of electricity, kt eq. CO_2/TWh; $\beta_{hydro} = 15 kteq.CO_2 / TWh$;

β_{oil} is the equivalent CO_2 emissions due to the use of heavy oil for the generation of electricity, kt eq. CO_2/TWh; $\beta_{oil} = 778 kteq.CO_2 / TWh$;

β_{gas} is the equivalent CO_2 emissions due to the use of natural gas for the generation of electricity, kt eq. CO_2/TWh; $\beta_{gas} = 443 kteq.CO_2 / TWh$;

$\beta_{nuclear}$ is the equivalent CO_2 emissions due to the use of nuclear for the generation of electricity, kt eq. CO_2/TWh; $\beta_{nuclear} = 15 kteq.CO_2 / TWh$;

E_{hydro} is the annual primary energy use of hydro power for the generation of electricity, TWh/year;

E_{oil} is the annual primary energy use of heavy oil for the generation of electricity, TWh/year;

E_{gas} is the annual primary energy use of natural gas for the generation of electricity, TWh/year;

$E_{nuclear}$ is the annual primary energy use of nuclear power for the generation of electricity, TWh/year.

The annual primary energy use depends on the efficiency of the electricity transmission and the contribution ratio of each kind of power plant and their efficiency, which are listed in Table 3.2. The annual electric energy of WLHP system is calculated as follows:

$$E_{system,input,annual} = (\sum_{1}^{n} \dot{E}_{system,input,j}) \times 10^{-9} \tag{5.2}$$

where

$E_{system,input,annual}$ is the annual electric energy of the WLHP system, TWh/year;

$\dot{E}_{system,\ input,\ j}$ is the total electric demand of the system in the jth hour, kW;

n is the total number of operating hours of the WLHP system during one year, in this study, n=4176 hrs.

The annual primary energy use of each source is calculated as follows:

$$E_{hydro} = \frac{E_{system,input,annual}}{\eta_{trans}} \times \frac{\alpha_{hydro}}{\eta_{hydro}} \tag{5.3}$$

where

η_{trans} is the overall efficiency of electricity transmission;

η_{hydro} is the overall efficiency of hydro power plants;

α_{hydro} is the contribution of hydro power plants to the electricity mix;

$$E_{oil} = \frac{E_{system,input,annual}}{\eta_{trans}} \times \frac{\alpha_{oil}}{\eta_{oil}} \tag{5.4}$$

where

η_{oil} is the overall efficiency of oil-fired power plants;

α_{oil} is the contribution of oil-fired power plants to the electricity mix;

$$E_{nuclear} = \frac{E_{system,input,annual}}{\eta_{trans}} \times \frac{\alpha_{nuclear}}{\eta_{nuclear}} \tag{5.5}$$

where

$\eta_{nuclear}$ is the overall efficiency of nuclear power plants;

$\alpha_{nuclear}$ is the contribution of nuclear power plants to the electricity mix;

$$E_{gas} = \frac{E_{system,input,annual}}{\eta_{trans}} \times \frac{\alpha_{gas}}{\eta_{gas}} \tag{5.6}$$

where

η_{gas} is the overall efficiency of natural gas-fired power plants;

α_{gas} is the contribution of natural gas-fired power plants to the electricity mix.

5.2 Sustainability performance of the WLHP system

As the definition of the sustainable development in the chapter 2, the WLHP system should provide the available work or have the efficiency as high as possible and impact on the environment as low as possible. To achieve these goals, the sustainability performance of the WLHP system is evaluated by two indicators: the exergy efficiency and the equivalent CO_2 emissions due to the system operation. The exergy efficiency presents how much available work is used by WLHP system corresponding to its surroundings. The equivalent CO_2 emissions reflect the environment impact due to the operation WLHP system.

The exergy efficiency of each component and of the whole system is presented in chapter 4. The equivalent CO_2 emissions due to the operation are calculated over the life cycle of the WLHP system. The life cycle equivalent CO_2 emissions due to the system due to the operation of system are calculated as follows:

$$EM_{co_2,\,LF} = EM_{co_2} \times N_{life} \tag{5.7}$$

where

$EM_{co_2,\,LF}$ is the equivalent CO_2 emissions over the lifecycle of WLHP system, t eq. CO_2;

N_{life} is the life cycle of the WLHP system, year, in this study, $N_{life} = 30 year$.

The equivalent CO_2 emissions can also be converted into monetary unit using environmental tax. After converted into economic value, the environmental impact could be compared with other costs, such as initial cost of HVAC system. The annual and life cycle environmental taxes are calculated as follows:

$$ET_{co_2} = EM_{co_2} \times T_{CO_2} \tag{5.8}$$

$$ET_{co_2,LF} = EM_{co_2,LF} \times T_{CO_2} \tag{5.9}$$

where

$ET_{co_2,LF}$ is the environmental tax due to equivalent CO_2 emissions over the lifecycle, CAN$;

ET_{co_2} is the environmental tax due to equivalent CO_2 emissions per year, CAN$/yr;

T_{CO_2} is the environmental tax for equivalent CO_2 emissions, $CAN\$/teq.CO_2$, in this study, T_{CO_2}=100 $CAN\$/teq.CO_2$.

Calculation results of the environmental impact and environmental tax for WLHP system, due to operation per year and for the life cycle are presented in Table 5.1. Table 5.2 presents the annual energy consumption and exergy efficiency of the WLHP system and overall system.

Table 5.1 Equivalent CO_2 emissions and environmental tax

Annual equivalent CO_2 emissions	Equivalent CO_2 emissions over lifecycle	Annual environmental tax	Environmental tax over lifecycle
[teq.CO_2/yr]	[teq.CO_2]	[×10^3 CAN$/yr]	[×10^3 CAN$]
19.34	580.3	1.93	58.03

Table 5.2 Annual energy consumption (kWh/m^{2}yr) and exergy efficiency (%) of the WLHP system and overall system

	WLHP system	Overall system
Energy consumption [kWh/m^{2}yr]	59.87	90.82
Exergy efficiency [%]	2.81	1.85

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

The research focused on the analysis and the evaluation of the exergy performance of the WLHP system and its components. The WLHP system, which is analyzed, is installed in an office building located in Montreal. The conclusions of analysis are presented as following:

- The first law of thermodynamics performance analysis, also called energy performance, is often used to evaluate the HVAC system. However, compared with energy performance analysis, the second law of thermodynamics performance analysis, also called the exergy performance analysis, can point out the inefficient components of the system with great improvement potential more accurately. Moreover, exergy analysis, integrated with the energy and entropy analysis, could give a comprehensive picture for the performance evaluation for the HVAC system.

- Nowadays, more and more new technologies have been applied into the HVAC system in order to improve the energy efficiency, but many of them fail to meet the expectation. The reason is that those improvements are not used in the right place. The exergy destruction should be paid enough attentions whenever the renewable energy or new technologies are selected to achieve a sustainable HVAC system.

- For the heat pumps, the high COP does not mean the high exergy efficiency. The exergy efficiency of the heat pumps is affected by the outside temperature and the space thermal loads and the exergy efficiency will vary in different work mode. For example, the heat pumps in the east zone has an average exergy efficiency of 3.1% when they work in heating mode in January, February and December, and their average exergy efficiency is 7.0% when they work in cooling mode in June, July and August. However, the COP of the heat pumps in heating mode, about 4.2, is higher than that in cooling mode, about 2.5. The exergy efficiency of the circulating pump and the fan for outside air throttle in a relative narrow range, about 64.8% and 67.5% respectively, because the water and outside air mass flow rate are constant value and their rotation speed are also constant value. The exergy efficiency of the boiler is mainly affected by the return loop water temperature but the exergy efficiency of the cooling tower is also affected by the temperature and humidity of the outside air besides the return loop water temperature.

- In this study, the WLHP system is installed in an office building located in Montreal. Based on the exergy destruction analysis, more than half of the exergy is destructed by the boiler, the heat pumps in the core zone and the cooling tower. To achieve better whole system's exergy performance, the recommend improvements should focus on theses three kinds of components. The recommend optimizations include that use new high efficiency boiler taking place the present one and supply the energy from renewable source, such as solar energy or wind, instead of electricity from power plant. Other optimum solution is that set an acceptable range for the return water temperature to reduce the operation time of the boiler and the cooling tower. In addition, the different results will be achieved in the different seasons even by the same improvement. In order to reach the better exergy performance, the surroundings change should be considered and analyzed as well.

- The greenhouse gases emissions have been analyzed corresponding with both annual and life cycle consideration. Although the electricity is used as the principle energy source and there is almost no on-site greenhouse gases produced directly, most greenhouse gases are released by the energy generation plants due to the WLHP system operation. The energy efficient technologies, such as air side economizer, boiler economizer or the variable return water temperature, would reduce the electricity demand and the greenhouse gases emissions.

6.2 Future work

The present research mainly focused on the performance of the WLHP system in Montreal, Therefore, the future work should include:

- The performance analysis for the WLHP system based in other cities of Canada, for example, Toronto, Vancouver or Regina.

- The analysis should be used for more complex buildings, such as shopping malls or the multiple function commercial buildings in order to benefit from the full advantages offered by the exergy analysis method.

- In the model of the WLHP system, the impact of air humidity on the system exergy performance is not taken into account, and the dead state is selected as outside temperature. In the future work, the variable air humidity and different dead state should be considered.

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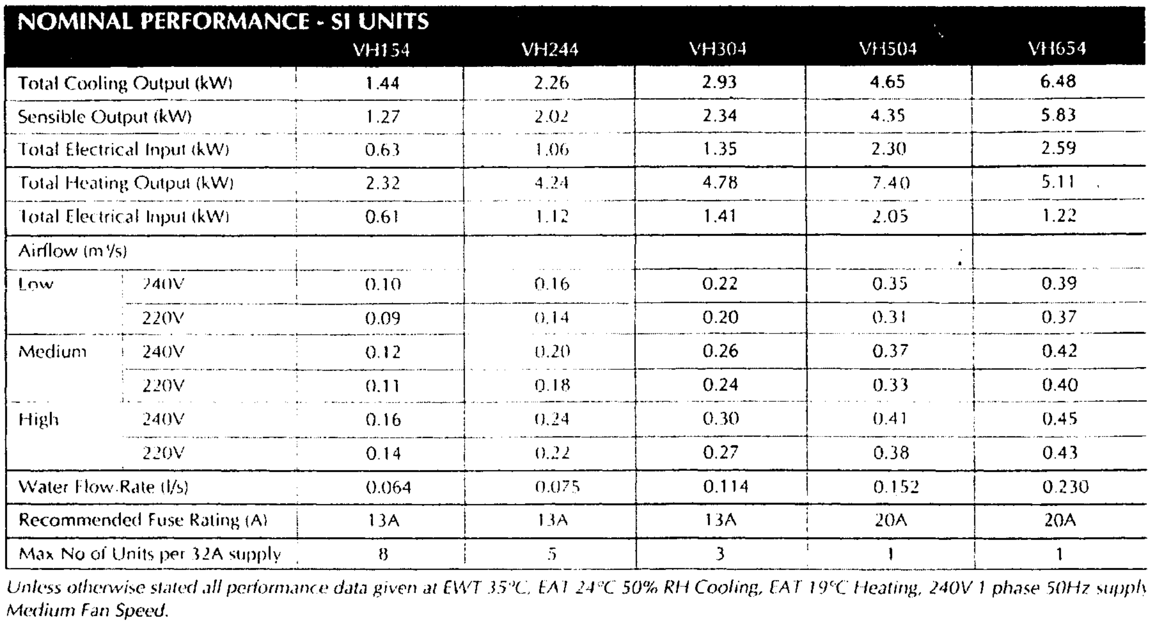
APPENDIX A.

Catalogue Data for Heat Pumps

Table A1 contains the performance data of the heat pump used in this study which is the VH654 type from the IBK Compac Koudetechniek & Air Conditioning Company. There are three options for the airflow rate and the average value, 0.42 m^3/s, is selected as the constant airflow rate in this study.

Table A1 Technical Specifications of the heat pump



NOMINAL PERFORMANCE - SI UNITS		VH154	VH244	VH304	VH504	VH654
Total Cooling Output (kW)		1.44	2.26	2.93	4.65	6.48
Sensible Output (kW)		1.27	2.02	2.34	4.35	5.83
Total Electrical Input (kW)		0.63	1.06	1.35	2.30	2.59
Total Heating Output (kW)		2.32	4.24	4.78	7.40	5.11
Total Electrical Input (kW)		0.61	1.12	1.41	2.05	1.22
Airflow (m^3/s)						
Low	240V	0.10	0.16	0.22	0.35	0.39
	220V	0.09	0.14	0.20	0.31	0.37
Medium	240V	0.12	0.20	0.26	0.37	0.42
	220V	0.11	0.18	0.24	0.33	0.40
High	240V	0.16	0.24	0.30	0.41	0.45
	220V	0.14	0.22	0.27	0.38	0.43
Water Flow Rate (l/s)		0.064	0.075	0.114	0.152	0.230
Recommended Fuse Rating (A)		13A	13A	13A	20A	20A
Max No of Units per 32A supply		8	5	3	1	1

Unless otherwise stated all performance data given at EWT 35°C, EAT 24°C 50% RH Cooling, EAT 19°C Heating, 240V 1 phase 50Hz supply Medium Fan Speed.

APPENDIX B.

First and Second Law Analysis Program for the WLHP system

```
"!determine if the boiler work"
{w is T_R; x is RHO_water; y is V_dot_water; z is C_p_water, u is the lower set point
temperature}
Function test1(u,w,x,y,z,n)
a=0
If (w<u) Then a:=n*x*y*z*(u-w)
 test1:=a
End test1

"!determine if the cooling tower work"
{w is T_R; x is RHO_water; y is V_dot_water; z is C_p_water, t is the upper set point
temperature}
Function test2(t,w,x,y,z,n)
b=0
If (w>t) Then b:=n*x*y*z*(w-t)
 test2:=b
End test2

"!Thermal load for each zone"
{estimate the number of HPs in zone}
function test16(Q_dot_sens,Q_dot_lat, C_p_air, V_fresh, RHO_air, T_inside, T_out_dry,
V_dot_fresh_total, E_dot_fan, n_HP, V_air_HP)
T_mix=V_fresh*T_out_dry/(n_HP*V_air_HP)+(n_HP*V_air_HP-
V_fresh)*T_inside/(n_HP*V_air_HP)
```

```
CAP_h=5.11
CAP_c=6.48

if (Q_dot_sens*Convert(btu/h, kW)+Q_dot_lat*Convert(btu/h, kW)<0) then Q_load=-
n_HP*CAP_h
if (Q_dot_sens*Convert(btu/h, kW)+Q_dot_lat*Convert(btu/h, kW)>0) then
Q_load=n_HP*CAP_c

T_supply=-(Q_load)/C_p_air*(n_HP*V_air_HP)*RHO_air+T_mix
Q=abs((n_HP*V_air_HP)*C_p_air*RHO_air*(T_supply-T_inside))-
abs((Q_dot_sens*Convert(btu/h, kW)+Q_dot_lat*Convert(btu/h, kW)))

test16:=Q
end test16


"!Coil load"
{For Q_loop calculation}
function test18(Q_dot_sens,Q_dot_lat, C_p_air, V_fresh, RHO_air, T_inside, T_out_dry,
V_dot_fresh_total, E_dot_fan, n_HP, V_air_HP, V_total)
T_fresh=T_out_dry+E_dot_fan/(V_total*C_p_air*RHO_air)
T_mix=V_fresh*T_fresh/(n_HP*V_air_HP)+(n_HP*V_air_HP-
V_fresh)*T_inside/(n_HP*V_air_HP)
T_supply=-(Q_dot_sens*Convert(btu/h, kW)+Q_dot_lat*Convert(btu/h,
kW))/(C_p_air*(n_HP*V_air_HP)*RHO_air)+T_inside

Q=-n_HP*V_air_HP*RHO_air*C_p_air*(T_supply-T_mix)

test18:=Q
end test18
```

```
"!E_dot_input_central calculation"
{ c is the number of heat pumps in a zone; e is the electricity demand for whole heat
pumps in a zone; q is the zone load}
{function test24(c,Q_dot_load_central, V_dot_fresh, T_out_dry,V_dot _air_HP)}
function test24(c,Q_load)
e:=0

q:=Q_load

 if (q>0) then  e=2.59*c*(q/(6.48*c)) {cooling mode, T_r >EWT}

if (q<0) then e=1.22*c*(q/(5.11*c)) {heating mode, T_r <EWT}

test24:=abs(e)
End

"!Number of heat pumps calculation"
{v is max water flow rate for one heat pump; q is max load of a zone; c is max CAP for
one heat pump}
function test36(q)
c:=0
a:=0

if (q>0) then c=6.48 {cooling mode, T_r >EWT}

if (q<0) then c=5.11 {heating mode, T_r <EWT}

n=abs(q)/c
```

```
if (round(n+1)-n<1) then a:=round(n+1) else a:=round(n)
test36:=a
End

"!Q_dot_loop calculation"
{c is Q_loop, d is COPcooling, e is COPheating,n is the number of heat pumps in a zone,
COP_h is the COP of heating, COP_n is the COP of cooling }
function Loopload(Q_load, n, COP_h, COP_c, e, v, v_t)
q:=Q_load

CAP_h=5.11
CAP_c=6.48

if q>0 then  c=(q)*(1+1/COP_c)

if q<0 then  c=(q)*(1-1/COP_h)

LoopLoad:=c
End



"!E_dot_boiler calculation"
function test29(a, n)
b:=a/n

test29:=b
end

"!E_dot_tower calculation"
function test30(q, q_max, e_fan)
b:=q*e_fan/q_max
```

```
test30:=b
end


"!PLR_boiler calculation"
function test37(q, q_max)
a:=0

if q=0 then a:=0 else a:=q/q_max

test37:=a
End



"!EE of boiler"
function test51(q, T_lower, T_R, T_0, RHO_water, V_dot_water, E_dot_boiler, H_0,
S_0, n_floor, PLR_boiler)
if q=0 then n:=0
if (q<>0)  then
m_water=n_floor*RHO_water*V_dot_water*PLR_boiler

H_water_out_boiler=enthalpy(Water, P=101, T=T_lower)
H_water_in_boiler=enthalpy(Water, P=101,T=T_R)

S_water_in_boiler=entropy(Water, P=101, T=T_R)
S_water_out_boiler=entropy(Water, P=101, T=T_lower)

X_dot_in_boiler=m_water*((H_water_in_boiler-H_0)-(T_0+273)*(S_water_in_boiler-
S_0))
X_dot_out_boiler=m_water*((H_water_out_boiler-H_0)-
(T_0+273)*(S_water_out_boiler-S_0))
```

```
n:=(X_dot_out_boiler-X_dot_in_boiler)/E_dot_boiler

endif

test51:=n
end


"!EE of pump"
function test52 (T_R, T_0, RHO_water, V_dot_water, E_dot_pump, v_water_in, H_0,
S_0, n_floor, H)
m_water=n_floor*RHO_water*V_dot_water
V=1.2

C_p_water=specheat(Water, P=101, T=T_0)

P_in=(101*1000+V^2*RHO_water/2)/1000
P_out=P_in+H
T_in=T_R
T_out=T_in

H_water_in_pump=enthalpy(Water, P=P_in, T=T_in)
H_water_out_pump=enthalpy(Water, P=P_out, T=T_out)

S_water_in_pump=entropy(Water, P=P_in, T=T_in)
S_water_out_pump=entropy(Water, P=P_out, T=T_out)

X_dot_in_pump=m_water*((H_water_in_pump-H_0)-(T_0+273)*(S_water_in_pump-
S_0))
```

```
X_dot_out_pump=m_water*((H_water_out_pump-H_0)-
(T_0+273)*(S_water_out_pump-S_0))

n:=(X_dot_out_pump-X_dot_in_pump)/E_dot_pump

test52:=n
end



"!EE of fan"
function test53(T_out_dry, T_out_wet, T_0, E_dot_fan, V_dot_fresh_total, RHO_air,
C_p_air, H_0, S_0, n_floor)
m_fresh=n_floor*RHO_air*V_dot_fresh_total
T_out_fan=T_out_dry+E_dot_fan/(m_fresh*C_p_air)

w=humrat(AIRH2O, P=101, T=T_out_dry, B=T_out_wet)
if w>0 then W_in:=w
if (w=0) or (w<0) then W_in:=0.00000000001

H_fresh_in=enthalpy(AIRH2O, P=101, T=T_out_dry, B=T_out_wet)
H_fresh_out=enthalpy(AIRH2O, P=101.8, T=T_out_fan, W=W_in)

S_fresh_in=entropy(AIRH2O, P=101, T=T_out_dry, B=T_out_wet)
S_fresh_out=entropy(AIRH2O, P=101.8, T=T_out_fan, W=W_in)

X_dot_in_fan=m_fresh*((H_fresh_in-H_0)-(T_0+273)*(S_fresh_in-S_0))
X_dot_out_fan=m_fresh*((H_fresh_out-H_0)-(T_0+273)*(S_fresh_out-S_0))

n:=(X_dot_out_fan- X_dot_in_fan)/E_dot_fan

test53:=n
```

```
end


"!EE of cooling tower"
{The cooling tower is selected for the whole building with 5 floors. The leaving water
temperature is T_upper; The make up water temperature is 10C averagely; the mass flow
rate of the make up water temperature is 5% of that of water entering the cooling tower.}
function test54(q, T_upper, T_R, T_0, RHO_water, V_dot_water, E_dot_tower,
T_out_dry, T_out_wet, q_max, H_0, S_0, V_dot_air_tower, RHO_air, C_p_air,
C_p_water)
if q=0 then n:=0
if (q<>0)  then

PLR_tower=q/q_max

m_air=PLR_tower*RHO_air*V_dot_air_tower
m_water=PLR_tower*RHO_water*V_dot_water*5
m_water_makeup=PLR_tower*m_water*0.05

T_makeup=10[C]
R_air_out=0.95

T_air_out_tower=(q+E_dot_tower+C_p_water*m_water*T_makeup+C_p_air*m_air*T_
out_dry)/(C_p_water*m_water+C_p_air*m_air)

H_air_in_tower=enthalpy(AIRH2O, P=101, T=T_out_dry, B=T_out_wet)
H_air_out_tower=enthalpy(AIRH2O, P=101, T=T_air_out_tower, R=R_air_out)

R_outside=RELHUM(AIRH2O, P=101, T=T_out_dry, B=T_out_wet)

H_water_in_makeup=enthalpy(Water, P=101, T=T_makeup)
```

```
H_water_out_makeup=enthalpy(Water, P=101, T=T_air_out_tower)

S_air_in_tower=entropy(AIRH2O, P=101, T=T_out_dry, B=T_out_wet)
S_air_out_tower=entropy(AIRH2O, P=105, R=R_air_out, T=T_air_out_tower)

H_water_out_tower=enthalpy(Water, P=101, T=T_upper)
H_water_in_tower=enthalpy(Water, P=101, T=T_R)

S_water_in_tower=entropy(Water, P=101, T=T_R)
S_water_out_tower=entropy(Water, P=101, T=T_upper)

S_water_in_makeup=entropy(Water, P=101, T=T_makeup)
S_water_out_makeup=entropy(Water, P=101, T=T_air_out_tower)


X_dot_air_in_tower=m_air*((H_air_in_tower-H_0)-(T_0+273)*(S_air_in_tower-S_0))
X_dot_air_out_tower=m_air*((H_air_out_tower-H_0)-(T_0+273)*(S_air_out_tower-
S_0))

X_dot_water_in_tower=(m_water*((H_water_in_tower-H_0)-
(T_0+273)*(S_water_in_tower-S_0)))
X_dot_water_out_tower=(m_water)*((H_water_out_tower-H_0)-
(T_0+273)*(S_water_out_tower-S_0))

X_dot_water_in_makeup=m_water_makeup*((H_water_in_makeup-H_0)-
(T_0+273)*(S_water_in_makeup-S_0))
X_dot_water_out_makeup=m_water_makeup*((H_water_out_makeup-H_0)-
(T_0+273)*(S_water_out_makeup-S_0))
```

```
X_D=X_dot_air_in_tower-X_dot_air_out_tower+X_dot_water_in_tower-
X_dot_water_out_tower+X_dot_water_in_makeup-
X_dot_water_out_makeup+E_dot_tower

n:=( X_dot_water_out_tower-
X_dot_water_in_tower)/(E_dot_tower+X_dot_air_in_tower-
X_dot_air_out_tower+X_dot_water_in_makeup-X_dot_water_out_makeup)
ENDIF

test54:=n
end



"!EE of HP"
function test55(Q_ld, Q_lp, n_HP, V_dot_water_HP, T_out_dry, T_out_wet, T_water_in,
C_p_air, C_p_water, V_fresh, H_0, S_0, T_0_dry, , V_air_HP, Q_sens, Q_lat,
E_dot_fan, V_total)
Q_load=Q_ld
Q_s=Q_sens*Convert(btu/h, kW)
Q_l=Q_lat*Convert(btu/h, kW)

CAP_h=5.11
CAP_c=6.48

E_HP_h=1.22
E_HP_c=2.59

COP_h=CAP_h/E_HP_h
COP_c=CAP_c/E_HP_c

T_inside=23[C]
```

```
T_0=T_0_dry
R_inside=0.5

m_water=V_dot_water_HP*n_HP*1000
m_air=0.42*1.29*n_HP
m_fresh=V_fresh*1.29

if Q_ld>0 then E_HP:=E_HP_c*n_HP*abs(Q_load/(CAP_c*n_HP))      {cooling mode}
if Q_ld<0 then E_HP:=E_HP_h*n_HP*abs(Q_load/(CAP_h*n_HP))      {heating mode}

if Q_ld >0 then Q_loop:=Q_load*(1+1/COP_c)         {cooling mode}
if Q_ld <0 then Q_loop:=Q_load*(1-1/COP_h)         {heating mode}


H_air_outside=enthalpy(AIRH2O, P=101,T=T_out_dry, B=T_out_wet)
H_inside=enthalpy(AIRH2O, P=101,T=T_inside, R=R_inside)
H_air_in=V_fresh*H_air_outside/(V_air_HP*n_HP)+(V_air_HP*n_HP-
V_fresh)*H_inside/(V_air_HP*n_HP)
H_air_out=H_air_in-Q_load/(m_air)

W_inside=humrat(AIRH2O, P=101, H=H_inside, R=R_inside)
w=humrat(AIRH2O, P=101, T=T_out_dry, B=T_out_wet)
if w>0 then W_outside:=w
if (w=0) or (w<0) then  W_outside=0

W_in=V_fresh/(V_air_HP*n_HP)*W_outside+(V_air_HP*n_HP-
V_fresh)/(V_air_HP*n_HP)*W_inside

T_fresh=T_out_dry+E_dot_fan/(V_total*C_p_air*1.29)
T_air_in=(m_fresh*T_fresh+(m_air-m_fresh)*T_inside)/m_air
T_air_out=T_inside-(Q_s+Q_l)/(m_air*C_p_air)
```

```
S_air_in=entropy(AIRH2O,P=101,T=T_air_in, W=W_in)
S_air_out=entropy(AIRH2O, P=101, T=T_air_out, W=W_in)

H_water_in=enthalpy(Water, P=101, T=T_water_in)
H_water_out=H_water_in+Q_loop/m_water
T_water_out=35+Q_loop/(m_water*C_p_water)

S_water_in=entropy(Water, P=101, T=T_water_in)
S_water_out=entropy(Water, P=101, T=T_water_out)

if (Q_ld>0) then
X_air_in=(m_air*((H_air_in-H_0)-(T_0+273)*(S_air_in-
S_0)))*abs(Q_load/(CAP_c*n_HP))
X_water_in=m_water*((H_water_in-H_0)-(T_0+273)*(S_water_in-
S_0))*abs(Q_load/(CAP_c*n_HP))

X_air_out=(m_air*((H_air_out-H_0)-(T_0+273)*(S_air_out-
S_0)))*abs(Q_load/(CAP_c*n_HP))
X_water_out=m_water*((H_water_out-H_0)-(T_0+273)*(S_water_out-
S_0))*abs(Q_load/(CAP_c*n_HP))

endif

if (Q_ld<0) then
X_air_in=(m_air*((H_air_in-H_0)-(T_0+273)*(S_air_in-
S_0)))*abs(Q_load/(CAP_h*n_HP))
X_water_in=m_water*((H_water_in-H_0)-(T_0+273)*(S_water_in-
S_0))*abs(Q_load/(CAP_h*n_HP))
```

```
X_air_out=(m_air*((H_air_out-H_0)-(T_0+273)*(S_air_out-
S_0)))*abs(Q_load/(CAP_h*n_HP))
X_water_out=m_water*((H_water_out-H_0)-(T_0+273)*(S_water_out-
S_0))*abs(Q_load/(CAP_h*n_HP))

endif

X_D=X_air_in-X_air_out+X_water_in-X_water_out+E_HP

n_X=1-X_D/E_HP

test55:=n_X
end



"!EE of system"
"!Useful exergy of HP"
function test56(Q_ld, Q_lp, n_HP, V_dot_water_HP, T_out_dry, T_out_wet, T_water_in,
C_p_air, C_p_water, V_fresh, H_0, S_0, T_0_dry, , V_air_HP, Q_sens, Q_lat,
E_dot_fan, V_total)
Q_load=Q_ld
Q_s=Q_sens*Convert(btu/h, kW)
Q_l=Q_lat*Convert(btu/h, kW)

CAP_h=5.11
CAP_c=6.48

E_HP_h=1.22
E_HP_c=2.59

COP_h=CAP_h/E_HP_h
```

```
COP_c=CAP_c/E_HP_c

T_inside=23[C]
T_0=T_0_dry
R_inside=0.5

m_water=V_dot_water_HP*n_HP*1000
m_air=0.42*1.29*n_HP
m_fresh=V_fresh*1.29

if Q_ld>0 then E_HP:=E_HP_c*n_HP*abs(Q_load/(CAP_c*n_HP))      {cooling mode}
if Q_ld<0 then E_HP:=E_HP_h*n_HP*abs(Q_load/(CAP_h*n_HP))      {heating mode}

if Q_ld >0 then Q_loop:=Q_load*(1+1/COP_c)          {cooling mode}
if Q_ld <0 then Q_loop:=Q_load*(1-1/COP_h)          {heating mode}

H_air_outside=enthalpy(AIRH2O, P=101,T=T_out_dry, B=T_out_wet)
H_inside=enthalpy(AIRH2O, P=101,T=T_inside, R=R_inside)
H_air_in=V_fresh*H_air_outside/(V_air_HP*n_HP)+(V_air_HP*n_HP-
V_fresh)*H_inside/(V_air_HP*n_HP)
H_air_out=H_air_in-Q_load/(m_air)

W_inside=humrat(AIRH2O, P=101, H=H_inside, R=R_inside)
w=humrat(AIRH2O, P=101, T=T_out_dry, B=T_out_wet)
if w>0 then W_outside:=w
if (w=0) or (w<0) then  W_outside=0

W_in=V_fresh/(V_air_HP*n_HP)*W_outside+(V_air_HP*n_HP-
V_fresh)/(V_air_HP*n_HP)*W_inside

T_fresh=T_out_dry+E_dot_fan/(V_total*C_p_air*1.29)
```

```
T_air_in=(m_fresh*T_fresh+(m_air-m_fresh)*T_inside)/m_air
T_air_out=T_inside-(Q_s+Q_l)/(m_air*C_p_air)

S_air_in=entropy(AIRH2O,P=101,T=T_air_in, W=W_in)
S_air_out=entropy(AIRH2O, P=101, T=T_air_out, W=W_in)

H_air_inside=H_inside
S_air_inside=entropy(AIRH2O,P=101,T=T_inside, R=R_inside)

H_water_in=enthalpy(Water, P=101, T=T_water_in)
H_water_out=H_water_in+Q_loop/m_water
T_water_out=35+Q_loop/(m_water*C_p_water)

S_water_in=entropy(Water, P=101, T=T_water_in)
S_water_out=entropy(Water, P=101, T=T_water_out)

if (Q_ld>0) then
X_air_in=(m_air*((H_air_in-H_0)-(T_0+273)*(S_air_in-
S_0)))*abs(Q_load/(CAP_c*n_HP))
X_water_in=m_water*((H_water_in-H_0)-(T_0+273)*(S_water_in-
S_0))*abs(Q_load/(CAP_c*n_HP))

X_air_out=(m_air*((H_air_out-H_0)-(T_0+273)*(S_air_out-
S_0)))*abs(Q_load/(CAP_c*n_HP))
X_water_out=m_water*((H_water_out-H_0)-(T_0+273)*(S_water_out-
S_0))*abs(Q_load/(CAP_c*n_HP))

X_air_inside=(m_air*((H_air_inside-H_0)-(T_0+273)*(S_air_inside-
S_0)))*abs(Q_load/(CAP_c*n_HP))

endif
```

```
if (Q_ld<0) then
X_air_in=(m_air*((H_air_in-H_0)-(T_0+273)*(S_air_in-
S_0)))*abs(Q_load/(CAP_h*n_HP))
X_water_in=m_water*((H_water_in-H_0)-(T_0+273)*(S_water_in-
S_0))*abs(Q_load/(CAP_h*n_HP))

X_air_out=(m_air*((H_air_out-H_0)-(T_0+273)*(S_air_out-
S_0)))*abs(Q_load/(CAP_h*n_HP))
X_water_out=m_water*((H_water_out-H_0)-(T_0+273)*(S_water_out-
S_0))*abs(Q_load/(CAP_h*n_HP))

X_air_inside=(m_air*((H_air_inside-H_0)-(T_0+273)*(S_air_inside-
S_0)))*abs(Q_load/(CAP_h*n_HP))

endif

X=abs(X_air_out-X_air_inside)

n_X=X

test56:=n_X
end



"!EE of system"
function test60(X_C, X_N, X_E, X_W, X_S, E_C, E_N, E_E, E_S, E_W, E_dot_fan,
E_dot_pump, E_dot_boiler, E_dot_tower, n_floor)

X_useful=(X_C+X_N+X_E+X_W+X_S)*n_floor
```

```
X_supply=E_dot_fan+E_dot_pump+E_dot_boiler+E_dot_tower+n_floor*(E_C+E_N+E
_E+E_S+E_W)

n=(X_useful)/(X_supply)

test60:=n
end



"!EE dis"
function test61(Q_ld, Q_lp, n_HP, V_dot_water_HP, T_out_dry, T_out_wet, T_water_in,
C_p_air, C_p_water, V_fresh, H_0, S_0, T_0_dry, , V_air_HP, Q_sens, Q_lat,
E_dot_fan, V_total)
Q_load=Q_ld
Q_s=Q_sens*Convert(btu/h, kW)
Q_l=Q_lat*Convert(btu/h, kW)

CAP_h=5.11
CAP_c=6.48

E_HP_h=1.22
E_HP_c=2.59

COP_h=CAP_h/E_HP_h
COP_c=CAP_c/E_HP_c

T_inside=23[C]
T_0=T_0_dry
R_inside=0.5

m_water=V_dot_water_HP*n_HP*1000
```

```
m_air=0.42*1.29*n_HP
m_fresh=V_fresh*1.29

if Q_ld>0 then E_HP:=E_HP_c*n_HP*abs(Q_load/(CAP_c*n_HP))      {cooling mode}
if Q_ld<0 then E_HP:=E_HP_h*n_HP*abs(Q_load/(CAP_h*n_HP))       {heating mode}

if Q_ld >0 then Q_loop:=Q_load*(1+1/COP_c)          {cooling mode}
if Q_ld <0 then Q_loop:=Q_load*(1-1/COP_h)          {heating mode}

H_air_outside=enthalpy(AIRH2O, P=101,T=T_out_dry, B=T_out_wet)
H_inside=enthalpy(AIRH2O, P=101,T=T_inside, R=R_inside)
H_air_in=V_fresh*H_air_outside/(V_air_HP*n_HP)+(V_air_HP*n_HP-
V_fresh)*H_inside/(V_air_HP*n_HP)
H_air_out=H_air_in-Q_load/(m_air)

W_inside=humrat(AIRH2O, P=101, H=H_inside, R=R_inside)
w=humrat(AIRH2O, P=101, T=T_out_dry, B=T_out_wet)
if w>0 then W_outside:=w
if (w=0) or (w<0) then  W_outside=0

W_in=V_fresh/(V_air_HP*n_HP)*W_outside+(V_air_HP*n_HP-
V_fresh)/(V_air_HP*n_HP)*W_inside

T_fresh=T_out_dry+E_dot_fan/(V_total*C_p_air*1.29)
T_air_in=(m_fresh*T_fresh+(m_air-m_fresh)*T_inside)/m_air
T_air_out=T_inside-(Q_s+Q_l)/(m_air*C_p_air)

S_air_in=entropy(AIRH2O,P=101,T=T_air_in, W=W_in)
S_air_out=entropy(AIRH2O, P=101, T=T_air_out, W=W_in)

H_water_in=enthalpy(Water, P=101, T=T_water_in)
```

```
H_water_out=H_water_in+Q_loop/m_water
T_water_out=35+Q_loop/(m_water*C_p_water)

S_water_in=entropy(Water, P=101, T=T_water_in)
S_water_out=entropy(Water, P=101, T=T_water_out)

if (Q_ld>0) then
X_air_in=(m_air*((H_air_in-H_0)-(T_0+273)*(S_air_in-
S_0)))*abs(Q_load/(CAP_c*n_HP))
X_water_in=m_water*((H_water_in-H_0)-(T_0+273)*(S_water_in-
S_0))*abs(Q_load/(CAP_c*n_HP))

X_air_out=(m_air*((H_air_out-H_0)-(T_0+273)*(S_air_out-
S_0)))*abs(Q_load/(CAP_c*n_HP))
X_water_out=m_water*((H_water_out-H_0)-(T_0+273)*(S_water_out-
S_0))*abs(Q_load/(CAP_c*n_HP))

endif

if (Q_ld<0) then
X_air_in=(m_air*((H_air_in-H_0)-(T_0+273)*(S_air_in-
S_0)))*abs(Q_load/(CAP_h*n_HP))
X_water_in=m_water*((H_water_in-H_0)-(T_0+273)*(S_water_in-
S_0))*abs(Q_load/(CAP_h*n_HP))

X_air_out=(m_air*((H_air_out-H_0)-(T_0+273)*(S_air_out-
S_0)))*abs(Q_load/(CAP_h*n_HP))
X_water_out=m_water*((H_water_out-H_0)-(T_0+273)*(S_water_out-
S_0))*abs(Q_load/(CAP_h*n_HP))

endif
```

```
X_D=abs(X_air_in-X_air_out+X_water_in-X_water_out+E_HP)

test61:=X_D
end


"!Exergy Destruction of Fan"
function test62(T_out_dry, T_out_wet, T_0, E_dot_fan, V_dot_fresh_total, RHO_air,
C_p_air, H_0, S_0, n_floor)
m_fresh=n_floor*RHO_air*V_dot_fresh_total
T_out_fan=T_out_dry+E_dot_fan/(m_fresh*C_p_air)

w=humrat(AIRH2O, P=101, T=T_out_dry, B=T_out_wet)
if w>0 then W_in:=w
if (w=0) or (w<0) then W_in:=0.00000000001

H_fresh_in=enthalpy(AIRH2O, P=101, T=T_out_dry, B=T_out_wet)
H_fresh_out=enthalpy(AIRH2O, P=101.8, T=T_out_fan, W=W_in)

S_fresh_in=entropy(AIRH2O, P=101, T=T_out_dry, B=T_out_wet)
S_fresh_out=entropy(AIRH2O, P=101.8, T=T_out_fan, W=W_in)

X_dot_in_fan=m_fresh*((H_fresh_in-H_0)-(T_0+273)*(S_fresh_in-S_0))
X_dot_out_fan=m_fresh*((H_fresh_out-H_0)-(T_0+273)*(S_fresh_out-S_0))

X_D:=abs(-X_dot_out_fan+ X_dot_in_fan+E_dot_fan)

test62:=X_D
end
```

```
"!Exergy Destruction of Pump"
function test63 (T_R, T_0, RHO_water, V_dot_water, E_dot_pump, v_water_in, H_0,
S_0, n_floor, H)
m_water=n_floor*RHO_water*V_dot_water
V=1.2

C_p_water=specheat(Water, P=101, T=T_0)

P_in=(101*1000+V^2*RHO_water/2)/1000
P_out=P_in+H
T_in=T_R
T_out=T_in

H_water_in_pump=enthalpy(Water, P=P_in, T=T_in)
H_water_out_pump=enthalpy(Water, P=P_out, T=T_out)

S_water_in_pump=entropy(Water, P=P_in, T=T_in)
S_water_out_pump=entropy(Water, P=P_out, T=T_out)

X_dot_in_pump=m_water*((H_water_in_pump-H_0)-(T_0+273)*(S_water_in_pump-
S_0))
X_dot_out_pump=m_water*((H_water_out_pump-H_0)-
(T_0+273)*(S_water_out_pump-S_0))

X_D:=abs(-X_dot_out_pump+X_dot_in_pump+E_dot_pump)

test63:=X_D
end
```

```
"!Exergy Destruction of Boiler"
function test64(q, T_lower, T_R, T_0, RHO_water, V_dot_water, E_dot_boiler, H_0,
S_0, n_floor, PLR_boiler)
if q=0 then X_D:=0
if (q<>0)  then
m_water=n_floor*RHO_water*V_dot_water*PLR_boiler

H_water_out_boiler=enthalpy(Water, P=101, T=T_lower)
H_water_in_boiler=enthalpy(Water, P=101,T=T_R)

S_water_in_boiler=entropy(Water, P=101, T=T_R)
S_water_out_boiler=entropy(Water, P=101, T=T_lower)

X_dot_in_boiler=m_water*((H_water_in_boiler-H_0)-(T_0+273)*(S_water_in_boiler-
S_0))
X_dot_out_boiler=m_water*((H_water_out_boiler-H_0)-
(T_0+273)*(S_water_out_boiler-S_0))

 X_D:=abs(-X_dot_out_boiler+X_dot_in_boiler+E_dot_boiler)

endif

test64:=X_D
end


"!Exergy Destruction of Cooling Tower"
function test65(q, T_upper, T_R, T_0, RHO_water, V_dot_water, E_dot_tower,
T_out_dry, T_out_wet, q_max, H_0, S_0, V_dot_air_tower, RHO_air, C_p_air,
C_p_water)
if q=0 then X_D:=0
```

```
if (q<>0)  then

PLR_tower=q/q_max

m_air=PLR_tower*RHO_air*V_dot_air_tower
m_water=PLR_tower*RHO_water*V_dot_water*5
m_water_makeup=PLR_tower*m_water*0.05

T_makeup=10[C]
R_air_out=0.95

T_air_out_tower=(q+E_dot_tower+C_p_water*m_water*T_makeup+C_p_air*m_air*T_out_dry)/(C_p_water*m_water+C_p_air*m_air)

H_air_in_tower=enthalpy(AIRH2O, P=101, T=T_out_dry, B=T_out_wet)
H_air_out_tower=enthalpy(AIRH2O, P=101, T=T_air_out_tower, R=R_air_out)

R_outside=RELHUM(AIRH2O, P=101, T=T_out_dry, B=T_out_wet)



H_water_in_makeup=enthalpy(Water, P=101, T=T_makeup)
H_water_out_makeup=enthalpy(Water, P=101, T=T_air_out_tower)

S_air_in_tower=entropy(AIRH2O, P=101, T=T_out_dry, B=T_out_wet)
S_air_out_tower=entropy(AIRH2O, P=105, R=R_air_out, T=T_air_out_tower)

H_water_out_tower=enthalpy(Water, P=101, T=T_upper)
H_water_in_tower=enthalpy(Water, P=101, T=T_R)

S_water_in_tower=entropy(Water, P=101, T=T_R)
S_water_out_tower=entropy(Water, P=101, T=T_upper)
```

```
S_water_in_makeup=entropy(Water, P=101, T=T_makeup)
S_water_out_makeup=entropy(Water, P=101, T=T_air_out_tower)


X_dot_air_in_tower=m_air*((H_air_in_tower-H_0)-(T_0+273)*(S_air_in_tower-S_0))
X_dot_air_out_tower=m_air*((H_air_out_tower-H_0)-(T_0+273)*(S_air_out_tower-
S_0))

X_dot_water_in_tower=(m_water*((H_water_in_tower-H_0)-
(T_0+273)*(S_water_in_tower-S_0)))
X_dot_water_out_tower=(m_water)*((H_water_out_tower-H_0)-
(T_0+273)*(S_water_out_tower-S_0))

X_dot_water_in_makeup=m_water_makeup*((H_water_in_makeup-H_0)-
(T_0+273)*(S_water_in_makeup-S_0))
X_dot_water_out_makeup=m_water_makeup*((H_water_out_makeup-H_0)-
(T_0+273)*(S_water_out_makeup-S_0))

X_D=X_dot_air_in_tower-X_dot_air_out_tower+X_dot_water_in_tower-
X_dot_water_out_tower+X_dot_water_in_makeup-
X_dot_water_out_makeup+E_dot_tower

n:=( X_dot_water_out_tower-
X_dot_water_in_tower)/(E_dot_tower+X_dot_air_in_tower-
X_dot_air_out_tower+X_dot_water_in_makeup-X_dot_water_out_makeup)

X_D:=abs(E_dot_tower+X_dot_water_in_tower-
X_dot_water_out_tower+X_dot_water_in_makeup-X_dot_water_out_makeup)

ENDIF
```

```
test65:=X_D
end


"!Exergy Destruction Distribution Ratio"
function test71(D_HP_C, D_HP_N, D_HP_E, D_HP_W, D_HP_S, D_fan, D_pump,
D_boiler, D_tower, X_D)

n:=(X_D)/(D_HP_C+D_HP_N+D_HP_E+D_HP_W+D_HP_S+D_fan+D_pump+D_boil
er+D_tower)

test71:=n
end




"!Main program"
RHO_air=1.29[kg/m^3]
RHO_water=1000[kg/m^3]

C_p_air=1[kJ/(kg*C)]
C_p_water=specheat(Water, P=101, T=35)

"!Max flow rate for one heat pump"
v_water_in=1.2[m/s]
V_dot_water_HP=0.23[l/s]*Convert(l/s, m^3/s)
V_dot_air_HP=0.42[m^3/s]
```

```
n_floor=5
T_inside=23[C]

n_trans=0.86
n_hydro=0.8
n_gas=0.431
n_oil=0.33
n_nuclear=0.3
a_hydro=0.967
a_gas=0.011
a_oil=0.011
a_nuclear=0.011
n_boiler_theory=0.9

b_hydro=15[kteq.CO2/TWh]
b_oil=778[kteq.CO2/TWh]
b_gas=443[kteq.CO2/TWh]
b_nuclear=15[kteq.CO2/TWh]

T_0_dry=T_out_dry
T_0_wet=T_out_wet

ME=0.65
Rd_water=1.00
Rd_air=0.0012
H_water=85[ka]
H_air=0.8[kPa]

T_upper=35[C]
T_lower=35[C]
EWT=35[C]
```

```
V_dot_air_tower=9500*convert(cfm, m^3/s)
E_dot_fan_CT=3*convert(hp, kW)

Q_dot_boiler_max=213*1.1
Q_dot_tower_max=322.8*1.1


"!The zone area and the occupant density"
A_C=587[m^2]
A_N=113[m^2]
A_E=93[m^2]
A_S=113[m^2]
A_W=93[m^2]
D=25[m^2/person]

V_dot_need=25*convert(cfm, m^3/s)


"!COP calculation"
COP_heating=5.11/1.22
COP_cooling=6.48/2.59


"!Fresh air requirement"
{V_dot_fresh_total is for ONE floor}
N_people_C=A_C/D
N_people_N=A_N/D
N_people_E=A_E/D
N_people_S=A_S/D
N_people_W=A_W/D
```

```
V_dot_fresh_C=N_people_C*V_dot_need
V_dot_fresh_N=N_people_N*V_dot_need
V_dot_fresh_E=N_people_E*V_dot_need
V_dot_fresh_S=N_people_S*V_dot_need
V_dot_fresh_W=N_people_W*V_dot_need

V_dot_fresh_total=(V_dot_fresh_C+V_dot_fresh_N+V_dot_fresh_E+V_dot_fresh_S+V
_dot_fresh_W)


"!The energy supplied into the fun to supply fresh air"
E_dot_fan=V_dot_fresh_total*H_air/ME {ONE floor}

E_dot_fan_total=n_floor*V_dot_fresh_total*H_air/ME


"!Number of heat pump calculation under the peak condition for one floor"
N_c=3
N_n=2
N_e=2
N_s=2
N_w=2

"!Q_dot_load calculation for one floor"
{Estimate the number of HPs in zone}
Q_dot_load_c=test16(Q_dot_sens_c,Q_dot_lat_c, C_p_air, V_dot_fresh_C, RHO_air,
T_inside, T_out_dry, V_dot_fresh_total, E_dot_fan, N_c, V_dot_air_HP)
Q_dot_load_n=test16(Q_dot_sens_n,Q_dot_lat_n, C_p_air, V_dot_fresh_N, RHO_air,
T_inside, T_out_dry,  V_dot_fresh_total, E_dot_fan, N_n, V_dot_air_HP)
```

```
Q_dot_load_e=test16(Q_dot_sens_e,Q_dot_lat_e, C_p_air, V_dot_fresh_E, RHO_air,
T_inside, T_out_dry, V_dot_fresh_total, E_dot_fan, N_e, V_dot_air_HP)
Q_dot_load_s=test16(Q_dot_sens_s,Q_dot_lat_s, C_p_air, V_dot_fresh_S, RHO_air,
T_inside, T_out_dry, V_dot_fresh_total, E_dot_fan, N_s, V_dot_air_HP)
Q_dot_load_w=test16(Q_dot_sens_w,Q_dot_lat_w, C_p_air, V_dot_fresh_W, RHO_air,
T_inside, T_out_dry, V_dot_fresh_total, E_dot_fan, N_w, V_dot_air_HP)

{Coil Load}
Q_dot_load_central=test18(Q_dot_sens_c,Q_dot_lat_c, C_p_air, V_dot_fresh_C,
RHO_air, T_inside, T_out_dry, V_dot_fresh_total, E_dot_fan, N_c, V_dot_air_HP,
V_dot_fresh_total)
Q_dot_load_north=test18(Q_dot_sens_n,Q_dot_lat_n, C_p_air, V_dot_fresh_N,
RHO_air, T_inside, T_out_dry,  V_dot_fresh_total, E_dot_fan, N_n, V_dot_air_HP,
V_dot_fresh_total)
Q_dot_load_east=test18(Q_dot_sens_e,Q_dot_lat_e, C_p_air, V_dot_fresh_E, RHO_air,
T_inside, T_out_dry, V_dot_fresh_total, E_dot_fan, N_e, V_dot_air_HP,
V_dot_fresh_total)
Q_dot_load_south=test18(Q_dot_sens_s,Q_dot_lat_s, C_p_air, V_dot_fresh_S,
RHO_air, T_inside, T_out_dry, V_dot_fresh_total, E_dot_fan, N_s, V_dot_air_HP,
V_dot_fresh_total)
Q_dot_load_west=test18(Q_dot_sens_w,Q_dot_lat_w, C_p_air, V_dot_fresh_W,
RHO_air, T_inside, T_out_dry, V_dot_fresh_total, E_dot_fan, N_w, V_dot_air_HP,
V_dot_fresh_total)


"!air flow rate for each zone"
V_dot_air_HP_C=N_c*V_dot_air_HP
V_dot_air_HP_N=N_n*V_dot_air_HP
V_dot_air_HP_E=N_e*V_dot_air_HP
V_dot_air_HP_S=N_s*V_dot_air_HP
V_dot_air_HP_W=N_w*V_dot_air_HP
```

```
"!Water flow rate calculation"
{V_water is the total volume rate for ONE floor, m^3/s }
V_dot_water_central_total=N_c*V_dot_water_HP
V_dot_water_north_total=N_n*V_dot_water_HP
V_dot_water_east_total=N_e*V_dot_water_HP
V_dot_water_south_total=N_s*V_dot_water_HP
V_dot_water_west_total=N_w*V_dot_water_HP

V_dot_water=V_dot_water_central_total+V_dot_water_north_total+V_dot_water_east_total+V_dot_water_south_total+V_dot_water_west_total


"!The energy supplied into pump calculation"
E_dot_pump=n_floor*V_dot_water*H_water/ME


"!Q_dot_loop calculation for  heat pumps in ONE floor"
Q_dot_loop_central=Loopload(Q_dot_load_central, N_c, COP_heating, COP_cooling, E_dot_fan, V_dot_fresh_C, V_dot_fresh_total)
Q_dot_loop_north=Loopload(Q_dot_load_north, N_n, COP_heating, COP_cooling, E_dot_fan, V_dot_fresh_N, V_dot_fresh_total)
Q_dot_loop_east=Loopload(Q_dot_load_east, N_e, COP_heating, COP_cooling, E_dot_fan, V_dot_fresh_E, V_dot_fresh_total)
Q_dot_loop_south=Loopload(Q_dot_load_south, N_s, COP_heating, COP_cooling, E_dot_fan, V_dot_fresh_S, V_dot_fresh_total)
Q_dot_loop_west=Loopload(Q_dot_load_west, N_w, COP_heating, COP_cooling, E_dot_fan, V_dot_fresh_W, V_dot_fresh_total)
```

```
Q_dot_loop=Q_dot_loop_central+Q_dot_loop_north+Q_dot_loop_east+Q_dot_loop_south+Q_dot_loop_west


"!System return water temperature calculation"
T_R=EWT+Q_dot_loop/(V_dot_water*RHO_water*C_p_water)


"!The energy supplied by the boiler"
Q_dot_boiler=test1(T_lower,T_R, RHO_water, V_dot_water, C_p_water, n_floor)
PLR_boiler=test37(Q_dot_boiler, Q_dot_boiler_max)
n_boiler_actual=n_boiler_theory*(0.563+0.921*PLR_boiler-0.518*PLR_boiler^2)


"!The energy transferred by the cooling tower"
Q_dot_tower=test2(T_upper, T_R, RHO_water, V_dot_water, C_p_water, n_floor)
PLR_tower=test37(Q_dot_tower, Q_dot_tower_max)


"!COP of system calculation"
Q_dot_output=n_floor*abs(abs(Q_dot_load_central)+abs(Q_dot_load_north)+abs(Q_dot_load_east)+abs(Q_dot_load_south)+abs(Q_dot_load_west))

E_dot_input_central=test24(N_c, Q_dot_load_central)
E_dot_input_north=test24(N_n, Q_dot_load_north)
E_dot_input_east=test24(N_e, Q_dot_load_east)
E_dot_input_south=test24(N_s, Q_dot_load_south)
E_dot_input_west=test24(N_w, Q_dot_load_west)

E_dot_heatpump_total=n_floor*(E_dot_input_central+E_dot_input_north+E_dot_input_east+E_dot_input_south+E_dot_input_west)
```

```
E_dot_boiler=test29(Q_dot_boiler, n_boiler_actual)

E_dot_tower=test30(Q_dot_tower, Q_dot_tower_max, E_dot_fan_CT)

E_dot_systeminput=E_dot_heatpump_total+E_dot_tower+E_dot_boiler+E_dot_pump+E
_dot_fan_total

COP_average_heatpump=Q_dot_output/E_dot_heatpump_total

COP_system=Q_dot_output/E_dot_systeminput


"!Overall COP calculation"
n_overall=(1/n_trans)*(a_hydro/n_hydro+a_gas/n_gas+a_nuclear/n_nuclear+a_oil/n_oil)

COP_ovall=Q_dot_output/(E_dot_systeminput*n_overall)


"!EXERGY EFFICIENCY"
"!H and S of environment"
H_0=enthalpy(AIRH2O, P=101, T=T_0_dry , B=T_0_wet)
S_0=entropy(AIRH2O, P=101, T=T_0_dry, B=T_0_wet)


"!EE of boiler"
n_X_boiler=test51(Q_dot_boiler, T_lower, T_R, T_0_dry, RHO_water, V_dot_water,
E_dot_boiler, H_0, S_0, n_floor, PLR_boiler)


"!EE of cooling tower"
```

```
n_X_tower=test54(Q_dot_tower, T_upper, T_R, T_0_dry, RHO_water, V_dot_water,
E_dot_tower, T_out_dry, T_out_wet,  Q_dot_tower_max, H_0, S_0, V_dot_air_tower,
RHO_air, C_p_air, C_p_water)


"!EE of pump"
n_X_pump=test52(T_R, T_0_dry, RHO_water, V_dot_water, E_dot_pump, v_water_in,
H_0, S_0, n_floor, H_water)


"!EE of fan"
n_X_fan=test53(T_out_dry, T_out_wet, T_0_dry, E_dot_fan_total, V_dot_fresh_total,
RHO_air, C_p_air, H_0, S_0, n_floor)


"!EE of HP"
n_X_HP_C=test55(Q_dot_load_central, Q_dot_loop_central, N_c, V_dot_water_HP,
T_out_dry, T_out_wet, EWT, C_p_air, C_p_water, V_dot_fresh_C, H_0, S_0, T_0_dry,
V_dot_air_HP, Q_dot_sens_c,Q_dot_lat_c, E_dot_fan, V_dot_fresh_total)
n_X_HP_N=test55(Q_dot_load_north, Q_dot_loop_north, N_n, V_dot_water_HP,
T_out_dry, T_out_wet, EWT, C_p_air, C_p_water, V_dot_fresh_N, H_0, S_0, T_0_dry,
V_dot_air_HP, Q_dot_sens_n,Q_dot_lat_n, E_dot_fan, V_dot_fresh_total)
n_X_HP_E=test55(Q_dot_load_east, Q_dot_loop_east, N_e, V_dot_water_HP,
T_out_dry, T_out_wet, EWT, C_p_air, C_p_water, V_dot_fresh_E, H_0, S_0, T_0_dry,
V_dot_air_HP, Q_dot_sens_e,Q_dot_lat_e, E_dot_fan, V_dot_fresh_total)
n_X_HP_W=test55(Q_dot_load_west, Q_dot_loop_west, N_w, V_dot_water_HP,
T_out_dry, T_out_wet, EWT, C_p_air, C_p_water, V_dot_fresh_W, H_0, S_0, T_0_dry,
V_dot_air_HP, Q_dot_sens_w,Q_dot_lat_w, E_dot_fan, V_dot_fresh_total)
n_X_HP_S=test55(Q_dot_load_south, Q_dot_loop_south, N_s, V_dot_water_HP,
T_out_dry, T_out_wet, EWT, C_p_air, C_p_water, V_dot_fresh_S, H_0, S_0, T_0_dry,
V_dot_air_HP, Q_dot_sens_s,Q_dot_lat_s, E_dot_fan, V_dot_fresh_total)
```

```
"!EE of system"
X_HP_C=test56(Q_dot_load_central, Q_dot_loop_central, N_c, V_dot_water_HP,
T_out_dry, T_out_wet, EWT, C_p_air, C_p_water, V_dot_fresh_C, H_0, S_0, T_0_dry,
V_dot_air_HP, Q_dot_sens_c,Q_dot_lat_c, E_dot_fan, V_dot_fresh_total)
X_HP_N=test56(Q_dot_load_north, Q_dot_loop_north, N_n, V_dot_water_HP,
T_out_dry, T_out_wet, EWT, C_p_air, C_p_water, V_dot_fresh_N, H_0, S_0, T_0_dry,
V_dot_air_HP, Q_dot_sens_n,Q_dot_lat_n, E_dot_fan, V_dot_fresh_total)
X_HP_E=test56(Q_dot_load_east, Q_dot_loop_east, N_e, V_dot_water_HP, T_out_dry,
T_out_wet, EWT, C_p_air, C_p_water, V_dot_fresh_E, H_0, S_0, T_0_dry,
V_dot_air_HP, Q_dot_sens_e,Q_dot_lat_e, E_dot_fan, V_dot_fresh_total)
X_HP_W=test56(Q_dot_load_west, Q_dot_loop_west, N_w, V_dot_water_HP,
T_out_dry, T_out_wet, EWT, C_p_air, C_p_water, V_dot_fresh_W, H_0, S_0, T_0_dry,
V_dot_air_HP, Q_dot_sens_w,Q_dot_lat_w, E_dot_fan, V_dot_fresh_total)
X_HP_S=test56(Q_dot_load_south, Q_dot_loop_south, N_s, V_dot_water_HP,
T_out_dry, T_out_wet, EWT, C_p_air, C_p_water, V_dot_fresh_S, H_0, S_0, T_0_dry,
V_dot_air_HP, Q_dot_sens_s,Q_dot_lat_s, E_dot_fan, V_dot_fresh_total)

n_X_system=test60(X_HP_C, X_HP_N, X_HP_E, X_HP_W, X_HP_S,
E_dot_input_central, E_dot_input_north, E_dot_input_east, E_dot_input_south,
E_dot_input_west, E_dot_fan_total, E_dot_pump, E_dot_boiler, E_dot_tower, n_floor)

n_X_overall=n_X_system/n_overall


"!GHG emission"
E_hydro=(E_dot_systeminput/n_trans)*(a_hydro/n_hydro)*(1/10^9)
E_gas=(E_dot_systeminput/n_trans)*(a_gas/n_gas)*(1/10^9)
E_oil=(E_dot_systeminput/n_trans)*(a_oil/n_oil)*(1/10^9)
E_nuclear=(E_dot_systeminput/n_trans)*(a_nuclear/n_nuclear)*(1/10^9)
```

```
EM_CO2=b_hydro*E_hydro+b_gas*E_gas+b_oil*E_oil+b_nuclear*E_nuclear


"!Exergy destruction distribution of components"
D_HP_C=test61(Q_dot_load_central, Q_dot_loop_central, N_c, V_dot_water_HP,
T_out_dry, T_out_wet, EWT, C_p_air, C_p_water, V_dot_fresh_C, H_0, S_0, T_0_dry,
V_dot_air_HP, Q_dot_sens_c,Q_dot_lat_c, E_dot_fan, V_dot_fresh_total)
D_HP_N=test61(Q_dot_load_north, Q_dot_loop_north, N_n, V_dot_water_HP,
T_out_dry, T_out_wet, EWT, C_p_air, C_p_water, V_dot_fresh_N, H_0, S_0, T_0_dry,
V_dot_air_HP, Q_dot_sens_n,Q_dot_lat_n, E_dot_fan, V_dot_fresh_total)
D_HP_E=test61(Q_dot_load_east, Q_dot_loop_east, N_e, V_dot_water_HP, T_out_dry,
T_out_wet, EWT, C_p_air, C_p_water, V_dot_fresh_E, H_0, S_0, T_0_dry,
V_dot_air_HP, Q_dot_sens_e,Q_dot_lat_e, E_dot_fan, V_dot_fresh_total)
D_HP_W=test61(Q_dot_load_west, Q_dot_loop_west, N_w, V_dot_water_HP,
T_out_dry, T_out_wet, EWT, C_p_air, C_p_water, V_dot_fresh_W, H_0, S_0, T_0_dry,
V_dot_air_HP, Q_dot_sens_w,Q_dot_lat_w, E_dot_fan, V_dot_fresh_total)
D_HP_S=test61(Q_dot_load_south, Q_dot_loop_south, N_s, V_dot_water_HP,
T_out_dry, T_out_wet, EWT, C_p_air, C_p_water, V_dot_fresh_S, H_0, S_0, T_0_dry,
V_dot_air_HP, Q_dot_sens_s,Q_dot_lat_s, E_dot_fan, V_dot_fresh_total)

D_fan=test62(T_out_dry, T_out_wet, T_0_dry, E_dot_fan_total, V_dot_fresh_total,
RHO_air, C_p_air, H_0, S_0, n_floor)
D_pump=test63(T_R, T_0_dry, RHO_water, V_dot_water, E_dot_pump, v_water_in,
H_0, S_0, n_floor, H_water)
D_boiler=test64(Q_dot_boiler, T_lower, T_R, T_0_dry, RHO_water, V_dot_water,
E_dot_boiler, H_0, S_0, n_floor, PLR_boiler)
D_tower=test65(Q_dot_tower, T_upper, T_R, T_0_dry, RHO_water, V_dot_water,
E_dot_tower, T_out_dry, T_out_wet,  Q_dot_tower_max, H_0, S_0, V_dot_air_tower,
RHO_air, C_p_air, C_p_water)
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n_X_HP_C_dis=test71(D_HP_C, D_HP_N, D_HP_E, D_HP_W, D_HP_S, D_fan,
D_pump, D_boiler, D_tower, D_HP_C)
n_X_HP_N_dis=test71(D_HP_C, D_HP_N, D_HP_E, D_HP_W, D_HP_S, D_fan,
D_pump, D_boiler, D_tower,D_HP_N)
n_X_HP_E_dis=test71(D_HP_C, D_HP_N, D_HP_E, D_HP_W, D_HP_S, D_fan,
D_pump, D_boiler, D_tower,D_HP_E)
n_X_HP_S_dis=test71(D_HP_C, D_HP_N, D_HP_E, D_HP_W, D_HP_S, D_fan,
D_pump, D_boiler, D_tower,D_HP_S)
n_X_HP_W_dis=test71(D_HP_C, D_HP_N, D_HP_E, D_HP_W, D_HP_S, D_fan,
D_pump, D_boiler, D_tower,D_HP_W)
n_X_fan_dis=test71(D_HP_C, D_HP_N, D_HP_E, D_HP_W, D_HP_S, D_fan,
D_pump, D_boiler, D_tower, D_fan)
n_X_pump_dis=test71(D_HP_C, D_HP_N, D_HP_E, D_HP_W, D_HP_S, D_fan,
D_pump, D_boiler, D_tower, D_pump)
n_X_boiler_dis=test71(D_HP_C, D_HP_N, D_HP_E, D_HP_W, D_HP_S, D_fan,
D_pump, D_boiler, D_tower, D_boiler)
n_X_tower_dis=test71(D_HP_C, D_HP_N, D_HP_E, D_HP_W, D_HP_S, D_fan,
D_pump, D_boiler, D_tower, D_tower)
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