ENERGY AND EXERGY ANALYSES
OF
A HIGH SCHOOL HEATING SYSTEM

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Approval of the Graduate School of Natural and Applied Sciences.

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This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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ABSTRACT

ENERGY AND EXERGY ANALYSES OF A HIGH SCHOOL HEATING SYSTEM

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This thesis presents energy, exergy and economic analyses of the heating system of an existing building, the Konya Central Informatics Technical High School. The heat requirement for each room of the building is found by calculating heat losses. Radiator lengths that can provide the heat requirements are selected. For the exergy analysis, the system is divided into three parts: Heat generator, radiators and rooms. Comparisons are made according to minimum outdoor temperature, insulation quality of the structural elements, fuel type, heating water temperature and heat generator type (boiler, heat pump, cogeneration unit with heat pump) to see their effects on energy usage, exergy consumption, capital costs and annual operating cost of the system. Results show that the largest heat loss is due to infiltration but it should not be reduced because of the fresh air requirement. Minimum energy usage, exergy consumptions and annual operating cost is achieved by using the cogeneration unit with the heat pump. However, due to high capital cost it has a long payback period (45.3 years). The shortest payback period (3.2 years) is calculated for upgrading the windows to 4 mm double glass panes and 12 mm stagnant air gap.

Keywords: High school heating system, energy, exergy

ÖZ

BİR LİSE ISITMA SİSTEMİNİN
ENERJİ VE EKSERJİ ANALİZİ

Dilek, Murat
Yüksek Lisans, Makina Mühendisliği Bölümü
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Bu tez, mevcut bir bina olan Konya Merkez Bilişim Meslek Lisesi'nin ısıtma sisteminin ekserji, enerji ve ekonomik analizini sunmuştur. Binanın her odası için ısıtma gereksinimi, ısı kaybı hesaplanarak bulunmuştur. Isıtma gereksinimini karşılayacak radyatör boyları seçilmiştir. Ekserji analizi için sistem üç bölüme ayrılmıştır: Isı üretici, radyatörler ve odalar. Enerji kullanımı, ekserji tüketimi, sistemin ilk yatırım ve yıllık işletme maliyetine olan etkilerini görmek amacıyla en düşük dış hava sıcaklığı, yapı bileşenlerinin ısı yalıtımı, yakıt türü, sıcak su rejimi ve ısı üreticinin türüne (kazan, ısı pompası, kojenerasyon ile ısı pompası) göre kıyaslamalar yapılmıştır. Sonuçlar göstermiştir ki en yüksek ısı kaybı infiltrasyondan dolayıdır fakat bu değer taze hava ihtiyacı nedeniyle düşürülmemelidir. En düşük enerji kullanımı, ekserji tüketimi ve yıllık işletme maliyeti, kojenerasyon ünitesinin ısı pompası ile kullanılması ile elde edilir, fakat yüksek sermaye maliyeti nedeniyle uzun bir geri ödeme süresine sahiptir (45.3 yıl). En kısa geri ödeme süresi (3.2 yıl) pencerelerin kalitesinin 12 mm hava boşluklu 4 mm'lik çift cama yükseltilmesi durumunda hesaplanmıştır.

Anahtar Kelimeler: Lise ısıtma sistemi, enerji, ekserji

To My Family

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A	Area [m^2]
C_P	Constant pressure specific heat [kJ/kg K]
C_v	Constant volume specific heat [kJ/kg K]
e	Specific flow exergy [kJ/kg]
$\dot{E}$	Flow exergy rate [W] or [kW]
g	Acceleration of gravity [m/s^2]
h	Specific enthalpy [kJ/kg]
$\dot{I}$	Irreversibility rate [W] or [kW]
$\dot{m}$	Mass flow rate [kg/s]
M	Molecular mass [kg/kmol]
n	Mole number
P	Pressure [kPa]
$\dot{Q}$	Heat transfer rate [W]
R	Thermal resistance [m^2K/W]
s	Specific entropy [kJ/kg K]
T	Temperature [^oC]
U	Overall heat transfer coefficient [W/m^2 K]
v	Specific volume [m^3/kg]
V	Velocity [m/s]
$\dot{W}$	Power [W]
z	Height [m]

Subscripts

cond	Conduction
conv	Convection

CV	Control volume
D	Destruction
ECW	Exterior concrete wall
EW	Exterior wall
f	Saturated liquid
gen	Generation
i	Infiltration
ICW	Interior concrete wall
ID	Interior door
IW	Interior wall
L	Loss
liq	Liquid
p	product
r	reactant
rad	Radiator
RC	Roof ceiling
ref	Reference
0	Ambient

Superscripts

CH	Chemical
KN	Kinetic
PH	Physical
PT	Potential

Greek Letters

ε	Exergetic efficiency
φ	Exergy factor: Chemical exergy/lower heating value ratio
η	Efficiency

CHAPTER 1

INTRODUCTION

1.1 The Intention of the Thesis

There is an increasing attention to exergy analysis during recent decades, especially after the first “oil crisis” in 1973 (e.g., [1],[2],[3]). Due to the decrease of fossil fuels, developing thermal systems that effectively use energy resources such as oil, natural gas and coal is important. Effective use is determined with both the first and second laws of thermodynamics. According to the first law, energy cannot be destroyed or created. According to the first and second laws, exergy can be destroyed but not created. The idea that something can be destroyed is useful in the design and analysis of thermal systems. Moreover, it is exergy and not energy properly gauge the quality of energy. The exergy value of heat, or its capacity to perform useful work, can contribute to the formation of a good basis for determining a fair economic price for heat. The exergy method is used in different places. Power plants, air cooling systems and heating systems are some of them.

The main intention of the thesis is to derive a simplified analysis of energy and exergy usage in a high school heating system and to point out the effects of different factors on energy and exergy usage and costs.

1.2 Literature Survey

The paper ‘Analysis of Exergy Losses in Domestic Heating Systems‘ by Skorek and Kruppa [4] presents an energy and exergy analysis of domestic heating systems. Two types of heat source are considered for the system, a natural gas fired boiler and a heat pump. Exergy losses in the system elements, and energy and exergy usage of the system are calculated. Additionally, the influence of the heating water temperature on the consumption values is presented. The results show that the energy and exergy consumptions can be reduced by decreasing the heating water temperature when a heat pump is used as the heat generator.

The paper ‘Energy, Exergy and Space Heating System’ by Prek [5] gives an example of exergy analysis for heating of a residential house. The analysis is made by separating the whole system into two elements called combustion and heat transfer. The energy and exergy efficiency values for the boiler, the exergy factor for the radiators and the exergetic efficiency for the whole system are calculated. The calculations are repeated for different heating water temperatures. It is concluded that the largest amount of exergy destruction occurs in the boiler and the exergetic efficiency of the boiler is very low in spite of the high energy efficiency. Improvements in the exergetic efficiency must therefore be found by matching exergy supply and exergy demand, rather than by improving the boiler energy efficiency.

The paper ‘Exergy Analysis of HVAC Systems for a House in Montreal’ by Wu and Zmeureanu [6] presents the integrated energy, entropy and exergy analysis of the HVAC system of a house in Montreal. These analyses are done for three systems: space heating; ventilating; and domestic water heating. According to alternatives for each of these three systems, 17 different combinations are investigated in the paper. Results are reported both at annual operating conditions and at peak design conditions. From the calculations the best one of these 17 alternatives in terms of exergy utilizes the combination of radiant floor heating with ground source heat pump for heating; air-to-air heat exchanger and earth tube heat exchanger for ventilating; and, both ground source heat pump and gas-fired water heater for domestic water heating.

The paper ‘Effects of Common Fuel and Heating System Options on the Energy Usage, Pollutant Emissions and Economy’ by Ileri and Moshiri [7] focuses on the effects of fuel and heating system selection on energy consumption and air pollution. Values are calculated for four locations in Turkey to see the effect of climate. For individual, central and district heating systems economic analyses are given. It is concluded that the district natural gas and fuel-oil systems are the cheapest and they are recommended for comfort, economy and environment. Due to the following reasons coal, lignite and direct heating with electricity are not suggested: for coal, difficult control and discomfort; for lignite, high SO_2 discharge; for direct heating with electricity, low efficiency.

The paper ‘Exergy Analysis and Experimental Study of Heat Pump Systems’ by Bilgen and Takahashi [8] presents an exergy analysis and experimental study of a heat pump system. The Matsushita room air conditioner CS-XG28M is selected for the experimental study. The coefficient of performance and efficiency values for both energy and exergy analyses are derived. For the system, a simulation program is developed according to exergy relations. It is concluded that the performance of the heat pumps may be improved by 20 to 30 % when optimum design is achieved.

CHAPTER 2

BUILDING HEATING SYSTEMS

2.1 Introduction

Space heating is one of the major energy demands. For example, in Turkey, 35% of the total primary energy consumption is consumed in buildings, and 80% of this amount is for space heating [7] [9]. Such a high level of energy usage shows the importance of the optimization of the heating system. The selection of the system, building construction and fuel, which affects the energy and exergy analyses, capital cost and annual operating cost of space heating, is very important for this optimization.

2.2 Variety of Heating Systems

2.2.1 Boiler System

The boiler is the heat generator in this system. Heat can be generated by using electric current or by a combustion reaction. The most common way is by combustion in which the chemical energy of the fuel is converted to heat and this heat is transferred to the heating water in the boiler. Then the heating water is pumped to the radiators. The radiators are placed in the spaces that will be heated. While the heating water flows through the radiators, heat is transferred from the heating water to the heated space, and then heating water returns back to the boiler. A schematic drawing of a boiler system is given in Figure 1.

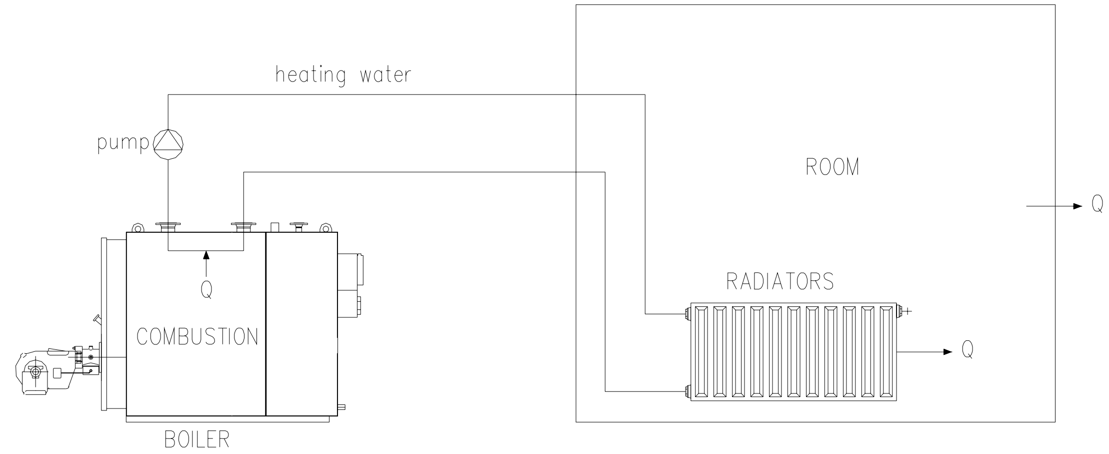

Figure 1 Schematic drawing of a boiler system

2.2.2 Heat Pump System

A heat pump, in the common thermodynamic sense, is a system in which refrigeration components (compressors, condensers, evaporators and expansion devices) are used in such a manner as to take heat from a low temperature source like air, water, ground, etc. and give it to a high temperature sink [10]. The energy needed to drive a heat pump can be provided by electricity or fossil fuels.

In this study an air to water heat pump which is driven by electricity is considered. The heat pump system is the same with the boiler system except that the heat generator is a heat pump instead of boiler. The schematic drawing of a heat pump system is given in Figure 2.

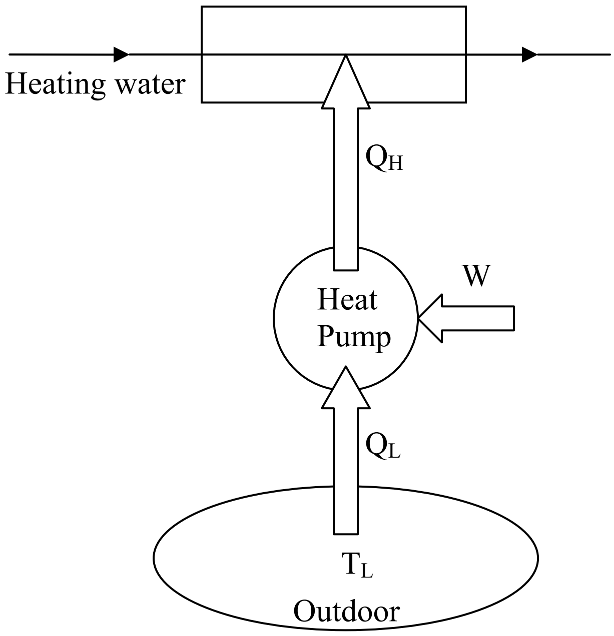

Figure 2 Schematic drawing of a heat pump system

2.2.3 Cogeneration Unit Powered Heat Pump

Cogeneration is the production of electrical energy and useful thermal energy from the same energy source. In conventional electricity generation, only a small portion of the chemical energy in the fuel is converted into electricity and the remaining is lost as waste heat. Cogeneration reduces this loss by using part of this waste heat.

In this study, a natural gas fired cogeneration unit will be considered. The electrical energy will be used to drive an air source heat pump. The schematic drawing of the system is given in Figure 3.

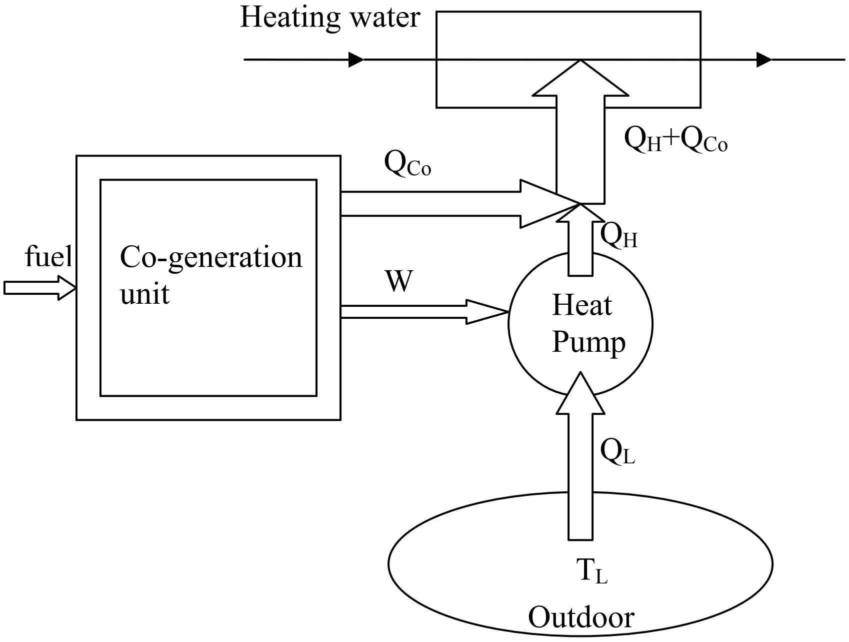

Figure 3 Schematic drawing of a cogeneration unit powered heat pump system

CHAPTER 3

ENERGY ANALYSIS

3.1 Introduction

The temperature difference between the inside and outside of a building causes heat loss in the winter months. The greater this difference, the higher the heat loss rate of the building. Since the inside temperature of buildings must be kept in a suitable range for thermal comfort, heat loss increases with decreasing outside temperature. Wind also increases the heat loss during the winter since moving air is more efficient at removing heat from walls and roofs. Shrubs and windbreaks to keep the high winds from impacting the walls will help reduce this energy loss. Winds can also force their way through cracks in the structure, causing infiltration and drafts [11].

3.2 Heat Loss

The rate of heat transfer from a building during the coldest periods in the winter is called the design heat loss. Ordinarily it is made up of two basic quantities: transmission heat losses ($\dot{Q}_{\text{transmission}}$), which are the heat losses through the walls, roof, floor, window surface and door surface; and, the infiltration heat loss ($\dot{Q}_{\text{i}}$), which is the heat needed to raise the temperature of the cold air that is entering the room through window and door cracks [11]. The total heat loss of a room can be calculated as,

$$\dot{Q}_{\text{room}} = \dot{Q}_{\text{transmission}} + \dot{Q}_{\text{i}} \tag{1}$$

3.2.1 Transmission Heat Losses

According to the publication of the Mechanical Engineering Chamber [12], the rate of transmission heat loss can then be calculated as,

$$\dot{Q}_{\text{transmission}} = \dot{Q}_{\text{net}} \cdot (1 + \frac{Z_D + Z_H + Z_W}{100}) \tag{2}$$

where, Z_D is a coefficient based on operating period of the heating system (see Table B.1 in Appendix B), Z_H is a coefficient based on the direction of the exterior walls of the room (see Table B.2); and Z_W is a coefficient based on the total number of floors in the building and the floor of the room considered (see Table B.3).

The net rate of transmission heat loss ($\dot{Q}_{\text{net}}$) is calculated as,

$$\dot{Q}_{\text{net}} = \sum \dot{Q}_{\text{walls}} + \sum \dot{Q}_{\text{windows}} + \sum \dot{Q}_{\text{door}} + \sum \dot{Q}_{\text{ceiling}} + \sum \dot{Q}_{\text{floor}} \tag{3}$$

The heat transfer rate through the wall, roof, floor, window and door can be calculated as,

$$\dot{Q} = U \cdot A \cdot \Delta T \tag{4}$$

Here U refers to overall heat transfer coefficient; A is the heat transfer area and ΔT is the temperature difference between the two sides of the wall, roof, floor, window or door.

The overall heat transfer coefficient can be calculated as,

$$R = \frac{1}{h_i \cdot A} + \frac{L_1}{k_1 \cdot A} + \frac{L_2}{k_2 \cdot A} + \frac{L_3}{k_3 \cdot A} + \ldots + \frac{1}{h_e \cdot A} \tag{5}$$

$$U = \frac{1}{R \quad \cdot A} \tag{6}$$

where R is thermal resistance, L is the slab thickness, k is thermal conductivity, and h_i and h_e are inner and outer film coefficients ,respectively.

3.2.2 Infiltration Heat Loss

From the window and door cracks the air of the building shifts because of the pressure difference between the inside and outside causing cold outside air to enter and warm air to leave. The cold air, which leaks inside, must be heated to the room temperature. The amount of heat required for this process is called the infiltration heat requirement and its exact value is very difficult to calculate.

The heat loss caused by infiltration can be calculated approximately as,

$$\dot{Q}_i = \sum a \cdot L \cdot R \cdot H \cdot \Delta T \cdot Z_e \tag{7}$$

where,

a: Air infiltration coefficient (m^3/m.h) (Table B.4)
L: Circumference of window/door area that can be opened. (m)
R: Coefficient based on air flow in the room. Its value is given according to the window area / interior door area ratio. (Table B.5)
H: Building position coefficient (kW.h/m^3.K) (Table B.6)
Z_e: Coefficient based on number of walls with windows. (-) (Table B.7)

3.3 Heat Supply

The heat loss value of each room in the building gives the heat requirement for this room. To provide this requirement, radiators are used. For small spaces, where mechanical ventilation is not required, heating with radiators is the most common application. The heat is transferred from the heating water through the radiators' surfaces to the heated space. A heat generator like a boiler, heat pump or co-generation unit supplies this heating water. Heating water flows inside insulated pipes from the heat generator to radiators.

Summing $\dot{Q}_{\text{room}}$ across all rooms yields $\dot{Q}_{\text{building}}$. The rate of heat transfer to the heating water in the heat generator can be calculated as,

$$\dot{Q}_{\text{building}} = \dot{m}_{\text{water}} \cdot (h_{\text{water out}} - h_{\text{water in}}) \tag{8}$$

where $\dot{Q}_{\text{building}}$ is the total heat requirement of the building, $h_{\text{water out}}$ is the enthalpy of the outlet water from the generator and $h_{\text{water in}}$ is the enthalpy of the inlet water to the generator. The inlet and outlet temperatures of the heating water designate the regime of the heating system. In this study, the performance of different heat generators is investigated for a number of regimes.

In a boiler, the heat output is generally during combustion reaction. In combustion, the oxidation of combustible elements in the fuel releases energy as combustion products are formed. The three major combustible chemical elements in the most common fuels are carbon, hydrogen and sulfur. A fuel is said to have undergone complete combustion if all of the carbon present in the fuel is burned to carbon dioxide, all of the hydrogen is burned to water and all of the sulfur is burned to sulfur dioxide. The minimum amount of air that supplies sufficient oxygen for the complete combustion of all of the combustible chemical elements is called the theoretical or stoichiometric amount of air. In practice the amount of air may be greater than or less than the theoretical amount. The ratio of the actual fuel-air ratio to the theoretical fuel-air ratio is called the equivalence ratio [3].

$$\text{Equivalence ratio} = \frac{\text{actual fuel} - \text{air ratio}}{\text{theoretical fuel} - \text{air ratio}} \tag{9}$$

The rate of heat output ($\bar{q}_{\text{combustion}}$) during a steady state combustion process is the difference between the rate that enthalpy enters with the reactants and leaves with the products on a per unit mole of fuel basis.

$$\bar{q}_{\text{combustion}} = \sum_{\text{reactant}} n_r \cdot (\bar{h}_f^o + \bar{h} - \bar{h}_o)_r - \sum_{\text{product}} n_p \cdot (\bar{h}_f^o + \bar{h} - \bar{h}_o)_p \tag{10}$$

where n_p is the number of moles of product, n_r is the number of moles of reactant, each on a per mole of fuel basis, $\bar{h}_f^o$ is the enthalpy of formation at the standard reference state of 25^oC and 1 atm, $\bar{h}$ is the enthalpy at the specified state and $\bar{h}_o$ is the enthalpy at the standard reference state [13] .

When complete combustion occurs and both reactants and products are at the same temperature and pressure, the difference between the enthalpy of the products and the enthalpy of the reactants is the enthalpy of combustion. The heating value of a fuel is a positive number equal to the magnitude of the enthalpy of combustion. If all of the water formed by combustion is liquid this value is called the higher heating value; if all of the water formed by combustion is vapor the value is called the lower heating value [3].

3.4 Conventional Efficiency of the Boiler

Each component in a heating system has a different first law efficiency. The largest energy loss occurs from the boiler to the technical room. This heat loss from the boiler body to the surroundings is quantified as the conventional boiler efficiency.

$$\eta_{boiler} = \frac{\dot{Q}_{building}}{\dot{m}_{fuel} \cdot q_{combustion}} \tag{11}$$

where $\dot{m}_{fuel}$ is the mass flow rate of the fuel, and $q_{combustion}$ is the heat output during combustion on a mass of fuel basis and can be calculated as,

$$q_{combustion} = \frac{\overline{q}_{combustion}}{M_{fuel}} \tag{12}$$

where M_{fuel} is the molecular mass of the fuel.

CHAPTER 4

EXERGY ANALYSIS

4.1 Introduction

An opportunity for doing useful work exists whenever two systems at different states are placed in communication, for in principle work can be developed as the two are allowed to come into equilibrium. When one of the two systems is a suitable idealized system called the environment and the other is some system of interest, exergy is the maximum theoretical useful work obtainable as the systems interact to equilibrium and heat transfer occurs with the environment only. Exergy can be represented in terms of four components: Physical, kinetic, potential and chemical [3].

$$E = E^{PH} + E^{KN} + E^{PT} + E^{CH} \qquad (13)$$

Or the total specific exergy can be defined as,

$$e = e^{PH} + e^{KN} + e^{PT} + e^{CH} \qquad (14)$$

4.2 Definitions

4.2.1 Environment

The environment is the part of the universe, outside the system boundary for which the intensive properties of each phase are uniform and do not change significantly as a result of interactions with the system [3].

4.2.2 Dead State

Equilibrium means a condition of balance. Thermal equilibrium refers to an equality of temperature, mechanical equilibrium to an equality of pressure and chemical equilibrium to an equality of chemical potentials. For complete thermodynamic equilibrium, all three of these types of equilibrium must exist individually.

When the temperature, pressure, composition, velocity and/or elevation of a system is different from the environment, there is an opportunity to do useful work. As the system changes state towards that of the environment, this opportunity diminishes, ceasing to exist when the two reach complete equilibrium. This state where the system is in complete equilibrium with the environment is called the dead state [3] as shown in Figure 4.

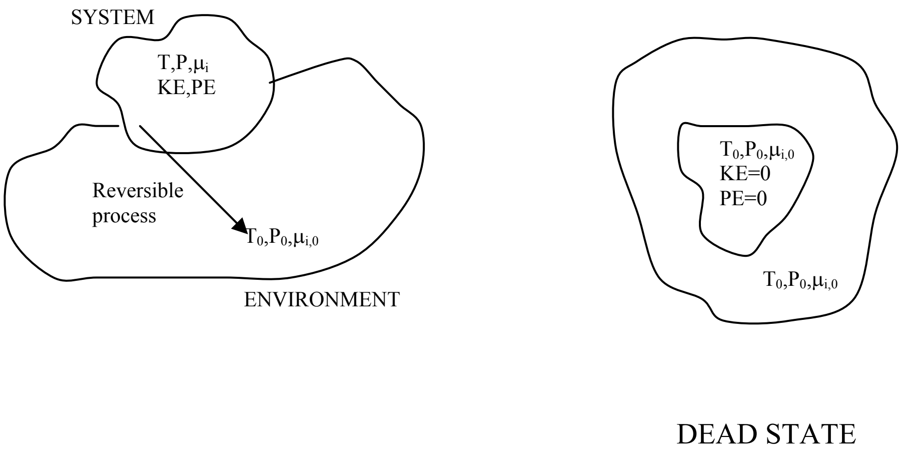

Figure 4 Schematic drawing of the Dead State

4.2.3 Restricted Dead State

The restricted dead state is a restricted form of equilibrium where only the conditions of mechanical (no pressure gradiants) and thermal (no temperature gradiants) equilibrium must be satisfied. At the restricted dead state, the fixed quantity of matter under consideration is imagined to be sealed in an envelope impervious to mass flow, at zero velocity and elevation relative to coordinates in the environment and at the temperature T_0 and pressure P_0 [3] as shown in Figure 5.

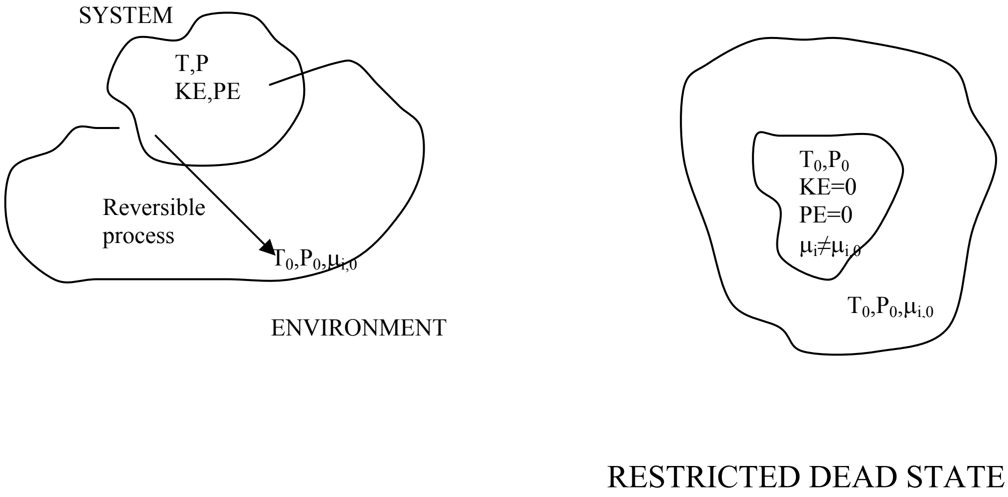

Figure 5 Schematic drawing of the Restricted Dead State

4.3 Physical Exergy

Physical exergy is the maximum theoretical useful work obtainable as the system, which is at rest relative to the environment ($e^{KN} = e^{PT} = 0$), passes from its initial state to the restricted dead state [3].

The physical component of the exergy transfer associated with a stream of matter is called flow exergy and can be written as [3],

$$e^{PH} = (h-h_0) - T_0(s-s_0) \tag{15}$$

Equation (15) can be formed for ideal gases with specific heat at constant pressure (C_P) as,

$$e_{gas}^{PH} = C_P \cdot T_0 \cdot \left[\frac{T}{T_0} - 1 - \ln(\frac{T}{T_0}) \right] + R \cdot T_0 \cdot \ln(\frac{P}{P_0}) \tag{16}$$

For an incompressible substance with constant specific heat C, Equation (15) can be written as ,

$$e_{liq}^{PH} = C \cdot T_0 \cdot \left[\frac{T}{T_0} - 1 - \ln(\frac{T}{T_0}) \right] \tag{17}$$

4.4 Kinetic and Potential Exergy

The kinetic and potential energy of a system are in principle fully convertible to work as the system is brought to rest relative to the environment so they are equal to the kinetic and potential exergies:

$$e^{KN} = V^2/2 \tag{18}$$

$$e^{PT} = gz \tag{19}$$

4.5 Exergy Balance

4.5.1 Exergy Transfer Associated with Heat Transfer

The rate of exergy transfer associated with heat transfer can be expressed as,

$$\dot{E}_q = (1 - \frac{T_0}{T_b})\dot{Q} \tag{20}$$

where $\dot{E}_q$ denotes the exergy transfer rate with heat transfer and T_b denotes the temperature at the boundary where exergy transfer by heat transfer occurs .

4.5.2 Exergy Transfer Associated with Mechanical Power

The exergy transfer rate associated with mechanical power can be expressed as,

$$\dot{E}_w = \dot{W} - P_0 \frac{dV}{dt} \tag{21}$$

where $\dot{E}_W$ is the exergy transfer rate of mechanical power.

In steady state or rigid systems, the atmospheric work term $P_0 \frac{dV}{dt}$ is zero and Equation (21) becomes [2],

$$\dot{E}_w = \dot{W} \tag{22}$$

4.5.3 Exergy Balance for Steady-State Steady-Flow Process

Exergy is an extensive property. It can be transferred into or out of a control volume with heat, work and streams of matter entering or exiting. The steady-state steady-flow model is used to analyse systems that operate continuously like turbines, compressors, heat exchangers, etc. According to this model, an exergy balance for a control volume can be written as [3],

$$0 = \sum \dot{E}_q - \dot{W}_{CV} + \sum_{in} (\dot{m}e)_{in} - \sum_{out} (\dot{m}e)_{out} - \dot{E}_D \tag{23}$$

where CV refers to control volume.

4.6 Chemical Exergy

Chemical exergy is the exergy component associated with the departure of the chemical composition of a system from that of the environment [3]. For simplicity, the standard chemical exergy, which is determined relative to a standard environment, is considered. Standard chemical exergy is based on standard compositions of the environment at temperature T_0 and pressure P_0. There are two standard exergy reference environments accepted for engineering evaluations. The first model is based on the equilibrium requirement of the thermodynamic theory and the chemical composition of the gas phase of this model approximates satisfactorily to the composition of the natural atmosphere. However, on an overall basis the second model presents an exergy reference environment with closer chemical composition to the composition of the natural environment. In this model, a reference substance is selected for each chemical element being considered and that are abundantly present in the natural environment. Calculated standard chemical exergy values for selected substances according to these two reference environment models can be taken from tables [3].

The standard chemical exergy of a substance not present in the environment can be evaluated by considering a reversible reaction of the substance with other substances found in large quantities in the environment for which the chemical exergies are known. In Figure 6 [3] a pure hydrocarbon fuel C_xH_y at T_0, P_0 reacts reversibly with oxygen to form carbon dioxide and liquid water. All substances are assumed to enter and exit unmixed at T_0, P_0 and heat transfer is only at temperature T_0.

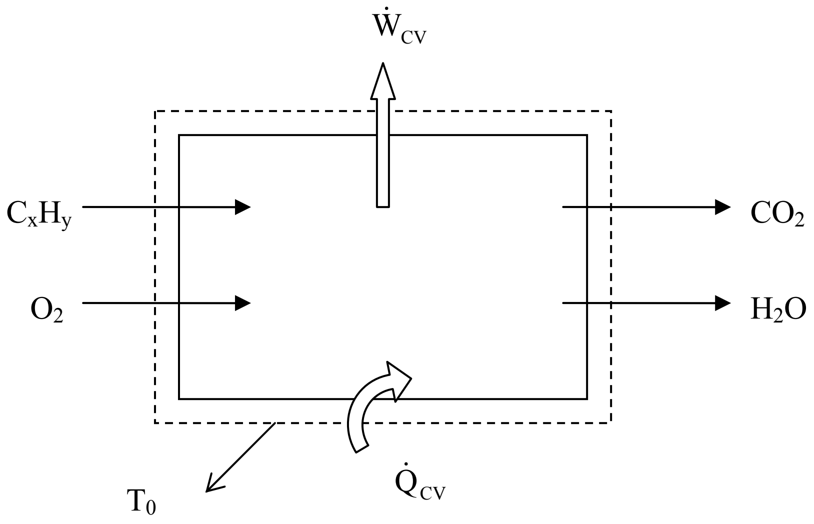

Figure 6 Device for evaluating the chemical exergy of a hydrocarbon fuel, C_xH_y

Assuming no irreversibilities, an exergy balance for the system can be written by using Equation (23) as [3],

$$\begin{aligned} 0 = \sum\left(1-\frac{T_0}{T_b}\right)\cdot\frac{\dot{Q}}{\dot{n}_{fuel}} - \left(\frac{\dot{W}_{CV}}{\dot{n}_{fuel}}\right)_{intrev} + \bar{e}^{CH}_{fuel} + \left(x+\frac{y}{4}\right)\cdot\bar{e}^{CH}_{O_2} \\ - x\cdot\bar{e}^{CH}_{CO_2} - \frac{y}{2}\cdot\bar{e}^{CH}_{H_2O(l)} - \dot{E}_D \end{aligned} \qquad (24)$$

where $\dot{n}$ denotes a molar flow rate and $(\sum(1-\frac{T_0}{T_b})\cdot\frac{\dot{Q}}{\dot{n}_{fuel}})$ term is zero because $T_b=T_0$. Applying the first and second low to this reaction, the work term can be written as [3],

$$(\frac{\dot{W}_{CV}}{\dot{n}_{fuel}})_{intrev}=\overline{HHV}-T_0\cdot\left[\bar{s}_{fuel}+(x+\frac{y}{4})\cdot\bar{s}_{O_2}-x\cdot\bar{s}_{CO_2}-\frac{y}{2}\cdot\bar{s}_{H_2O(l)}\right] \tag{25}$$

where, $\overline{HHV}$ is the higher heating value on mole basis defined at 25°C and 1 atm and all $\bar{s}$ are absolute entropy values defined at 25°C and 1 atm. Using Equations (24) and (25),

$$\begin{aligned}\bar{e}^{CH}_{fuel}=\overline{HHV}-T_0\cdot&\left[\bar{s}_{fuel}+(x+\frac{y}{4})\cdot\bar{s}_{O_2}-x\cdot\bar{s}_{CO_2}-\frac{y}{2}\cdot\bar{s}_{H_2O(l)}\right]\\&-(x+\frac{y}{4})\cdot\bar{e}^{CH}_{O_2}+x\cdot\bar{e}^{CH}_{CO_2}+\frac{y}{2}\cdot\bar{e}^{CH}_{H_2O(l)}\end{aligned} \tag{26}$$

In Equation (26) the value of the $\bar{s}_{fuel}$ term is not known for all fuels. To simplify the calculation of the chemical exergy of fuels, it is assumed that the ratio of the chemical exergy to the lower heating value for solid and liquid industrial fossil fuels, termed the exergy factor (φ), is the same as that for pure chemical substances having the same ratios of constituent chemicals. After computing values of this exergy factor for numerous pure organic substances containing C, H, O, N and S, correlations expressing the dependence of φ on the atomic ratios H/C, O/C, N/C and in some cases S/C were derived. It is seen that the applicability of the expressions obtained can be extended to cover industrial fossil fuels [1]. Therefore, in this research, the chemical exergy is assumed to be approximated by,

$$e^{CH}_{fuel}=\varphi\cdot LHV \tag{27}$$

where LHV is the lower heating value of the fuel.

4.7 Exergetic Efficiency

The exergetic efficiency is a parameter for evaluating thermodynamic performance. The exergetic efficiency (also called second-law efficiency, effectiveness, or rational efficiency) provides a true measure of the performance of an energy system from the thermodynamic viewpoint.

In defining the exergetic efficiency it is necessary to identify both a product and a fuel for the thermodynamic system being analysed. The product represents the desired result produced by the system and the fuel represents the resources expended to generate the product. Exergetic efficiency refers to an exergy comparison of the product of a process with the fuel [14], so a general expression for exergetic efficiency can be written as,

$$\varepsilon = \frac{\dot{E}_P}{\dot{E}_{fuel}} \tag{28}$$

where $\dot{E}_P$ is the exergy rate of the product. As an illustration, for a system at steady state the exergy rate balance is,

$$\dot{E}_{fuel} = \dot{E}_P + \dot{E}_D + \dot{E}_L \tag{29}$$

where $\dot{E}_D$ and $\dot{E}_L$ denote the rate of exergy destruction and exergy loss, respectively. In this study, the term irreversibility ($\dot{I}$), defined as the summation of exergy loss and exergy destruction, is used.

$$\dot{I} = \dot{E}_D + \dot{E}_L \tag{30}$$

From Equations (28) - (30) the exergetic efficiency of a hot water boiler is,

$$\varepsilon_{boiler} = \frac{\Delta\dot{E}_{water}}{\dot{E}_{fuel}} = 1 - \frac{\dot{I}_{boiler}}{\dot{E}_{fuel}} \tag{31}$$

where $\dot{I}_{\text{boiler}}$ is the irreversibility in the boiler and $\Delta\dot{E}_{\text{water}}$ is the exergy difference between the boiler outlet and boiler inlet for the heating water.

An exergy analysis based on consumption of primary fuels is a more meaningful method to compare the different heating systems than one based on direct exergy consumption (i.e., exergy supplied to the building). Such an analysis accounts for the exergetic efficiency of electricity production from the primary fuel at the power station (ε_{el}) and the exergetic efficiency of electricity transformation and transmission (ε_{tr}) for the electricity used by the heat pump. In addition, for the different fuels the cumulative exergetic efficiency of fuel mining, reprocessing and transporting (ε_{cum}) must be taken into account. These relations are given below [4].

$$\dot{I}_{\text{system (primary)}} = \frac{\dot{I}_{\text{system (direct)}}}{\varepsilon_{\text{el}} \cdot \varepsilon_{\text{tr}}} \tag{32}$$

$$\dot{I}_{\text{system (cum)}} = \frac{\dot{I}_{\text{system (primary)}}}{\varepsilon_{\text{cum}}} \tag{33}$$

where $\dot{I}_{\text{system (primary)}}$ denotes the primary irreversibility rate for the system and $\dot{I}_{\text{system (cum)}}$ is the cumulative irreversibility rate of the system. The direct and primary irreversibility rates are equal to each other for a boiler system and are presented as $\dot{I}_{\text{boiler system}}$.

CHAPTER 5

ANALYSIS OF THE SYSTEM

5.1 Introduction

In this chapter energy and exergy analyses of the heating system of a three floor high school building in Konya are performed. First, the existing system is considered. To show the calculation method a classroom is selected and calculations are performed. Results for other heated spaces are given in tables. Simulations are then performed exploring the effects of the following factors:

- Outdoor temperature
- Thermal insulation grade
- Fuel type (natural gas, fuel oil, coal)
- Heating water temperature of the system (90-70 ^{o}C, 75-65 ^{o}C, 80-60 ^{o}C, 50-35 ^{o}C)
- Heat generator (boiler, heat pump, cogeneration unit powered heat pump)

5.2 Description of the System

Konya Central Informatics Technical High School is an educational building with 16 classrooms. It is located in the Yazır district in the center of Konya, Turkey. The general plan of the school area is given in Figure 7. It is a three floor building with an additional basement floor shown in Figure 8. There is a technical center on the basement floor. The boiler, pumps and expansion tank of the heating system are in the technical center. In the existing system, natural gas is used as the fuel and analyses are repeated for other fuels. There is also a potable hot water system in the technical center, and this system will not be taken into consideration because it is not related to the space heating system. Electrical water heaters provide the potable hot water requirement of the school, so no supply from the boiler is needed for potable water. The heating load of the boiler depends only on the heat loss rate from the building. Radiators are used to heat the rooms. The heating water, which is flowing through the radiators, is supplied by the boiler with a temperature regime of 90-70^{o}C. The 90^{o}C hot boiler outlet water goes through the expansion tank and is pumped to the radiators. The water, which loses heat in the radiators, then returns to the boiler. This circulation water flows inside well insulated pipes. In the existing system, natural gas is used as the fuel, so the expansion tank is a closed type and located in the technical room. In addition, there is an automatic control system mounted to the boiler. The working period of the burner is controlled automatically by this control system to maintain the 70^{o}C boiler inlet water temperature. In this study, other heating water temperatures will be examined to see the differences in performance.

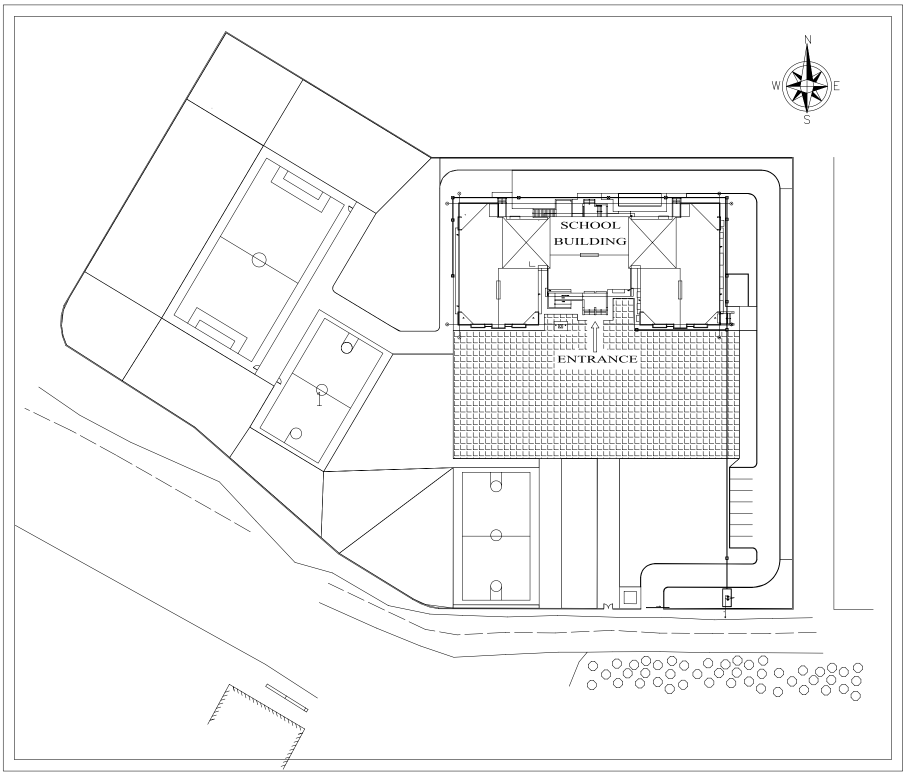

Figure 7 General plan of school area

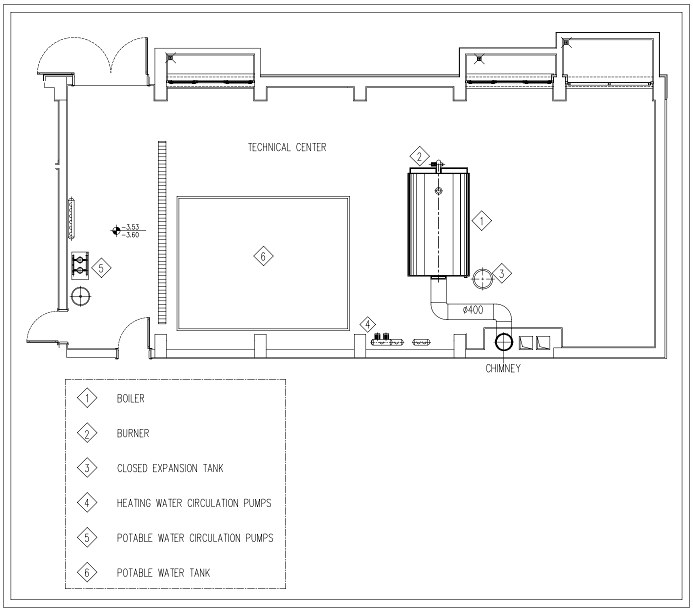

Figure 8 Schematic drawing of Technical Center of the building

5.3 Energy Analysis

5.3.1 Heat Loss Calculation

5.3.1.1 Defining Neighbors of the Heated Room

The heat loss calculation will be performed for Classroom 203. In Figure 9 Classroom 203 and its neighboring spaces on the same floor are shown. To provide a conservative heat loss estimate, heat gains from warmer neighboring spaces are neglected and heat loss via transmission to colder neighboring spaces is accounted for. The room temperatures that are used in the present study are given in Table 1. In the table, the room temperatures are the values given in the publication of the Chamber [12] for thermal comfort. The minimum outdoor temperature for winter in Konya is taken as -12^{o}C [12].

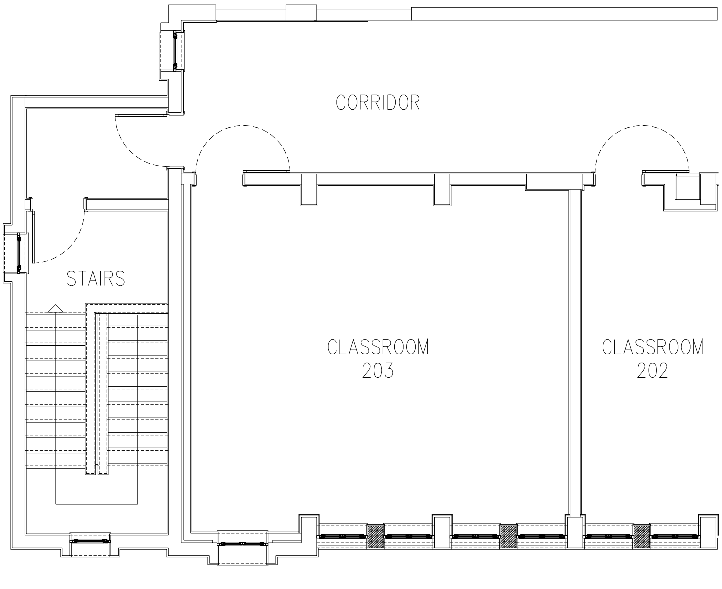

Figure 9 Partial drawing of the second floor

Table 1 Room temperatures [12]

Room	**Temperature (^oC)**	**Room**	**Temperature (^oC)**
Infirmary	24	Activity Room	22
Dressing Room	24	Worker Room	22
Classroom	22	WC	18
Teachers Room	22	Prep.Room	18
Meeting Room	22	Corridor	18
Computer Room	22	Laboratory	18
Library	22	Canteen	18
Official	22	Workshop	18
Manager room	22	Shelter	18
Publication	22	Training Hall	18
Music Room	22	Storage	15
Guidance	22	Equipment Room	15
Manager Assistant	22	Archive	15
Social Room	22		

5.3.1.2 Overall Heat Transfer Coefficient Calculation

The overall heat transfer coefficients are calculated using Equations (5) and (6), and calculations for the walls, ceiling and floor are summarized in Tables 2-6. In the Appendix A, the heat conduction coefficients of structure components are given in Table A.1 and the heat convection coefficients are given in Table A.3 [15]. The overall heat transfer coefficients for a range of windows and doors are given in Table A.2 [15]. In the existing building the heat transfer coefficient for the windows is 3.00 W/m^2K and the heat transfer coefficient for the doors is 5.50 W/m^2K.

Table 2 Overall heat transfer coefficient calculation for the exterior wall

OVERALL HEAT TRANSFER COEFFICIENT (U-FACTOR) CALCULATION					
ITEM	**DESCRIPTION**	**THICKNESS** **[mm]**	**HEAT TR. FILM COEF.** **h** **[W / m² K]**	**THERMAL CONDUCTIVITY** **k** **[W / m K]**	**THERMAL RESISTANCE** **R** **[m² K / W]**
1	**Exterior Walls**				
1.1	Indoor air film, still air, vertical surface, horizontal heat flow		7.692		0.130
1.2	Plaster	5.0		0.700	0.007
1.3	Plaster Clipboard	12.0		0.210	0.057
1.4	Extruded Polystrene Insulation (XPS)	40.0		0.031	1.290
1.5	Brick	190.0		0.500	0.380
1.6	Cement Plaster	30.0		1.400	0.021
1.7	Outdoor air film, 24 km/h wind (winter)		25		0.040
	Overall thermal resistance [m² K / W]				1.926
	Overall heat transfer coefficient - U [W / m² K]				**0.519**

Table 3 Overall heat transfer coefficient calculation for the exterior concrete wall

OVERALL HEAT TRANSFER COEFFICIENT (U-FACTOR) CALCULATION					
ITEM	**DESCRIPTION**	**THICKNESS [mm]**	**HEAT TR. FILM COEF. h [W / m^2 K]**	**THERMAL CONDUCTIVITY k [W / m K]**	**THERMAL RESISTANCE R [m^2 K / W]**
2	**Exterior Concrete Walls**				
2.1	Indoor air film, still air, vertical surface, horizontal heat flow		7.692		0.130
2.2	Plaster	5.0		0.700	0.007
2.3	Plaster Clipboard	12.0		0.210	0.057
2.4	Polythene Foil	1.0		0.190	0.005
2.5	Extruded Polystrene Insulation (XPS)	40.0		0.031	1.290
2.6	Concrete	250.0		2.100	0.119
2.7	Cement Plaster	30.0		1.400	0.021
2.8	Outdoor air film, 24 km/h wind (winter)		25		0.040
	Overall thermal resistance [m^2 K / W]				1.670
	Overall heat transfer coefficient - U [W / m^2 K]				**0.599**

Table 4 Overall heat transfer coefficient calculation for the exterior concrete wall-2

OVERALL HEAT TRANSFER COEFFICIENT (U-FACTOR) CALCULATION					
ITEM	**DESCRIPTION**	**THICKNESS [mm]**	**HEAT TR. FILM COEF. h [W / m^2 K]**	**THERMAL CONDUCTIVITY k [W / m K]**	**THERMAL RESISTANCE R [m^2 K / W]**
3	**Exterior Concrete Walls Underground**				
3.1	Indoor air film, still air, vertical surface, horizontal heat flow		5.882		0.170
3.2	Cement Plaster	20.0		0.870	0.023
3.3	Concrete	300.0		2.100	0.143
3.4	Extruded Polystrene Insulation (XPS)	40.0		0.028	1.429
3.5	Brick	85.0		0.500	0.170
	Overall thermal resistance [m^2 K / W]				1.934
	Overall heat transfer coefficient - U [W / m^2 K]				**0.517**

Table 5 Overall heat transfer coefficient calculation for the ceiling

OVERALL HEAT TRANSFER COEFFICIENT (U-FACTOR) CALCULATION					
ITEM	**DESCRIPTION**	**THICKNESS [mm]**	**HEAT TR. FILM COEF. h [W / m² K]**	**THERMAL CONDUCTIVITY k [W / m K]**	**THERMAL RESISTANCE R [m² K / W]**
4	**Ceiling**				
4.1	Indoor air film, still air, horizontal surface, upward heat flow		7.692		0.130
4.2	Plaster	20.0		0.870	0.023
4.3	Concrete	150.0		2.100	0.071
4.4	Rock wool	100.0		0.040	2.500
4.5	Outdoor air film, 24 km/h wind (winter)		13		0.080
	Overall thermal resistance [m² K / W]				2.804
	Overall heat transfer coefficient - U [W / m² K]				**0.357**

Table 6 Overall heat transfer coefficient calculation for the floor

OVERALL HEAT TRANSFER COEFFICIENT (U-FACTOR) CALCULATION					
ITEM	**DESCRIPTION**	**THICKNESS [mm]**	**HEAT TR. FILM COEF. h [W / m² K]**	**THERMAL CONDUCTIVITY k [W / m K]**	**THERMAL RESISTANCE R [m² K / W]**
5	**Floors**				
5.1	Indoor air film, still air, horizontal surface, downward heat flow		5.882		0.170
5.2	Concrete	25.0		1.740	0.014
5.3	Extruded Polystrene Insulation (XPS)	40.0		0.028	1.429
5.4	Concrete	400.0		2.100	0.190
5.5	Filling Concrete	500.0		1.740	0.287
5.6	Water insulation	1.0		0.190	0.005
5.7	Filling Concrete	130.0		1.740	0.075
	Overall thermal resistance [m² K / W]				2.171
	Overall heat transfer coefficient - U [W / m² K]				**0.461**

5.3.1.3 Transmission Heat Loss

The general expression for the rate of transmission heat loss is given in Equation (4). The heat loss rate calculation for Classroom 203 proceeds as follows,

For the window,

$$\dot{Q}_{window} = U_{window} \cdot A_{window} \cdot \Delta T \tag{34}$$

and the heat loss rate through the window is calculated as,

$$\dot{Q}_{window} = 3\,W/m^2K \cdot 9.9\,m^2 \cdot (22 - (-12))K$$
$$\dot{Q}_{window} = 1009.8\ W$$

Using the same procedure, the following heat loss rates are calculated: exterior wall (west), $\dot{Q}_{EW} = 111.2\ W$; exterior concrete wall (west), $\dot{Q}_{ECW} = 193.5\ W$; interior door, $\dot{Q}_{ID} = 52.8\ W$; interior wall, $\dot{Q}_{IW} = 94.2\ W$; interior concrete wall between the classroom and the hall, $\dot{Q}_{ICW} = 66.2\ W$; interior concrete wall between the classroom and the stairs, $\dot{Q}_{ICW} = 842.3\ W$; ceiling, $\dot{Q}_{RC} = 696.5\ W$.

The net rate of heat loss from the room can be calculated as,

$$\dot{Q}_{net} = \dot{Q}_{window} + \dot{Q}_{EW} + \dot{Q}_{ECW} + \dot{Q}_{ID} + \dot{Q}_{IW} + \sum \dot{Q}_{ICW} + \dot{Q}_{RC} \tag{35}$$
$$\dot{Q}_{net} = 3066.5\,W$$

The transmission heat loss is calculated using Equation (2). Z_D is defined for operating III as 25 from Table B.1, Z_H is 0 for west from Table B.2 and Z_W is taken as 0 for second floor from Table B.3. using these values,

$$\begin{aligned}\dot{Q}_{transmission} &= 3066.5\,W \cdot (1 + \frac{25+0+0}{100}) \\ \dot{Q}_{transmission} &= 3833\,W\end{aligned} \tag{36}$$

5.3.1.4 Heat Loss by Infiltration

There is no mechanical ventilation in the room. The heat loss rate by infiltration is calculated using Equation (7),

$$\dot{Q}_i = \sum a \cdot L \cdot R \cdot H \cdot \Delta T \cdot Z_e \qquad (37)$$

$$\dot{Q}_i = 1.5\,\mathrm{m^2/h} \cdot 45.3\,\mathrm{m} \cdot 0.9 \cdot 0.675\ \mathrm{Wh/m^3K} \cdot 34\,\mathrm{K} \cdot 1$$

$$\dot{Q}_i = 1404\,\mathrm{W}$$

The summation of infiltration heat loss and transmission heat loss gives the total heat loss of the room as given by Equation (1).

$$\dot{Q}_{room} = \dot{Q}_{transmission} + \dot{Q}_i \qquad (38)$$

$$\dot{Q}_{room} = 3833\,\mathrm{W} + 1404\,\mathrm{W}$$

$$\dot{Q}_{room} = 5237\,\mathrm{W}$$

A similar procedure is used to calculate the rate of heat loss from other rooms and these results are summarized in Table 7.

5.3.2 Radiator Selection

Heat transfer occurs from the hot water to the rooms via cast iron radiators. According to the heat loss of the rooms, radiator quantities and lengths are defined. The radiator capacities for different heating water temperatures are given in the appendix Table C1-C3 [16]. According to the heat loss values and the radiator capacities, the radiator selections are given in Table 7.

Table 7 Heat loss and radiator selections of rooms

NO.	ROOM NAME	HEAT LOSS (Watts)	ROOM TEMP. (°C)	RAD. TYPE	PIECE	GROUP CAP. (Watts)	GR. QTY	TOTAL HEAT CAP. (Watts)
201	CLASSROOM	5094	22	160/500	10	1280	4	5120
202	CLASSROOM	4186	22	160/500	11	1408	3	4224
203	CLASSROOM	5237	22	160/500	14	1792	3	5376
204	CLASSROOM	5312	22	160/500	11	1408	4	5632
205	MEN WC	801	18	160/500	6	840	1	840
206	WOMEN WC	801	18	160/500	6	840	1	840
207	TEACHERS ROOM	1073	22	160/500	9	1152	1	1152
208	CLASSROOM	4665	22	160/500	13	1664	3	4992
209	MEETING ROOM	6053	22	160/500	12	1536	4	6144
210	LIBRARY	9469	22	160/500	11	1408	7	9856
211	MEN WC	436	18	160/500	4	560	1	560
212	WOMEN WC	402	18	160/500	3	420	1	420
213	WOMEN WC	801	18	160/500	6	840	1	840
214	MEN WC	801	18	160/500	6	840	1	840
215	CLASSROOM	5312	22	160/500	11	1408	4	5632
216	COMPUTER ROOM	6784	22	160/500	11	1408	5	7040
217	PREP.ROOM	1153	18	160/500	9	1260	1	1260
218	LABORATORY	5029	18	160/500	9	1260	4	5040
225	CORRIDOR	10138	18	160/500	10	1400	8	11200
101	CLASSROOM	4221	22	160/500	9	1152	4	4608
102	CLASSROOM	3314	22	160/500	9	1152	3	3456
103	CLASSROOM	4365	22	160/500	12	1536	3	4608

Table 7 (continued)

NO.	ROOM NAME	HEAT LOSS (Watts)	ROOM TEMP. (°C)	RAD. TYPE	PIECE	GROUP CAP. (Watts)	GR. QTY	TOTAL HEAT CAP. (Watts)
104	CLASSROOM	4439	22	160/500	9	1152	4	4608
105	MEN WC	474	18	160/500	4	560	1	560
106	WOMEN WC	474	18	160/500	4	560	1	560
107	STORAGE	521	15	160/500	4	596	1	596
108	CLASSROOM	3993	22	160/500	11	1408	3	4224
109	CANTEEN	3662	18	160/500	7	980	4	3920
110	OFFICIAL	2400	22	160/500	10	1280	2	2560
111	MANAGER ROOM	3702	22	160/500	10	1280	3	3840
112	PUBLICATION	2400	22	160/500	10	1280	2	2560
113	MEN WC	290	18	160/500	3	420	1	420
114	WOMEN WC	290	18	160/500	3	420	1	420
115	WOMEN WC	474	18	160/500	4	560	1	560
116	MEN WC	474	18	160/500	4	560	1	560
117	CLASSROOM	4439	22	160/500	9	1152	4	4608
118	MUSIC ROOM	6074	22	160/500	10	1280	5	6400
119	STORAGE	807	15	160/500	6	894	1	894
120	MECHANICAL WORKSHOP	4492	18	160/500	9	1260	4	5040
124	CORRIDOR	5077	18	160/500	5	700	8	5600
Z01	CLASSROOM	5037	22	160/500	10	1280	4	5120
Z02	CLASSROOM	4074	22	160/500	11	1408	3	4224
Z03	CLASSROOM	5220	22	160/500	14	1792	3	5376
Z04	CLASSROOM	5279	22	160/500	11	1408	4	5632

Table 7 (continued)

NO.	ROOM NAME	HEAT LOSS (Watts)	ROOM TEMP. (°C)	RAD. TYPE	PIECE	GROUP CAP. (Watts)	GR. QTY	TOTAL HEAT CAP. (Watts)
Z05	MEN WC	499	18	160/500	4	560	1	560
Z06	WOMEN WC	499	18	160/500	4	560	1	560
Z07	EQUIPMENT ROOM	545	15	160/500	4	596	1	596
Z08	MEETING ROOM	1162	22	160/500	10	1280	1	1280
Z09	GUIDANCE	2737	22	160/500	11	1408	2	2816
Z10	ARCHIVE	840	15	160/500	6	894	1	894
Z11	INFIRMARY	4551	24	160/500	19	2318	2	4636
Z12	MANAGER ASSISTANT	2688	22	160/500	11	1408	2	2816
Z13	SOCIAL ROOM	2274	22	160/500	9	1152	2	2304
Z14	MEN WC	303	18	160/500	3	420	1	420
Z15	WOMEN WC	303	18	160/500	3	420	1	420
Z16	WOMEN WC	499	18	160/500	4	560	1	560
Z17	MEN WC	499	18	160/500	4	560	1	560
Z18	ACTIVITY ROOM	4585	22	160/500	9	1152	4	4608
Z19	OFFICE	913	18	160/500	7	980	1	980
Z20	ACTIVITY ROOM	4345	22	160/500	12	1536	3	4608
Z21	CLASSROOM	6368	22	160/500	13	1664	4	6656
Z22	CORRIDOR	8936	18	160/500	7	980	10	9800
B01	SHELTER	5965	18	160/900	6	1296	5	6480
B03	STORAGE	543	15	160/900	3	690	1	690
B05	WORKER DRESSING ROOM	1472	24	160/900	8	1520	1	1520
B06	WORKER ROOM	2036	22	160/900	11	2178	1	2178

Table 7 (continued)

NO.	**ROOM NAME**	**HEAT LOSS (Watts)**	**ROOM TEMP. (°C)**	**RAD. TYPE**	**PIECE**	**GROUP CAP. (Watts)**	**GR. QTY**	**TOTAL HEAT CAP. (Watts)**
B08	MEN WC	323	18	160/900	3	648	1	648
B09	WOMEN WC	307	18	160/900	3	648	1	648
B10	WOMEN WC	490	18	160/900	3	648	1	648
B11	MEN WC	454	18	160/900	3	648	1	648
B12	MEN DRESSING ROOM	1528	24	160/900	9	1710	1	1710
B13	SPOR EQ.ROOM	379	15	160/900	3	690	1	690
B14	WOMEN DRESSING ROOM	1592	24	160/900	9	1710	1	1710
B15	PHYSICAL TRAINING HALL	3173	18	160/900	5	1080	3	3240
B17	MEN TEACH.DRESS.ROOM	1528	24	160/900	9	1710	1	1710
B18	WOMEN TEACH.DRES.	2100	24	160/900	12	2280	1	2280
B19	CORRIDOR	1753	18	160/900	5	1080	2	2160
	TOTAL	**215727**		**160/500**	**1549**		**189**	**229996**
				160/900	**131**			

5.3.3 Energy Analysis of Boiler

In the existing system, the temperature regime is 90-70°C. The hot water boiler uses natural gas as its fuel. The heating water that is pumped to the radiators is heated in the boiler. The boiler is modeled as in Figure 10. In this model, the boiler is analysed in two parts to simplify the study.

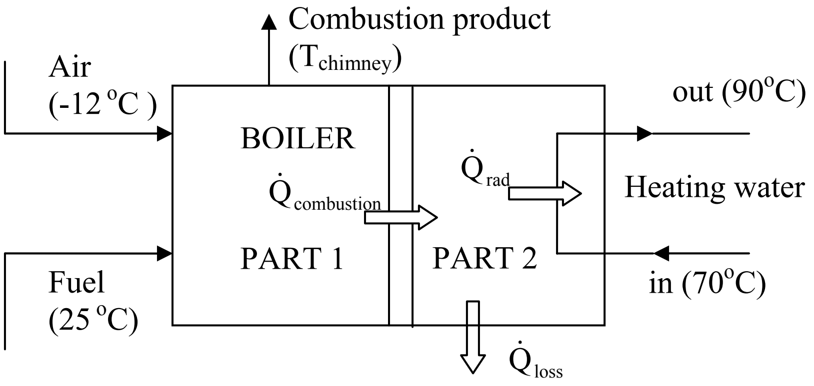

Figure 10 Schematic drawing of the boiler

PART I

In Part I, combustion occurs. Natural gas is modeled as methane so the stoichiometric combustion reaction can be written as,

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2 \tag{39}$$

In this study, combustion with an equivalence ratio=2/3 is analysed, thus the chemical equation becomes as,

$$CH_4 + 3(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 11.28N_2 + O_2 \tag{40}$$

Using Equations (10) and (12) the heat of combustion can be calculated. The enthalpy values can be taken from the thermodynamic tables [13].

$$\text{for}\,CH_4 \rightarrow h_f^o = -74850\,\text{kJ/kmol}$$
$$\bar{h} = \bar{h}_0\,(\text{at}\,298.15\,\text{K}) \Rightarrow \Delta h = 0$$

$$\text{for}\ O_2 \rightarrow h_f^o = 0\,\text{kJ/kmol}$$
$$\bar{h} = 7595\,\text{kJ/kmol}\,(\text{at}\,261\,\text{K})$$
$$\bar{h} = 13228\,\text{kJ/kmol}\,(\text{at}\,450\,\text{K})$$
$$\bar{h}_0 = 8682\,\text{kJ/kmol}$$

$$\text{for}\ N_2 \rightarrow h_f^o = 0\,\text{kJ/kmol}$$
$$\bar{h} = 7587\,\text{kJ/kmol}\,(\text{at}\,261\,\text{K})$$
$$\bar{h} = 12811\,\text{kJ/kmol}\,(\text{at}\,450\,\text{K})$$
$$\bar{h}_0 = 8669\,\text{kJ/kmol}$$

$$\text{for}\ CO_2 \rightarrow h_f^o = -393520\,\text{kJ/kmol}$$
$$\bar{h} = 15483\,\text{kJ/kmol}\,(\text{at}\,450\,\text{K})$$
$$\bar{h}_0 = 9364\,\text{kJ/kmol}$$

$$\text{for}\ H_2O \rightarrow h_f^o = 241820\,\text{kJ/kmol}$$
$$\bar{h} = 15080\,\text{kJ/kmol}\,(\text{at}\,450\,\text{K})$$
$$\bar{h}_0 = 9904\,\text{kJ/kmol}$$

From Equation (10) and for 450K chimney temperature [17], the heat output during combustion is,

$$\bar{q}_{\text{combustion}} = 719105\,\text{kJ/kmol}\,CH_4$$

If it is converted from mole basis to mass basis by using Equation (12),

$$q_{\text{combustion}} = 44826\,\text{kJ/kg}\,CH_4$$

PART II

In Part II, the heat of combustion is transferred to the heating water, but the heat lost from the boiler to the surroundings must be taken into account.

$\dot{Q}_{building}$ is taken from heat loss calculation for the whole building (Table 7) as 216kW and η_{boiler} is taken as 90% [17]. From Equation (11),

$$\dot{Q}_{combustion} = \frac{\dot{Q}_{building}}{0.90} \tag{41}$$

the heat output during combustion can be calculated as,

$$\dot{Q}_{combustion} = 240\,\mathrm{kW}$$

$$\dot{Q}_{combustion} = \dot{m}_{fuel} \cdot q_{combustion} \tag{42}$$

and using Equation (42), the fuel consumption for 2/3 equivalence ratio and 450K chimney temperature is calculated as,

$$\dot{m}_{fuel} = \frac{240\,\mathrm{kW}}{44826\,\mathrm{kJ/kg\,CH_4}} 3600\frac{\mathrm{s}}{\mathrm{h}} = 19.25\,\mathrm{kg/h} \tag{43}$$

5.4 Exergy Analysis

5.4.1 Exergy Analysis of Boiler

In this study the environmental temperature "T_0" is taken equal to the lowest outdoor temperature. The school building is in Konya therefore "T_0" is taken for general calculations as 261.15 K. However, in section "5.5.1 Outdoor Temperatures", this value is changed to investigate the effects of outdoor temperature on these analyses.

In the boiler, the chemical reaction (destroys exergy) and the exhaust of the combustion products from the system and the heat loss to the environment result in exergy losses. From Equation (23), by taking into consideration that W=0, the exergy balance for the boiler can be written as,

$$\dot{E}_{fuel} + \dot{E}_{water\,in} + \dot{E}_{air} = \dot{E}_{water\,out} + \dot{E}_D + \dot{E}_L \tag{44}$$

the summation of exergy losses and exergy destruction are taken as the irreversibility.

$$\dot{I}_{boiler} = \dot{E}_D + \dot{E}_L \tag{45}$$

The exergy supplied by the fuel consists of chemical and physical exergies. The kinetic and potential exergies are assumed negligible.

$$\dot{E}^{KN}_{fuel} = \dot{E}^{PT}_{fuel} = 0 \tag{46}$$

so for the fuel, Equation (13) becomes,

$$\dot{E}_{fuel} = \dot{E}^{PH}_{fuel} + \dot{E}^{CH}_{fuel} \tag{47}$$

The air is supplied without preheating and it is at the environment conditions, therefore the exergy of air is zero. According to these relations Equation (44) becomes,

$$\dot{E}^{PH}_{fuel} + \dot{E}^{CH}_{fuel} - (\dot{E}_{water\,out} - \dot{E}_{water\,in}) = \dot{I}_{boiler} \tag{48}$$

and this equation can be written as,

$$\dot{I}_{boiler} = \dot{m}_{fuel} \cdot (e^{PH}_{fuel} + e^{CH}_{fuel}) - \dot{m}_{water}(e_{water\,out} - e_{water\,in}) \tag{49}$$

The physical properties of natural gas are given in Table 8.

Table 8 Physical properties of natural gas [13]

Natural Gas	
T (K)	298.15
P (kPa)	600
C_P(kJ/kgK)	2.254
R(kJ/kgK)	0.5183
T_0 (K)	261.15
P_0 (kPa)	101

From Equation (16) and Table 8, the physical exergy of the natural gas can be calculated as,

$$e^{PH}_{fuel} = 246.58\,\text{kJ/kg}$$

The chemical exergy for natural gas as the fuel can be calculated by using Equation (27), and the chemical exergy factor "φ" is taken as 1.04 [1].

$$e_{fuel}^{CH} = 1.04 \cdot 50010 \, kJ/kg \tag{50}$$

$$e_{fuel}^{CH} = 52010.4 \, kJ/kg$$

From the results it can be seen that the physical exergy of fuel is very small relative to its chemical exergy. The physical properties of the heating water are given in Table 9.

Table 9 Physical properties of heating water [13]

Heating Water	Outlet	Inlet
T (^{o}C)	90	70
P (kPa)	70.14	31.19
h (kJ/kg)	376.92	292.98
s (kJ/kgK)	1.1925	0.9549

The heating water does not go through a chemical reaction, so the chemical exergy values of inlet and outlet water are equal and cancel in the exergy equation. The physical exergy difference between inlet and outlet water can be obtained by using Equation (15) as,

$$e_{water\,out} - e_{water\,in} = h_{water\,out} - h_{water\,in} - T_0 \cdot (s_{water\,out} - s_{water\,in}) \tag{51}$$

By substituting the values in Table 9 into Equation (51), the exergy change of the heating water in the boiler can be calculated as,

$$e_{\text{water out}} - e_{\text{water in}} = 21.891\,\text{kJ/kg} \tag{52}$$

From Equation (8) the mass flow rate of heating water is,

$$\dot{m}_{\text{water}} = \frac{216\,\text{kW}}{(376.92 - 292.98)\,\text{kJ/kg}} = 2.57\,\text{kg/s} \tag{53}$$

The irreversibility in the boiler can be found by substituting the calculated values into Equation (49),

$$\begin{aligned} \dot{I}_{\text{boiler}} &= 19.25\text{kg/h} \cdot \frac{1}{3600}\text{h/s} \cdot (246.58 + 52010.4)\text{kJ/kg} \\ &\quad - 2.57\text{kg/s} \cdot (21.891\text{kJ/kg}) \end{aligned} \tag{54}$$

$$\dot{I}_{\text{boiler}} = 223.17\,\text{kW}$$

The conventional efficiency of boiler is 90% for the boiler; from Equation (31) the second law efficiency can be calculated as,

$$\varepsilon_{\text{boiler}} = \frac{2.57\,\text{kg/s} \cdot 21.891\text{kJ/kg}}{\frac{19.25}{3600}\text{kg/s} \cdot (246.58 + 52010.4)\text{kJ/kg}} \tag{55}$$

$$\varepsilon_{\text{boiler}} = 0.20$$

5.4.2 Exergy Destruction Associated with Heat Transfer from the Radiators

In the previous sections, it was mentioned that radiators are used to heat the school building; during the heat transfer from the water in the radiators to rooms, there is also exergy destruction. This control volume is modeled as in Figure 11.

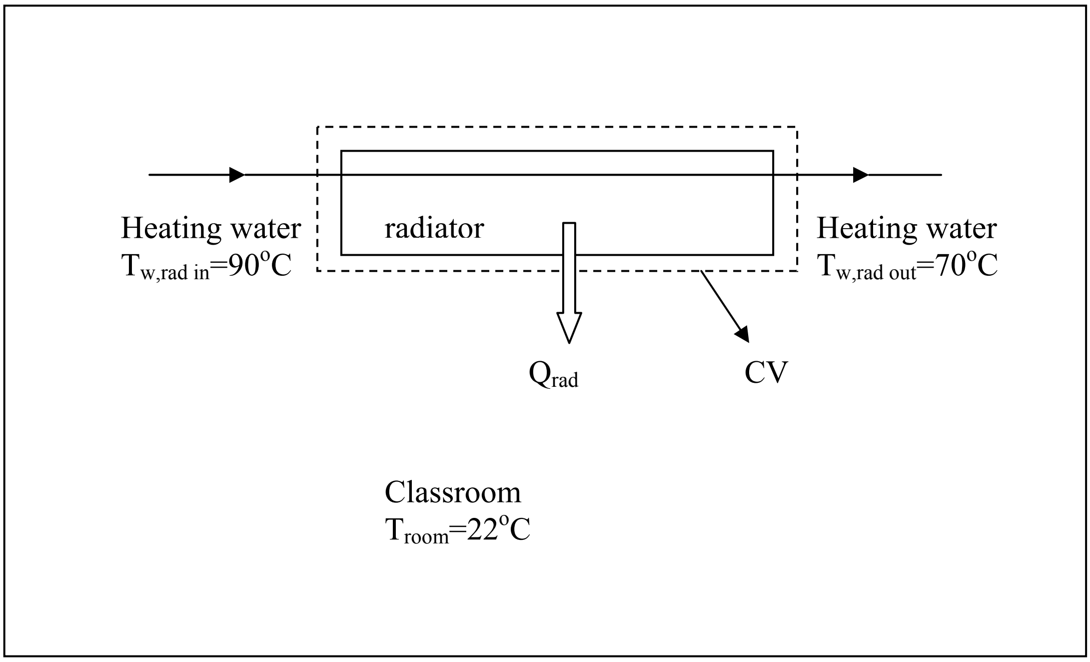

Figure 11 Heat transfer from heating water to room

The modeled room is classroom number 203. Its energy loss was calculated as 5237W. Three radiator groups were selected.

$$\dot{Q}_{room} = 5237\,W$$
$$n_{rad} = 3$$
$$\dot{Q}_{rad} = \frac{\dot{Q}_{room}}{n_{rad}} = \frac{5237\,W}{3} = 1745.67\,W \tag{56}$$
$$T_{room} = 22^{o}C = 295.15\,K$$

The inlet and outlet temperatures of the hot water are respectively 90°C and 70°C. The properties for water are given as [13],

$$h_{90^\circ C} = 376.90\,\text{kJ/kg} \qquad s_{90^\circ C} = 1.1924\,\text{kJ/kgK}$$
$$h_{70^\circ C} = 292.96\,\text{kJ/kg} \qquad s_{70^\circ C} = 0.9548\,\text{kJ/kgK}$$

And from Equation (23),

$$\dot{E}_{water,90^\circ C} = \dot{E}_{water,70^\circ C} - \dot{Q}_{rad} \cdot (1 - \frac{T_0}{T_{room}}) + \dot{I} \tag{57}$$

To define the irreversibility, Equation (57) can be rearranged as,

$$\dot{I}_{rad} = \dot{E}_{water,90^\circ C} - \dot{E}_{water,70^\circ C} + \dot{Q}_{rad} \cdot (1 - \frac{T_0}{T_{room}}) \tag{58}$$

The exergy difference between the outlet and inlet hot water streams can be calculated as,

$$\dot{E}_{water,90^\circ C} - \dot{E}_{water,70^\circ C} = \dot{m}_{water} \cdot \left[h_{90^\circ C} - h_{70^\circ C} - T_0 \cdot (s_{90^\circ C} - s_{70^\circ C})\right] \tag{59}$$

where $\dot{m}_{water}$ is the hot water mass flow rate that the radiator requires to supply the calculated heat to the room and is calculated as,

$$\dot{m}_{water} = \frac{\dot{Q}_{rad}}{(h_{90^\circ C} - h_{70^\circ C})} = \frac{1745.67 \cdot 10^{-3}\,\text{kW}}{(376.90 - 292.96)\,\text{kJ/kg}} = 20.8 \cdot 10^{-3}\,\text{kg/s} \tag{60}$$

The total hot water mass flow rate requirement of the room can be calculated by multiplying the radiator number of the room with the value found in Equation (60) as,

$$\dot{m}_{\text{water total}} = n_{\text{rad}} \cdot \dot{m}_{\text{water}} = 3 \cdot 20.8 \cdot 10^{-3}\,\text{kg/s} = 62.4 \cdot 10^{-3}\,\text{kg/s} = 224.6\,\text{kg/h} \tag{61}$$

These results are substituted into Equation (59) and the exergy difference of the hot water is calculated as,

$$\Delta\dot{E}_{\text{water}} = 20.8 \cdot 10^{-3}\,\text{kg/s} \cdot [376.90 - 292.96 - 261.15 \cdot (1.1924 - 0.9548)]\,\text{kJ/kg} \tag{62}$$

$$\Delta\dot{E}_{\text{water}} = 455.33\,\text{W}$$

The irreversibility during the heat transfer from a radiator in this room to the room itself is calculated as,

$$\dot{I}_{\text{rad}} = 455.33\,\text{W} - 1745.67\,\text{W} \cdot (1 - \frac{261.15}{295.15}) \tag{63}$$

$$\dot{I}_{\text{rad}} = 254.24\,\text{W}$$

It has been said that there are three radiators in this room, therefore the total radiator irreversibility in this room is,

$$\dot{I}_{\text{rad total}} = n_{\text{rad}} \cdot \dot{I}_{\text{rad}} = 3 \cdot 254.24\,\text{W} = 762.7\,\text{W} \tag{64}$$

A second way to define the irreversibility due to the heat transfer from the radiators is,

$$\dot{I}_{\text{rad}} = T_0 \cdot \dot{S}_{\text{gen}} \tag{65}$$

where entropy generation rate can be calculated as,

$$\dot{S}_{gen} = \dot{S}_{out} - \dot{S}_{in} - \frac{\dot{Q}_{rad}}{T_{room}} = \dot{m}_{water}(s_{out} - s_{in}) - \frac{\dot{Q}_{rad}}{T_{room}} \tag{66}$$

$$\dot{S}_{gen} = \left[20.8 \cdot 10^{-3}\,\mathrm{kg/s} \cdot (0.9548 - 1.1924)\,\mathrm{kJ/kgK} - \frac{(-1745.67 \cdot 10^{-3}\,\mathrm{kW})}{295.15\,\mathrm{K}} \right] \cdot 10^{3}\,\frac{\mathrm{W}}{\mathrm{kW}}$$

$$\dot{S}_{gen} = 0.973\,\mathrm{W/K}$$

By using the calculated values above, the irreversibility can be calculated.

$$\dot{I}_{rad} = 261.15\,\mathrm{K} \cdot 0.9735\,\mathrm{W/K} \tag{67}$$

$$\dot{I}_{rad} = 254.24\,\mathrm{W}$$

$$\dot{I}_{rad\,total} = 3 \cdot 254.24\,\mathrm{W} = 762.7\,\mathrm{W}$$

Both solutions give equal results. The irreversibility of the heat transfer from the radiators for each room are summarized in Table 10.

5.4.3 Exergy Loss of the Rooms

During the heat loss from Classroom 203 to the environment, there will be irreversibilities. In Figure 12, $\dot{Q}_I$ is the infiltration heat loss and $\dot{Q}_{II}$ is the transmission heat loss. When the control volume is selected as in Figure 12, the summation of these two heat losses can be taken as the total heat loss.

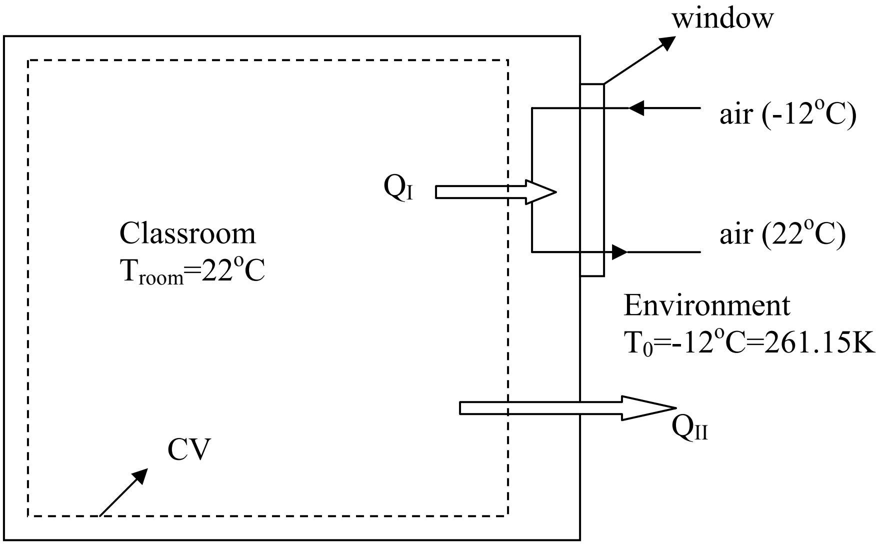

Figure 12 Heat loss from Classroom 203 to outside

$$\dot{Q}_{I} + \dot{Q}_{II} = \dot{Q}_{room} = 5237\,W \tag{68}$$

$$\dot{E}_{loss} = \dot{Q}_{room} \cdot (1 - \frac{T_0}{T_{room}}) = 5237\,W \cdot (1 - \frac{261.15}{295.15}) = 603.28\,W \tag{69}$$

The exergy losses due to heat losses for each room are given in Table 10. In the third column of this table, the heat losses for each room are also given. For Classroom 203, the heat loss is calculated using Equations (35) – (38). The required hot water mass flow rates are given in the fifth column. For Classroom-203, the water mass flow rate is calculated in Equation (60).

Table 10 Irreversibility of heat transfer from radiator and exergy loss from rooms

ROOM NO.	ROOM NAME	HEAT LOSS (Watts)	ROOM TEMP. (°C)	REQ. WATER FLOW (kg/h)	IRREV. RATES OF RAD. (Watts)	EXERGY LOSS IN ROOMS (Watts)
201	CLASSROOM	5094	22	218.45	741.59	586.75
202	CLASSROOM	4186	22	179.55	609.53	482.27
203	CLASSROOM	5237	22	224.60	762.47	603.27
204	CLASSROOM	5312	22	227.80	773.34	611.87
205	MEN WC	801	18	34.35	126.35	82.53
206	WOMEN WC	801	18	34.35	126.35	82.53
207	TEACHERS ROOM	1073	22	46.00	156.17	123.57
208	CLASSROOM	4665	22	200.09	679.26	537.43
209	MEETING ROOM	6053	22	259.59	881.25	697.25
210	LIBRARY	9469	22	406.10	1378.61	1090.77
211	MEN WC	436	18	18.70	68.80	44.94
212	WOMEN WC	402	18	17.26	63.48	41.46
213	WOMEN WC	801	18	34.35	126.35	82.53
214	MEN WC	801	18	34.35	126.35	82.53
215	CLASSROOM	5312	22	227.80	773.34	611.87
216	COMPUTER ROOM	6784	22	290.96	987.76	781.53
217	PREP.ROOM	1153	18	49.44	181.84	118.78
218	LABORATORY	5029	18	215.66	793.26	518.14
225	CORRIDOR	10138	18	434.80	1599.30	1044.63
101	CLASSROOM	4221	22	181.04	614.59	486.27
102	CLASSROOM	3314	22	142.14	482.53	381.78
103	CLASSROOM	4365	22	187.19	635.47	502.78
104	CLASSROOM	4439	22	190.39	646.34	511.39
105	MEN WC	474	18	20.33	74.79	48.85
106	WOMEN WC	474	18	20.33	74.79	48.85
107	STORAGE	521	15	22.35	87.09	48.84
108	CLASSROOM	3993	22	171.27	581.42	460.03
109	CANTEEN	3662	18	157.05	577.68	377.33
110	OFFICIAL	2400	22	102.93	349.43	276.47
111	MANAGER ROOM	3702	22	158.76	538.97	426.44
112	PUBLICATION	2400	22	102.93	349.43	276.47
113	MEN WC	290	18	12.43	45.74	29.87
114	WOMEN WC	290	18	12.43	45.74	29.87
115	WOMEN WC	474	18	20.33	74.79	48.85
116	MEN WC	474	18	20.33	74.79	48.85
117	CLASSROOM	4439	22	190.39	646.34	511.39
118	MUSIC ROOM	6074	22	260.49	884.30	699.66

Table 10 (continued)

ROOM NO.	ROOM NAME	HEAT LOSS (Watts)	ROOM TEMP. (°C)	REQ. WATER FLOW (kg/h)	IRREV. RATES OF RAD. (Watts)	EXERGY LOSS IN ROOMS (Watts)
119	STORAGE	807	15	34.59	134.77	75.57
120	MECHANICAL WORKSHOP	4492	18	192.67	708.69	462.90
124	CORRIDOR	5077	18	217.75	800.93	523.15
Z01	CLASSROOM	5037	22	216.03	733.39	580.26
Z02	CLASSROOM	4074	22	174.73	593.19	469.33
Z03	CLASSROOM	5220	22	223.88	760.03	601.34
Z04	CLASSROOM	5279	22	226.42	768.66	608.17
Z05	MEN WC	499	18	21.42	78.79	51.46
Z06	WOMEN WC	499	18	21.42	78.79	51.46
Z07	EQUIPMENT ROOM	545	15	23.36	91.02	51.04
Z08	MEETING ROOM	1162	22	49.81	169.11	133.80
Z09	GUIDANCE	2737	22	117.39	398.51	315.30
Z10	ARCHIVE	840	15	36.01	140.30	78.68
Z11	INFIRMARY	4551	24	195.17	635.46	551.33
Z12	MANAGER ASSISTANT	2688	22	115.27	391.30	309.60
Z13	SOCIAL ROOM	2274	22	97.52	331.05	261.93
Z14	MEN WC	303	18	13.00	47.80	31.22
Z15	WOMEN WC	303	18	13.00	47.80	31.22
Z16	WOMEN WC	499	18	21.42	78.79	51.46
Z17	MEN WC	499	18	21.42	78.79	51.46
Z18	ACTIVITY ROOM	4585	22	196.63	667.52	528.14
Z19	OFFICE	913	18	39.16	144.02	94.07
Z20	ACTIVITY ROOM	4345	22	186.33	632.55	500.48
Z21	CLASSROOM	6368	22	273.11	927.14	733.56
Z22	CORRIDOR	8936	18	383.24	1409.64	920.75
B01	SHELTER	5965	18	255.83	940.99	614.64
B03	STORAGE	543	15	23.29	90.74	50.88
B05	WORKER DRESSING ROOM	1472	24	63.13	205.55	178.33
B06	WORKER ROOM	2036	22	87.31	296.40	234.51
B08	MEN WC	323	18	13.85	50.95	33.28
B09	WOMEN WC	307	18	13.18	48.48	31.66
B10	WOMEN WC	490	18	21.01	77.29	50.48
B11	MEN WC	454	18	19.47	71.62	46.78

Table 10 (continued)

ROOM NO.	ROOM NAME	HEAT LOSS (Watts)	ROOM TEMP. (°C)	REQ. WATER FLOW (kg/h)	IRREV. RATES OF RAD. (Watts)	EXERGY LOSS IN ROOMS (Watts)
B12	MEN DRESSING ROOM	1528	24	65.52	213.31	185.07
B13	SPOR EQ.ROOM	379	15	16.25	63.31	35.50
B14	WOMEN DRESSING ROOM	1592	24	68.28	222.32	192.89
B15	PHYSICAL TRAINING HALL	3173	18	136.07	500.49	326.91
B17	MEN TEACH.DRESS.ROOM	1528	24	65.52	213.31	185.07
B18	WOMEN TEACH.DRES.	2100	24	90.04	293.18	254.36
B19	CORRIDOR	1753	18	75.19	276.57	180.65
	TOTAL	**215727**		**9252.06**	**32152.22**	**24107.41**

5.5 Effects of Several Factors on Energy, Exergy and Economic Analyses

5.5.1 Outdoor Temperature

The outdoor temperature directly affects the amount of heat loss from a building and therefore it affects both the energy and exergy analyses of a building. The selected system in this study is a school building in Konya, Turkey. It is said that the minimum outdoor temperature is -12^{o}C for Konya. For several other outdoor temperatures, the results from identical energy and exergy analyses are given in Table 11.

Table 11 Energy and exergy results for different outdoor temperatures

T_0(^{o}C)	**0**	**-6**	**-12**	**-18**	**-24**
$\dot{Q}_{loss}$ (kW)	146.060	181.156	215.727	250.824	285.395
$q_{combustion}$ (kJ/kg)	45,138	44,981	44,826	44,670	44,515
$\dot{m}_{fuel}$ (kg/h)	12.943	16.109	19.250	22.460	25.645
$\dot{I}_{boiler}$ (kW)	154.783	189.691	223.170	256.327	288.084
$\dot{I}_{rad}$ (kW)	22.703	27.588	32.152	36.555	40.641
$\dot{I}_{room}$ (kW)	10.427	16.580	24.107	33.118	43.481
$\dot{I}_{system}$ (kW)	187.913	233.859	279.429	326.000	372.206

The variation of the total irreversibility of the system with outdoor temperatures is given in Figure 13.

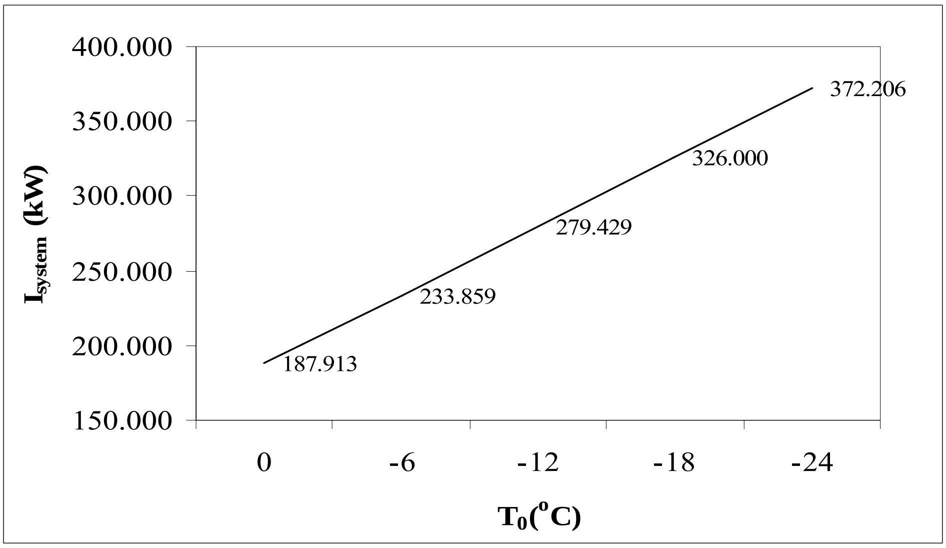

Figure 13 The change of total irreversibility with outdoor temperature

The calculations of heat losses and irreversibility values for these outdoor temperatures are given in Appendix D.

It is seen that the outdoor temperature has an important effect on the energy and exergy calculations. In this study thus far, the minimum outdoor temperature is used to define radiator lengths and heat generator capacities. However, to get results that are more realistic for annual consumptions, an average temperature for the winter months is calculated and the energy and exergy analyses are repeated according to this average temperature. This average temperature is determined by using statistical data results for the years 1975 to 2006, which are taken from the website of Turkish State Meteorological Service [18], resulting in an average winter temperature of 0^oC for Konya. Additionally, an annual fuel cost is calculated according to these analyses.

5.5.2 Thermal Insulation

The amount of thermal insulation in a building structure can have as large an impact on heat losses as the outdoor temperature. The selected system can be considered as a well insulated one. To analyse the effect of insulation on heat loss and exergy consumption, calculations are repeated for different insulation grades. In Figure 14, the sources of heat losses are shown for the existing design.

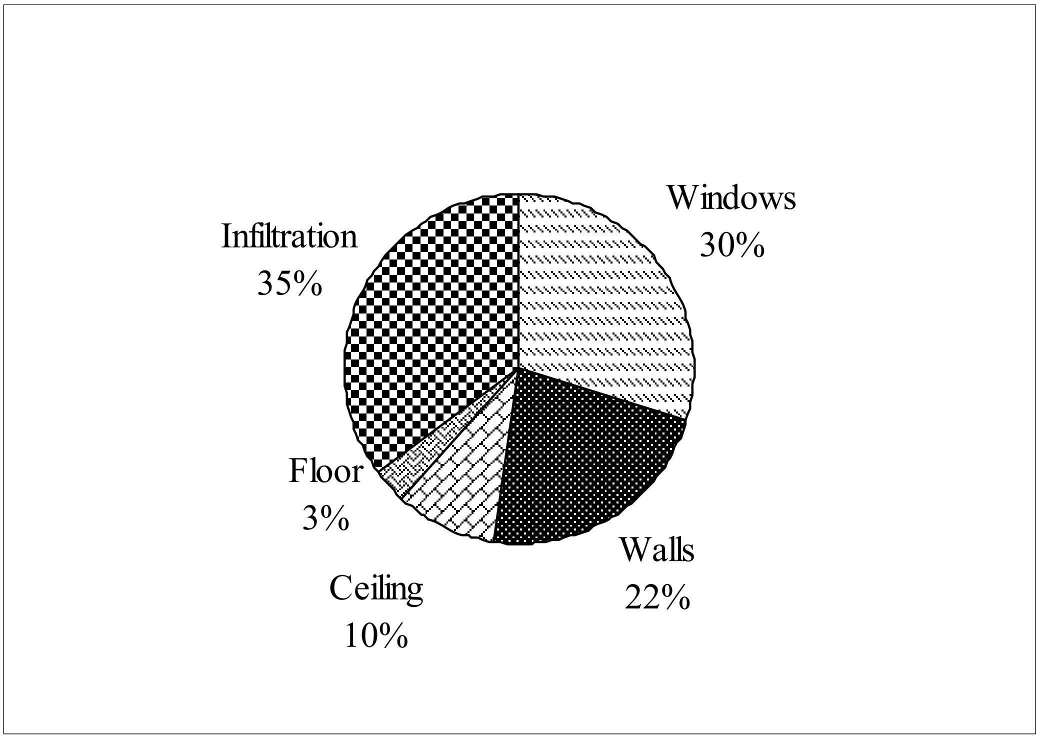

Figure 14 Sources of heat loss

From Figure 14, it can be seen that most (35%) of the heat loss occurs because of infiltration. However, some infiltration is required to maintain adequate indoor air quality and if infiltration rate is eliminated, ventilation must be applied. Heat recovered duct system can be used for ventilation. In this study, ventilation is not considered; infiltration rate is kept for fresh air requirement.

The fresh air flow rate ($\dot{V}_i$) due to infiltration is derived based on an energy balance as,

$$\dot{V}_i = \frac{\dot{Q}_i}{\rho_{air} \cdot C_{P,air} \cdot \Delta T} \tag{70}$$

where ρ_{air} is the density of air, $C_{P,air}$ is the constant pressure specific heat of air and ΔT is the temperature difference between indoor and outdoor. The air flow rate for Classroom 203 is calculated as,

$$\dot{V}_i = \frac{1404\,\mathrm{W}}{1.169\,\frac{\mathrm{kg}}{\mathrm{m}^3} \cdot 1004\,\frac{\mathrm{J}}{\mathrm{kg} \cdot {}^{\circ}\mathrm{C}} \cdot 34^{\circ}\mathrm{C}} \cdot 3600\,\frac{\mathrm{s}}{\mathrm{h}} = 127\,\mathrm{m}^3/\mathrm{h}$$

The fresh air requirement for a classroom is given as 3 l/s.person in ASHRAE [19]. By assuming that there are 30 students, the total fresh air need of the classroom ($\dot{V}_{required}$) is 90 l/s = 324 m^3/h. It is seen that $\dot{V}_i < \dot{V}_{required}$, so the infiltration cannot be decreased due to air quality concerns. This result can be generalized to the whole building because all classrooms are almost the same.

The heat loss from the windows is 30% of the total heat loss of the building. In the existing system, windows with plastic frames, 4 mm double glass panes and 9 mm stagnant air gap (4+9+4) are used. To see the effect of window choice on the energy and exergy analyses, the calculations are repeated for six different types of windows. The results are given in Table 12.

Table 12 Results for different window types for design (T_0=-12°C) and average (T_0=0°C) outdoor temperatures

Window glass type	**Double window (4+9+4)**	**Double window (4+12+4)**	**Double window (4+16+4)**	**Double window (4+9+4) Low-E**	**Double window (4+12+4) Low-E**	**Double window (4+16+4) Low-E**
U (W/m^2K)	3.0	2.8	2.7	2.2	2.1	1.9
According to minimum outdoor (design) temperature (T_0=-12 °C)						
$\dot{Q}_{building}$ (kW)	215.727	212.024	210.173	200.915	199.064	195.361
$q_{combustion}$ (kJ/kg)	44,826	44,826	44,826	44,826	44,826	44,826
$\dot{m}_{fuel}$ (kg/h)	19.250	18.920	18.754	17.928	17.763	17.433
$\dot{I}_{boiler}$ (kW)	223.170	219.339	217.424	207.847	205.932	202.101
$\dot{I}_{rad}$ (kW)	32.152	31.600	31.323	29.941	29.665	29.112
$\dot{I}_{room}$ (kW)	24.107	23.695	23.488	22.456	22.250	21.837
$\dot{I}_{system}$ (kW)	279.429	274.634	272.235	260.244	257.847	253.050
According to average outdoor temperature (T_0=0 °C)						
$\dot{Q}_{building}$ (kW)	146.060	143.718	142.547	136.691	135.520	133.178
$q_{combustion}$ (kJ/kg)	45,138	45,138	45,138	45,138	45,138	45,138
$\dot{m}_{fuel}$ (kg/h)	12.943	12.736	12.632	12.113	12.009	11.802
$\dot{I}_{boiler}$ (kW)	154.783	152.301	151.060	144.855	143.614	141.132
$\dot{I}_{rad}$ (kW)	22.703	22.338	22.155	21.243	21.060	20.695
$\dot{I}_{room}$ (kW)	10.427	10.261	10.177	9.762	9.679	9.513
$\dot{I}_{system}$ (kW)	187.913	184.900	183.392	175.860	174.353	171.340

The heat loss from the exterior walls is 22% of the total heat loss of the building. The walls include 4 cm Extruded Polystyrene Insulation. The results for different insulation thicknesses are given in Table 13.

Table 13 Results for different wall insulation thicknesses for design (T_0=-12^{o}C) and average (T_0=0^{o}C) outdoor temperatures

	Insulation thickness	**4 cm**	**5 cm**	**6 cm**	**7 cm**	**8 cm**
U (W/m^{2}K)	Exterior wall	0.519	0.445	0.389	0.346	0.311
	Exterior concrete wall	0.599	0.502	0.432	0.379	0.338
	Exterior concrete wall-2	0.517	0.436	0.378	0.333	0.297
According to minimum outdoor (design) temperature (T_0=-12 ^{O}C)						
$\dot{Q}_{building}$ (kW)		215.727	209.671	205.092	201.615	198.833
$q_{combustion}$ (kJ/kg)		44,826	44,826	44,826	44,826	44,826
$\dot{m}_{fuel}$ (kg/h)		19.250	18.710	18.301	17.991	17.742
$\dot{I}_{boiler}$ (kW)		223.170	216.905	212.168	208.571	205.693
$\dot{I}_{rad}$ (kW)		32.152	31.243	30.555	30.033	29.615
$\dot{I}_{room}$ (kW)		24.107	23.437	22.931	22.546	22.239
$\dot{I}_{system}$ (kW)		279.429	271.585	265.654	261.150	257.547
According to average outdoor temperature (T_0=0 ^{O}C)						
$\dot{Q}_{building}$ (kW)		146.060	142.122	139.143	136.879	135.068
$q_{combustion}$ (kJ/kg)		45,138	45,138	45,138	45,138	45,138
$\dot{m}_{fuel}$ (kg/h)		12.943	12.594	12.330	12.130	11.969
$\dot{I}_{boiler}$ (kW)		154.783	150.610	147.453	145.054	143.135
$\dot{I}_{rad}$ (kW)		22.703	22.085	21.618	21.262	20.978
$\dot{I}_{room}$ (kW)		10.427	10.151	9.943	9.785	9.658
$\dot{I}_{system}$ (kW)		187.913	182.846	179.014	176.101	173.771

The heat loss from the ceiling is 10% of the total heat loss of the building. In the building 10 cm rock wool is used for ceiling insulation. The results for different insulation thicknesses are given in Table 14.

Table 14 Results for different ceiling insulation thicknesses for design (T_0=-12^{o}C) and average (T_0=0^{o}C) outdoor temperatures

Insulation thickness	**10 cm**	**13 cm**	**15 cm**	**20 cm**
U (W/m^{2}K)	0.357	0.281	0.247	0.189
According to minimum outdoor (design) temperature (T_0=-12 ^{O}C)				
$\dot{Q}_{building}$ (kW)	215.727	211.919	210.239	207.495
$q_{combustion}$ (kJ/kg)	44,826	44,826	44,826	44,826
$\dot{m}_{fuel}$ (kg/h)	19.250	18.910	18.760	18.515
$\dot{I}_{boiler}$ (kW)	223.170	219.231	217.493	214.654
$\dot{I}_{rad}$ (kW)	32.152	31.577	31.323	30.908
$\dot{I}_{room}$ (kW)	24.107	23.690	23.506	23.205
$\dot{I}_{system}$ (kW)	279.429	274.498	272.322	268.767
According to average outdoor temperature (T_0=0 ^{O}C)				
$\dot{Q}_{building}$ (kW)	146.060	143.678	142.627	140.910
$q_{combustion}$ (kJ/kg)	45,138	45,138	45,138	45,138
$\dot{m}_{fuel}$ (kg/h)	12.943	12.732	12.639	12.487
$\dot{I}_{boiler}$ (kW)	154.783	152.259	151.145	149.326
$\dot{I}_{rad}$ (kW)	22.703	22.327	22.161	21.890
$\dot{I}_{room}$ (kW)	10.427	10.262	10.190	10.071
$\dot{I}_{system}$ (kW)	187.913	184.848	183.496	181.287

The smallest portion of the heat loss (3%) occurs through the floor. In the building, 4 cm Extruded Polystyrene Insulation is used in the floor construction. The results for different floor insulation thicknesses are given in Table 15.

Table 15 Results for different floor insulation thicknesses for design (T_0=-12°C) and average (T_0=0°C) outdoor temperatures

Insulation thickness	**4 cm**	**5 cm**	**6 cm**	**7 cm**	**8 cm**
U (W/m^2K)	0.461	0.396	0.347	0.308	0.278
According to minimum outdoor (design) temperature (T_0=-12 °C)					
$\dot{Q}_{building}$ (kW)	215.727	214.845	214.203	213.709	213.321
$q_{combustion}$ (kJ/kg)	44,826	44,826	44,826	44,826	44,826
$\dot{m}_{fuel}$ (kg/h)	19.250	19.171	19.114	19.070	19.035
$\dot{I}_{boiler}$ (kW)	223.170	222.258	221.593	221.082	220.681
$\dot{I}_{rad}$ (kW)	32.152	32.016	31.917	31.840	31.780
$\dot{I}_{room}$ (kW)	24.107	24.014	23.945	23.893	23.852
$\dot{I}_{system}$ (kW)	279.429	278.288	277.455	276.815	276.313
According to average outdoor temperature (T_0=0 °C)					
$\dot{Q}_{building}$ (kW)	146.060	145.456	145.016	144.678	144.412
$q_{combustion}$ (kJ/kg)	45,138	45,138	45,138	45,138	45,138
$\dot{m}_{fuel}$ (kg/h)	12.943	12.890	12.851	12.821	12.797
$\dot{I}_{boiler}$ (kW)	154.783	154.143	153.677	153.319	153.037
$\dot{I}_{rad}$ (kW)	22.703	22.606	22.535	22.481	22.438
$\dot{I}_{room}$ (kW)	10.427	10.387	10.358	10.336	10.318
$\dot{I}_{system}$ (kW)	187.913	187.136	186.570	186.136	185.793

The economic aspects of the different systems are estimated through a simple cost analysis performed for the different alternatives. The capital cost difference between the present and the alternative systems are expressed as additional capital costs that include decrease in radiator costs associated with any decrease in radiator lengths as the insulation is increased. Using the average winter temperature, annual fuel costs are estimated and simple payback periods found as,

$$\text{Payback period (year)} = \frac{\text{Additional capital cost (YTL)}}{\text{Decrease in annual fuel cost (YTL/year)}} \tag{71}$$

While these simple payback periods can be used to compare the alternatives, since the time value of money is not accounted for actual payback periods will be longer. The costs of the window frame, glass and rock wool insulation, extruded polystyrene insulation, radiators and boilers are taken from "Bayındırlık Bakanlığı Birim Fiyatları" [20] and are listed in Appendix E. The economic results for different window types are given in Table 16.

Table 16 Costs for different window types

Glass type	Additional Capital Cost YTL	Fuel Cost YTL/kWh	Fuel Cost YTL/h	Operating period hours/year	Annual Fuel Cost YTL/year	Pay-back period years
4+9+4	-	0.04123	6.69	1515	10,137	-
4+12+4	632	0.04123	6.56	1515	9,937	3.16
4+16+4	984	0.04123	6.53	1515	9,893	4.03
4+9+4 Low-E	3,605	0.04123	6.26	1515	9,486	5.55
4+12+4 Low-E	4,330	0.04123	6.21	1515	9,405	5.92
4+16+4 Low-E	4,607	0.04123	6.10	1515	9,243	5.15

The capital cost ratio (capital cost of considered system / capital cost of present system) and annual fuel cost ratio (annual fuel cost of considered system / annual fuel cost of present system) of the considered and present systems are given in Figure 15. It is seen that the curves are nearly mirror images. This shows the balance between capital and annual operating costs.

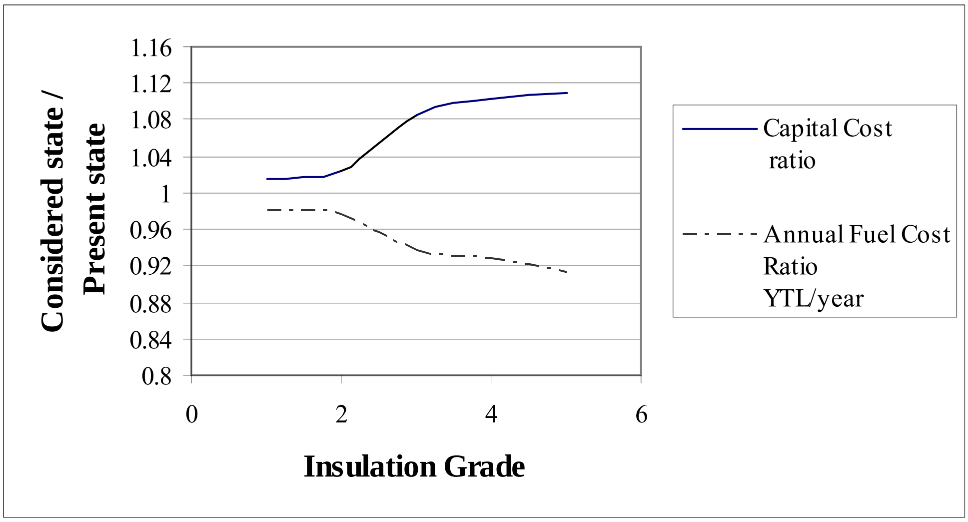

Figure 15 Capital and annual cost ratios according to window type

Extruded polystyrene with smooth surface is used for thermal insulation for the walls of the basement floor. Extruded polystyrene with rugged surface is used for the walls of the other floors. The results for different insulation thicknesses are given in Table 17.

Table 17 Costs for different wall insulation thicknesses

Insulation cm	**Additional Capital Cost YTL**	**Fuel Cost YTL/kWh**	**Fuel Cost YTL/h**	**Operating period hours/year**	**Annual Fuel Cost YTL/year**	**Pay-back period years**
4	-	0.04123	6.69	1515	10,137	-
5	3,722	0.04123	6.51	1515	9,863	13.62
6	7,601	0.04123	6.37	1515	9,657	15.83
7	11,345	0.04123	6.27	1515	9,500	17.81
8	15,238	0.04123	6.19	1515	9,374	19.97

The capital cost ratio and the annual fuel cost ratio of the considered and present systems are given in Figure 16. It is seen that the gradient of the capital cost ratio line is larger than the absolute gradient of the annual fuel cost ratio. This explains the high payback periods, in Table 17.

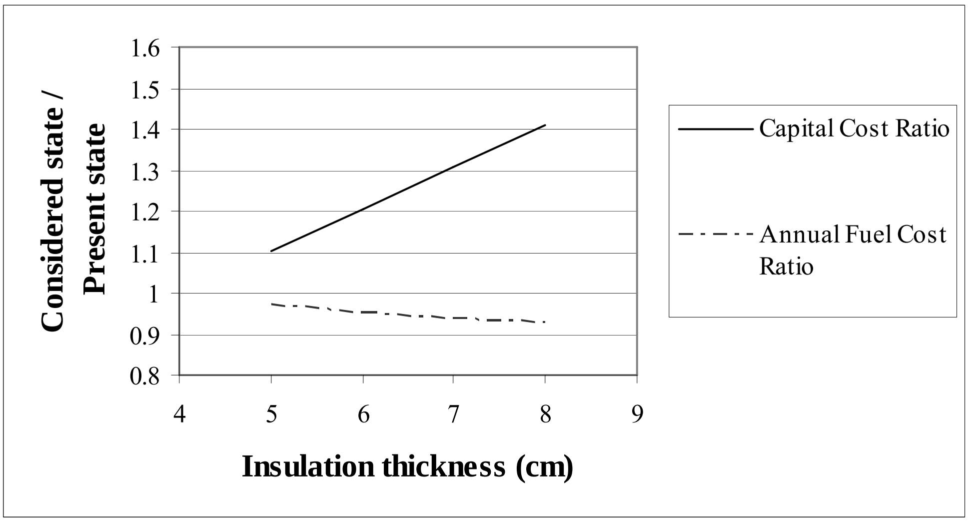

Figure 16 Capital and annual cost ratios according to wall insulation

For different ceiling insulation thicknesses. Rock wool is used for thermal insulation in the ceiling. The results for different insulation thicknesses are given in Table 18.

Table 18 Costs for different ceiling insulation thicknesses

Insulation cm	**Additional Capital Cost YTL**	**Fuel Cost YTL/kWh**	**Fuel Cost YTL/h**	**Operating period hours/year**	**Annual Fuel Cost YTL/year**	**Pay-back period years**
10	-	0.04123	6.69	1515	10,137	
13	7,040	0.04123	6.58	1515	9,971	42.59
15	11,050	0.04123	6.53	1515	9,898	46.38
20	22,359	0.04123	6.45	1515	9,779	62.56

The capital cost ratio and the annual fuel cost ratio of the considered and present systems are given in Figure 17. The gradient of the capital cost ratio line is larger than that for the wall. The cause of this is a large cost per unit insulation thickness.

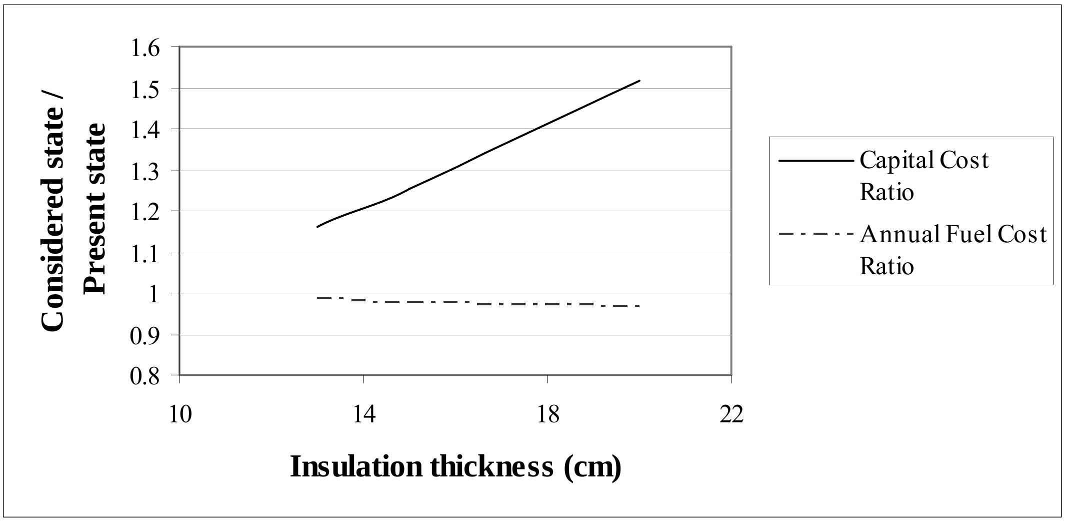

Figure 17 Capital and annual cost ratios according to ceiling insulation

Extruded polystyrene with smooth surface is used for thermal insulation for the floor. Additional capital costs and fuel costs for different insulation thicknesses are given in Table 19.

Table 19 Costs for different floor insulation thicknesses

Insulation cm	Additional Capital Cost YTL	Fuel Cost YTL/kWh	Fuel Cost YTL/h	Operating period hours/year	Annual Fuel Cost YTL/year	Pay-back period years
4	-	0.04123	6.69	1515	10,137	
5	2,658	0.04123	6.66	1515	10,095	63.41
6	5,316	0.04123	6.64	1515	10,064	73.37
7	8,055	0.04123	6.63	1515	10,041	83.99
8	10,795	0.04123	6.62	1515	10,022	94.38

The capital cost ratio and the annual fuel cost ratio of the considered and present systems are given in Figure 18. The annual fuel cost line is almost horizontal. This is because only 3% of the total heat loss of the building is from the floor.

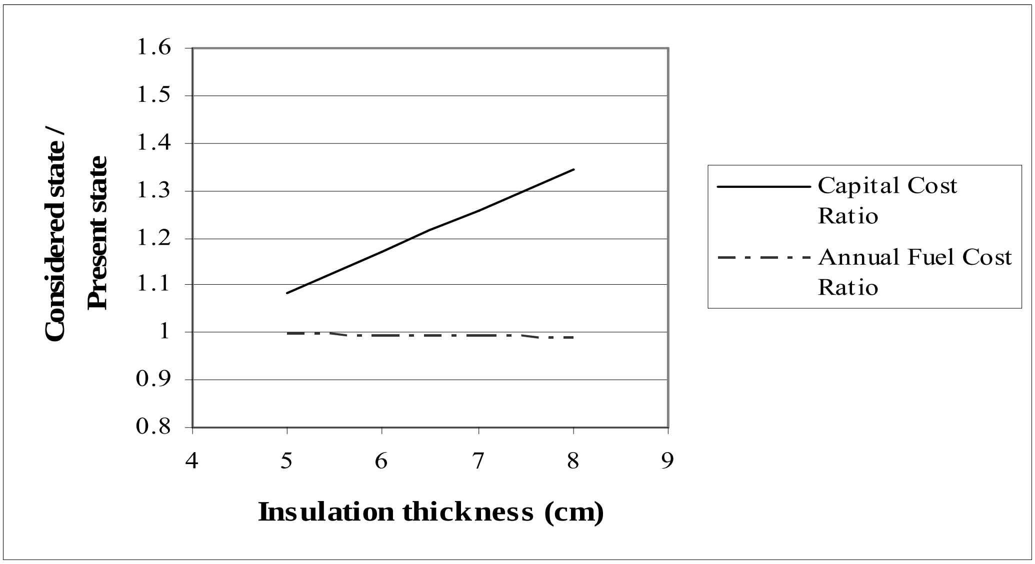

Figure 18 Capital and annual cost ratios according to floor insulation

From the results, it is seen that the shortest payback period (3 years) is for upgrading to (4+12+4) window glass, the lowest annual operating cost (9,243 YTL/year) is calculated for (4+16+4 Low-E) window glass, and a revision for windows is more effective than for other building structures. The longest payback period is calculated for 8 cm floor insulation (94 years). While upgrading the floor insulation it is seen that in spite of the increase in the capital cost, the annual operation cost is almost constant (see Figure 18). When the calculations are repeated for a non-insulated floor, the decrease in the capital cost is 11,000 YTL. When this saved money is used for upgrading the windows (using 4+16+4 Low-E glass), there is a decrease both in the capital cost (5300 YTL) and in the annual operating cost (355 YTL/year or 3%), relative to the base case.

5.5.3 Fuel Type

In the existing, system natural gas is used as the fuel. In order to determine the effect of fuel selection on energy and exergy consumptions of the system, the analyses are repeated for solid and liquid fuels. Fuel oil is selected as the liquid fuel and coal as the solid fuel. The fuel oil is assumed to have the chemical composition $C_{10}H_{22}$, and for the coal the ultimate analysis on an as-received basis is, by mass: 28.9% moisture, 3.5% H, 48.6% C, 0.5% S, 0.7% N, 12% O and 5.8% ash [14]. In Appendix F, the calculations of the lower heating values and heat outputs during combustion with 150% theoretical air (2/3 equivalence ratio) and 450K chimney temperature are given for both fuels [14], [21]. From the calculations it can seen that the ratios of the heat outlets during combustion to the lower heating values are almost the same for these three fuels. These values are summarized below,

$LHV_{\text{fuel oil}} = 44{,}600$ kJ/kg
$LHV_{\text{coal}} = 20{,}215$ kJ/kg
$q_{\text{combustion, fuel oil}}$ (for $-12^{o}C$ outdoor temperature) = 40,133 kJ/kg
$q_{\text{combustion, fuel oil}}$ (for $0^{o}C$ outdoor temperature) = 40,405 kJ/kg
$q_{\text{combustion, coal}}$ (for $-12^{o}C$ outdoor temperature) = 18,352 kJ/kg
$q_{\text{combustion, coal}}$ (for $0^{o}C$ outdoor temperature) = 18,466 kJ/kg

Based on these values, $\dot{m}_{\text{fuel,}}\ \dot{I}_{\text{boiler}}, \dot{I}_{\text{boiler system}}$ and $\dot{I}_{\text{boiler system (cum)}}$ for T_0=-12^{o}C and T_0=0^{o}C are given in Table 20.

Table 20 Results for different fuels for design (T_0=-12°C) and average (T_0=0°C) outdoor temperatures

Fuel	**Natural Gas**	**Fuel Oil**	**Coal**
φ	1.04	1.04	1.05
According to minimum outdoor (design) temperature (T_0=-12 °C)			
$q_{combustion}$ (kJ/kg)	44,826	40,133	18,352
$q_{combustion}$ / LHV	0.896	0.900	0.908
$\dot{m}_{fuel}$ (kg/h)	19.250	21.501	47.020
$\dot{I}_{boiler}$ (kW)	223.170	220.799	221.011
$\dot{I}_{boiler\ system}$ (kW)	279.429	277.058	277.270
$\dot{I}_{boiler\ system\ (cum)}$ (kW)	305.387	324.424	297.500
According to average outdoor temperature (T_0=0 °C)			
$q_{combustion}$ (kJ/kg)	45,138	40,405	18,466
$q_{combustion}$ / LHV	0.903	0.906	0.913
$\dot{m}_{fuel}$ (kg/h)	12.943	14.460	31.639
$\dot{I}_{boiler}$ (kW)	154.783	153.182	153.425
$\dot{I}_{boiler\ system}$ (kW)	187.913	186.312	186.555
$\dot{I}_{boiler\ system\ (cum)}$ (kW)	205.369	218.164	200.166

The irreversibilities of the radiators and rooms are affected only by the heat loss rate and therefore the fuel type does not change these values. It is seen that the irreversibility values are almost the same for different fuels. However, when the cumulative irreversibilites of the systems for these three fuels are calculated by taking into account the cumulative exergetic efficiencies of fuel mining, reprocessing and transporting (ε_{cum}), the minimum cumulative irreversibility is determined for coal. ε_{cum} values are taken as 0.932, 0.915 and 0.854 for coal, natural gas and fuel oil mining, respectively [4], [22].

The physical exergy values of the fuels are calculated using Equation (17) and for the chemical exergy values Equation (27) is used. From the calculations it was found that the physical exergy for solid and liquid fuels can be neglected (<0.1%) as compared to the amount of chemical exergy. However, in this study, the physical exergy values of the fuels are taken into consideration for completeness. While calculating the chemical exergies, "φ" is taken as 1.04 for fuel oil and 1.05 for coal [1]. The calculations for the irreversibility in the boiler are given in Appendix F.

The cost analysis is given in Table 21, which includes any change to boiler costs when using these fuels. The cost for natural gas is taken from the BOTAŞ website [23] and for fuel oil from the TÜPRAŞ website [24].

Table 21 Costs for different fuels

Fuel Type	**Additional Capital Cost YTL**	**Fuel Cost YTL/kWh**	**Fuel Cost YTL/h**	**Operating period hours/year**	**Annual Fuel Cost YTL/year**	**Pay-back period years**
Natural gas	-	0.04123	6.69	1515	10,137	
Fuel oil	7,093	0.04738	7.69	1515	11,649	Never
Coal	1,197	0.05459	8.86	1515	13,421	Never

It is seen that the fuel oil and coal have larger capital and annual costs than the natural gas. The extra labor cost to operate the coal system is not taken into account. In addition, the coal's contribution to air pollution, climate change and the uncomfortable control method are additional disadvantages for coal.

5.5.4 Heating Water Temperature of System

The heating water temperature of the existing system is 90-70 ^{o}C. In this part, different regimes will be analysed to see their effects on energy and exergy consumptions. The heating water temperature has no effect on heat loss of the building or on the heat output of the fuel during combustion. So the mass flow rate of fuel does not change with regime. According to Equation (69), the irreversibility associated with heat loss from the rooms is not related to regime either. Enthalpy and entropy values for water at different temperatures are given in Table 22.

Table 22 Enthalpy and entropy values for liquid water [13]

T (^{o}C)	**h (kJ/kg)**	**s (kJ/kgK)**
80	334.88	1.0752
75	313.91	1.0154
65	272.03	0.8934
60	251.11	0.8311
50	209.31	0.7037
35	146.66	0.5052

Using the values in Table 22 the irreversibilities of the radiators and boiler are calculated for each heating water temperature. For calculating the irreversibility of the radiators, the heating water flow rates are found using Equation (8) and for irreversibility Equation (58) is used. Results for each radiator group are given in Appendix G.

From Equation (49) it can be seen that the heating water temperature of the system affects the irreversibility of the boiler. By using this equation, boiler irreversibility values for all regimes can be calculated. The calculation for each regime is given in

Appendix G. The summary of the calculations is given in Table 23. The results for minimum (design) and average outdoor temperatures are shown in Figures 19 and 20, respectively.

Table 23 Irreversibilities for different heating water temperatures

Regime (^{o}C)	**90-70**	**80-60**	**75-65**	**50-35**
Δh_{water} (kJ/kg)	83.94	83.77	41.88	62.65
Δs_{water} (kJ/kgK)	0.2376	0.2441	0.1220	0.1985
Δe_{water} (kJ/kg)	21.891	20.024	10.020	10.812
According to minimum outdoor (design) temperature (T_0=-12 ^{O}C)				
$\dot{m}_{water}$ (kg/s)	2.570	2.575	5.151	3.443
$\dot{I}_{boiler}$ (kW)	223.170	227.865	227.817	242.201
$\dot{I}_{rad}$ (kW)	32.152	27.457	27.505	13.121
$\dot{I}_{room}$ (kW)	24.107	24.107	24.107	24.107
$\dot{I}_{boiler\,system}$ (kW)	279.429	279.429	279.429	279.429
According to average outdoor temperature (T_0=0 ^{O}C)				
$\dot{m}_{water}$ (kg/s)	1.740	1.744	3.488	2.331
$\dot{I}_{boiler}$ (kW)	154.783	158.108	158.074	168.260
$\dot{I}_{rad}$ (kW)	22.703	19.378	19.412	9.226
$\dot{I}_{room}$ (kW)	10.427	10.427	10.427	10.427
$\dot{I}_{boiler\,system}$ (kW)	187.913	187.913	187.913	187.913

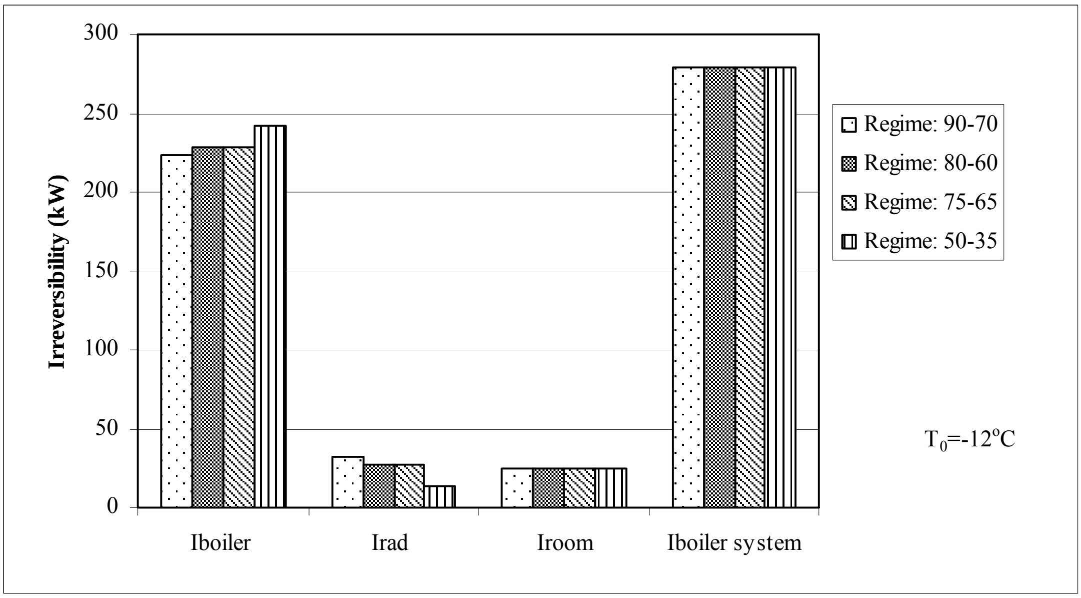

Figure 19 Irreversibilities for different heating water temperatures according to design outdoor temperature ($T_0 = -12^oC$)

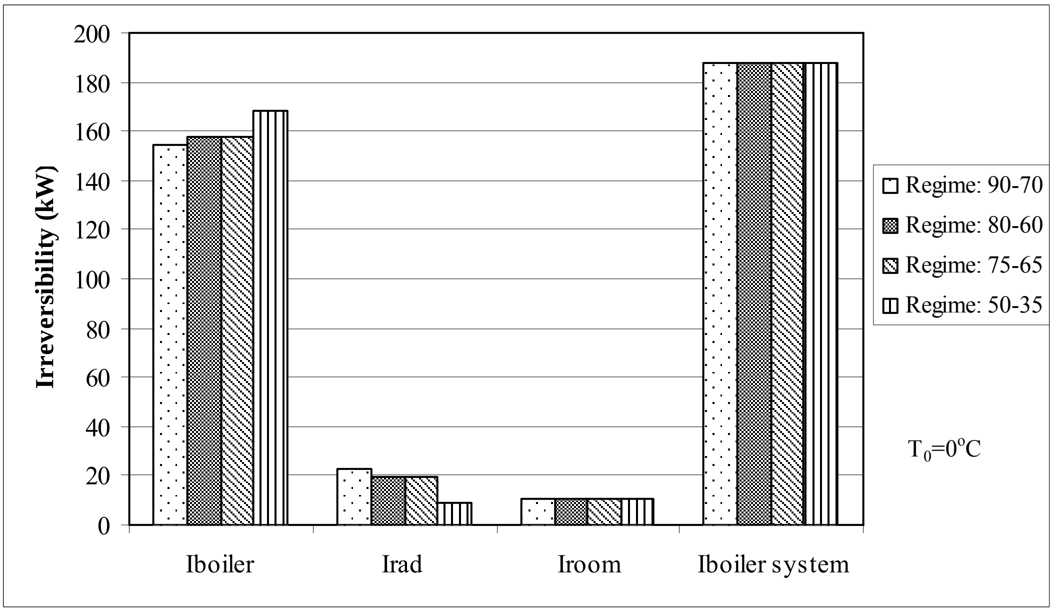

Figure 20 Irreversibilities for different heating water temperatures according to average winter outdoor temperature ($T_0 = 0^oC$)

The capital costs of radiators for different regimes are given in Table 24. The regime has no effect on the annual operating cost of the system. A decrease in regime temperature does cause capital cost to increase because of the required increase in radiator lengths.

Table 24 Capital costs of radiators for different regimes

Regime (^{o}C)	**Capital Cost of Radiators (YTL)**
90-70	20330
80-60	26106
75-65	26106
50-35	58555

5.5.5 Heat Generator

In the present system, the heat is generated by a conventional gas-fired low-pressure hot water boiler. In this part, two alternative systems are considered. The heat pump system, where an air source heat pump is powered using the grid; and the cogeneration + heat pump system, where the waste heat of a cogeneration unit is used to power an air source heat pump. The energy and exergy analyses for the heat generator part of these systems differs from the boiler system, but the energy and exergy analyses for the other parts of the systems are the same. There is no change in irreversibility values of the radiators and the rooms. A schematic drawing of the heat pump system is given in Figure 21.

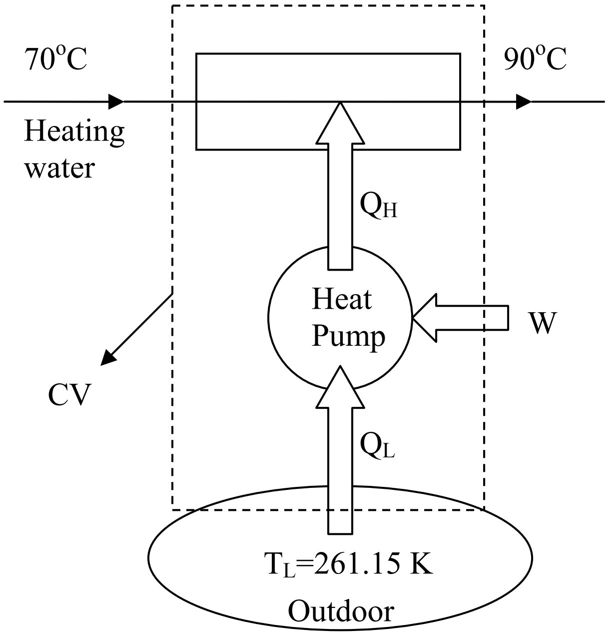

Figure 21 Schematic drawing of the heat pump system

From Equation (23) the exergy equation for the control volume that is shown in Figure 21, can be written as,

$$\dot{I} = \dot{E}_{\text{water in}} - \dot{E}_{\text{water out}} + \dot{Q}_L \cdot (1 - \frac{T_0}{T_L}) + \dot{E}_W \tag{72}$$

where,

$\dot{E}_{\text{water in}} = \dot{E}_{\text{water},70^{o}\text{C}}$ and $\dot{E}_{\text{water out}} = \dot{E}_{\text{water},90^{o}\text{C}}$. Also from Equation (22), the exergy of work is $\dot{E}_w = \dot{W}$, therefore Equation (72) can be formed as,

$$\dot{I} = \dot{m}_{\text{water}} \cdot (e_{\text{water},70^{o}\text{C}} - e_{\text{water},90^{o}\text{C}}) + \dot{Q}_L \cdot (1 - \frac{T_0}{T_L}) + \dot{W} \tag{73}$$

The water flow rate has been calculated in Equation (53) as 2.57 kg/s. From Equation (51) the expression $(e_{\text{water},70^{o}\text{C}} - e_{\text{water},90^{o}\text{C}})$ can be calculated as -21.891 kJ/kg.

$T_L = T_0$ therefore the $\dot{Q}_L \cdot (1 - \frac{T_0}{T_L})$ term becomes zero.

To calculate $\dot{W}$ the expression below can be used,

$$\dot{W} = \frac{\dot{Q}_H}{COP} \tag{74}$$

where $\dot{Q}_H$ is equal to the heat loss of the building and given in Table 7 as 216 kW and COP refers to ‘coefficient of performance’ of the heat pump. To determine the COP value a formula is derived by using literature data [8]. In this derivation, the condensing temperature (T_{HC}) is taken 10^{o}C higher than the heating water outlet temperature and the evaporating temperature (T_{LC}) is taken 10^{o}C lower than the air temperature (T_L). The assumed relation between COP and COP_{carnot} is,

$$COP = 1 + \frac{COP_{carnot} - 1}{2.1} \tag{75}$$

such that as COP_{carnot} approaches to 1, COP approaches to 1 and the system approximates an electrical resistance heater.

The experimental coefficient of performance values (COP_{exp}) that are taken from the literature and values calculated according to Equation (75) are shown in Table 25. Note that only a limited range of T_{HC}/T_{LC} experimental data are available and this must be extrapolated, which leads to uncertainty in the calculations.

Table 25 Data for coefficient of performance [8]

T_{HC}/T_{LC}	COP_{carnot}	COP_{exp}	(Calculated) COP	Error %
1.08	13.50	6.9	6.95	0.759
1.1	11.00	5.7	5.76	1.086
1.12	9.33	5	4.97	-0.635
1.14	8.14	4.55	4.40	-3.267

According to Equation (75) the calculated COP values for different temperatures are given in Table 26.

Table 26 Calculated COP values

T_{HC} (°C)	T_{LC} (°C)	COP_{carnot}	(Calculated) COP
100	-22	3.06	1.98
90	-22	3.24	2.07
85	-22	3.35	2.12
60	-22	4.06	2.46
100	-10	3.39	2.14
90	-10	3.63	2.25
85	-10	3.77	2.32
60	-10	4.76	2.79

The COP value is taken as 1.98 for the 90-70 °C hot water regime and -12 °C outdoor temperature. It is seen from the Table 26 that the coefficient of performance decreases with decreasing outdoor temperature and increasing hot water temperature as expected.

The heat pump power input is estimated using Equation (74),

$$\dot{W} = \frac{216\,\mathrm{kW}}{1.98} = 108.9\,\mathrm{kW} \tag{76}$$

Using Equation (73), the irreversibility of the heat pump is calculated as, $\dot{I} = 52.7\,\mathrm{kW}$. By adding the irreversibility values of the radiators and the rooms, the total irreversibility of the heat pump system can be found as 108.9 kW.

It can be seen that this value is very small relative to the irreversibility rate of the boiler system ($\dot{I}_{\text{boiler system}} = 279.5\,\text{kW}$). However, this value is the direct irreversibility of just the heat pump system. Using Equation (32), the primary irreversibility of the heat pump system is calculated as, $\dot{I}_{\text{HP system (primary)}} = 434.4\,\text{kW}$. In the existing system, natural gas is used as the fuel for the boiler, but the primary fuel for the heat pump system is coal. Using Equation (33), the cumulative irreversibilities for the boiler and the heat pump system are calculated as, $\dot{I}_{\text{boiler system (cum)}} = 305.4\,\text{kW}$; $\dot{I}_{\text{HP system (cum)}} = 466.1\,\text{kW}$. The exergetic efficiency values are taken as ε_{el} = 0.286, ε_{tr} = 0.877, for coal mining ε_{cum} = 0.932 and for natural gas mining ε_{cum} = 0.915 [4] [22]. The results from this irreversibility analyses are presented in Figure 22. From the graph, it can be seen that the direct irreversibility in the heat pump system is found to be much lower than in the boiler system. However, the primary and cumulative irreversibility values are higher than the boiler system.

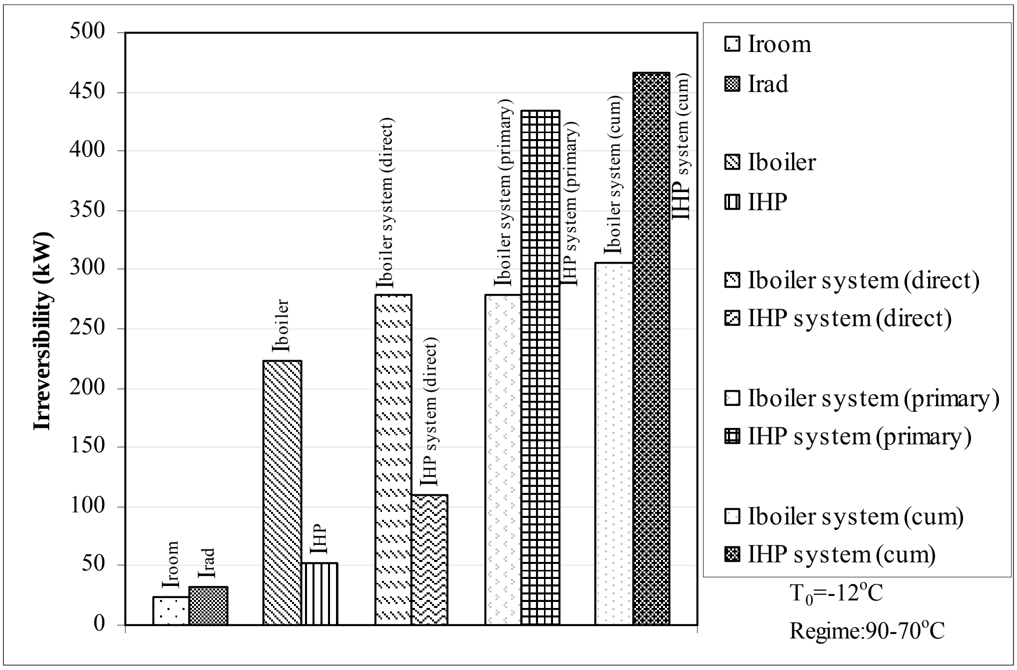

Figure 22 Irreversibilities of boiler system and heat pump system

A schematic drawing of the cogeneration + heat pump system is given in Figure 23

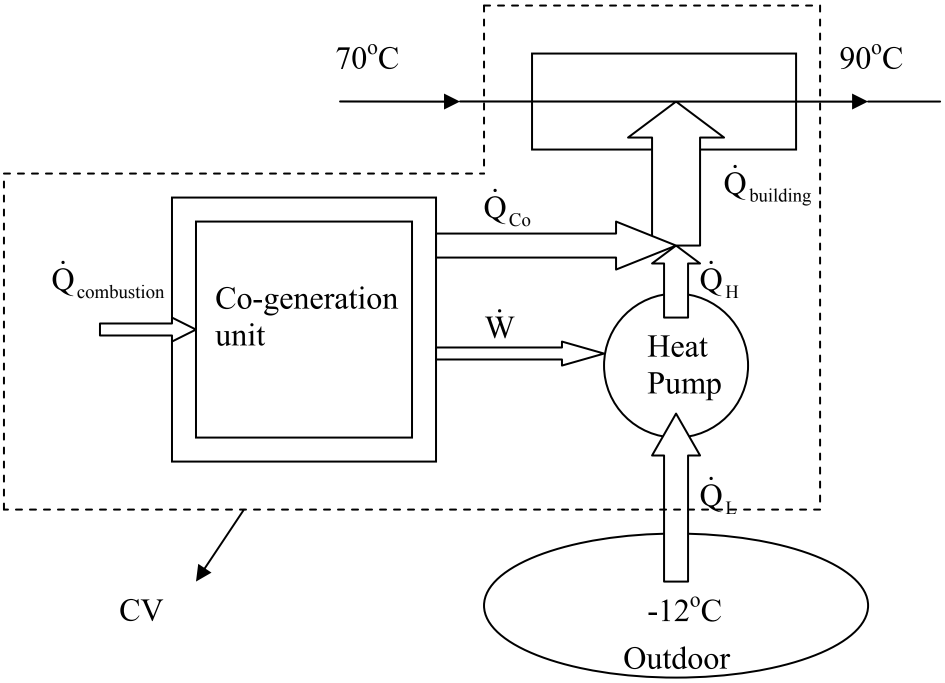

Figure 23 Schematic drawing of the cogeneration unit powered heat pump system

For the cogeneration + heat pump system the efficiency equations can be written as,

$$\dot{Q}_{Co} = \eta_{Co,heat} \cdot \dot{Q}_{combustion} \tag{77}$$

$$\dot{W} = \eta_{Co,elec} \cdot \dot{Q}_{combustion} \tag{78}$$

where, $\dot{Q}_{Co}$ is the heat output, $\dot{W}$ is the electrical output, $\eta_{Co,heat}$ is the thermal efficiency and $\eta_{Co,elec}$ is the electrical efficiency of the cogeneration unit. The values of $\eta_{Co,heat}$ and $\eta_{Co,elec}$ are assumed as 0.53 and 0.36, respectively [25].

From Equation (74) and Equation (78) the heat output of the heat pump can be written as,

$$\dot{Q}_H = \eta_{Co,elec} \cdot COP \cdot \dot{Q}_{combustion} \tag{79}$$

The summation of the heat output of the cogeneration unit and the heat pump is equal to the heat loss of the building,

$$\dot{Q}_{building} = \dot{Q}_{Co} + \dot{Q}_H \tag{80}$$

From Equations (77), (79) and (80) $\dot{Q}_{building}$ can be written as,

$$\dot{Q}_{building} = \eta_{Co,heat} \cdot \dot{Q}_{combustion} + \eta_{Co,elec} \cdot COP \cdot \dot{Q}_{combustion} \tag{81}$$

So,

$$\dot{Q}_{combustion} = \frac{\dot{Q}_{building}}{\eta_{Co,heat} + \eta_{Co,elec} \cdot COP} \tag{82}$$

By substituting the values into Equation (82),

$$\dot{Q}_{combustion} = \frac{216\,kW}{0.53 + 0.36 \cdot 1.98} = 173.6\,kW$$

From Equation (23) the exergy equation for the control volume that is shown in Figure 23 can be written as,

$$\dot{I}_{cogen+HP} = \dot{E}_{water\,in} - \dot{E}_{water\,out} + \dot{Q}_L \cdot (1 - \frac{T_0}{T_L}) + \dot{E}_{fuel} \tag{83}$$

Where $\dot{E}_{fuel}$ can be calculated by using Equations (16), (27), and (47).

When the values are substituted into Equation (83), the irreversibility of the unit is found as, $\dot{I}_{cogen+HP} = 146.1 kW$

By adding the irreversibility values of the radiators and the rooms, the total irreversibility of the cogeneration + heat pump system can be found as 202.4 kW. From Equation (33) the cumulative irreversibility of this system is calculated as 221.2 kW. The cumulative irreversibility values for three systems are shown in Figure 24 and Figure 25 according to the design and average outdoor temperatures, respectively. These results show that the cogeneration + heat pump system has the smallest irreversibility.

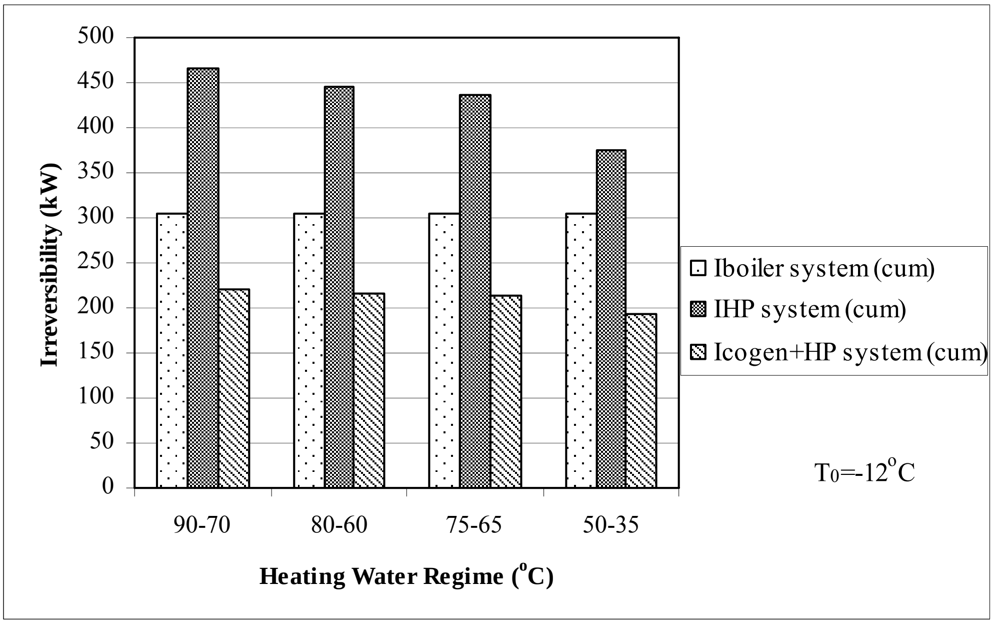

Figure 24 Cumulative irreversibilities for design outdoor temperature ($T_0 = -12^oC$)

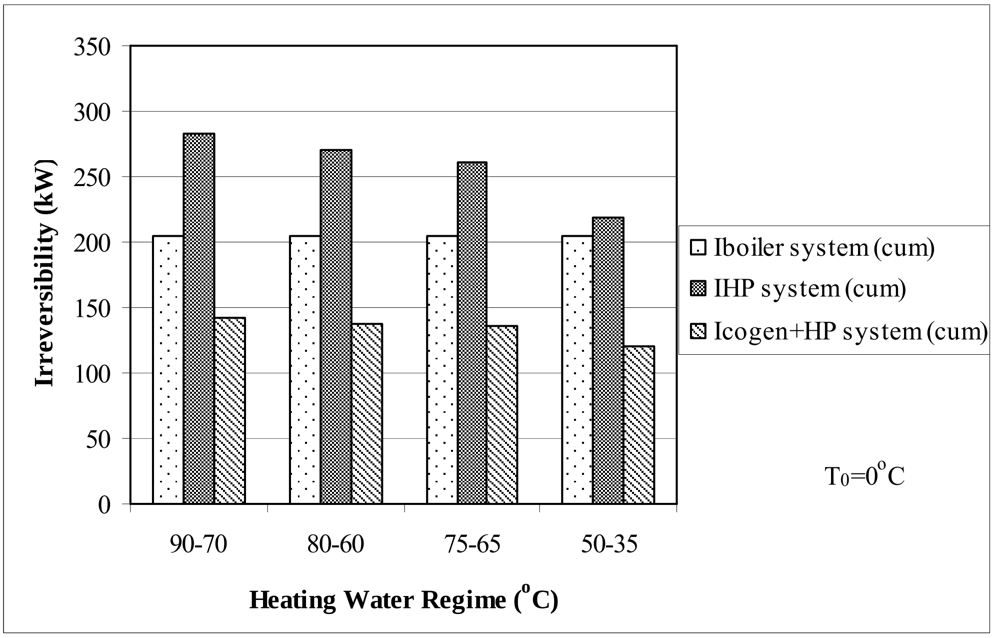

Figure 25 Cumulative irreversibilities for average outdoor temperature ($T_0 = 0^oC$)

From the figures, it can be seen that lowering the water temperature in the installation does not affect the boiler system irreversibility, however it decreases the irreversibility for a heat pump system and for cogeneration + heat pump system. This decrease is because of the increase in the heat pump's COP value. Figures 24 and 25 show that the cumulative irreversibility of the heat pump system decreases with increasing outdoor temperature. The smallest cumulative irreversibility for the heat pump system for the maximum outdoor temperature considered of 0^oC and minimum heating water temperature of 50-35 ^oC is still higher than the irreversibility of the boiler system. The cogeneration + heat pump system has the lowest irreversibility for all regimes for all conditions considered.

In Table 27, the capital and annual costs are given for the three different systems. The cost of electricity is taken from the TEDAŞ website [26]. The cost for heat pumps with 125 kW and 215 kW heating capacities are taken as 57,000YTL (31000

€) and 98000 YTL (53500 €) [27], respectively. For the cogeneration unit the cost is taken as 90,000 YTL (49000 €) [25]. The exchange rate (YTL/€) is obtained for the present day (30 March 2007) as 1.83 from the Central Bank of Republic of Turkey website [28].

It is seen that the heat pump system is never a good choice for these conditions. For cold regions, the COP value of an air source heat pump is not high enough to yield a better exergetic performance than a boiler system. The cogeneration system + heat pump system has a lower annual cost but the high capital cost causes long payback periods.

Table 27 Costs for different heat generators

Regime (^{o}C)	**System**	**Additional Capital Cost YTL**	**Fuel/Electric Cost YTL/h**	**Operating period hours/year**	**Annual Fuel Cost YTL/year**	**Payback period years**
90-70	Boiler	-	6.69088	1515	10,137	
90-70	Heat Pump	92,509	7.96710	1515	12,070	Never
90-70	Cogen +HP	141,509	4.63072	1515	7,016	45.3
80-60	Heat Pump	98,284	7.57759	1515	11,480	Never
80-60	Cogen +HP.	147,284	4.49387	1515	6,808	44.2
75-65	Heat Pump	98,284	7.34896	1515	11,134	Never
75-65	Cogen +HP.	147,284	4.41092	1515	6,683	42.6
50-35	Heat Pump	130,733	6.11096	1515	9,258	148.80
50-35	Cogen +HP	179,733	3.92453	1515	5,946	42.9

It is seen in Table 27 that the heat pump systems with 90-70^{o}C, 80-60^{o}C and 75-65^{o}C regimes do not payback, because the capital and annual costs are larger than the existing system. The payback period of the cogeneration + heat pump system initially decreases with decreasing regime temperature but then increases due to the increasing cost associated with the increasing radiator length.

CHAPTER 6

CONCLUSIONS

6.1 Conclusion of the Study

In this study, energy, exergy and economic analyses are applied to a space heating system in a high school building in Konya. In the existing system, a natural gas-fired hot water heating boiler is used for heat generation. The design outdoor temperature is -12^{o}C and for the heating fluid 90-70^{o}C hot water is used. The overall heat transfer coefficients of the structural elements of the building and heat loss values of the rooms are calculated. According to the design heating requirement, radiator lengths are selected. Inlet and outlet properties of the boiler are determined, first and second law analyses are applied by using the presented relations.

In the study, the system is separated into three parts for the exergy analysis. The first part is the heat generator. In the existing natural gas fired boiler system, the largest irreversibility occurs during combustion. The natural gas is assumed as methane and heating values for different outdoor temperatures are calculated. The calculations for this part are repeated for solid and liquid fuels, and for different outdoor temperatures, insulation grades, heating water temperatures and heat generators.

The second part is selected as the radiators. One of the aims of this study is to simplify the exergy analysis, therefore the control volumes are selected as to facilitate the calculations. The results of the calculations for all of the radiator groups are given in tables. The calculations of this part are repeated for different hot water regimes, outdoor temperatures, insulation qualities.

The third part is the heated room. Irreversibility because of the transmission and infiltration heat losses are calculated. Irreversibility values for all rooms are given in tables. These values are calculated also for different outdoor temperatures and insulation grades.

The effects of several parameters on the energy and exergy analyses are explored. One of the parameters is the outdoor temperature. The calculations are made for five different outdoor temperatures corresponding to 0, -6, -12, -18, -24^{o}C. Energy and exergy consumptions are found to increase linearly with decreasing outdoor temperature. Because of the important effect of the outdoor temperature on results, to get values that are more realistic for annual consumption, an average temperature for the winter months in Konya is calculated (as 0^{o}C). Annual operating costs are estimated according to this average winter outdoor temperature. The radiator lengths and heat generator capacities are defined according to the minimum outdoor temperature (-12 ^{o}C).

In the study, the effect of different insulation thicknesses for walls, ceiling, floor and different glass types for windows on energy and exergy analyses are considered. The maximum heat loss is due to infiltration losses (35% of total heat loss), but this fresh air is needed to maintain adequate indoor air quality. Consequently, methods to reduce infiltration losses are not explored. The largest transmission heat loss is through the windows (30% of total heat loss). The largest decrease (9.5 %) in heat loss is seen when a (4+16+4 Low-E) glass is used instead of the existing window type. To be able to compare these factors, a simple payback period calculation is performed. According to the payback periods, improving the windows is the most economical choice, with a simple payback period of 3-6 years. The shortest payback period (3.2 years) is calculated when (4+12+4) glass is used instead of the present (4+9+4) glass.

Fuel type is considered as another parameter. Analyses for gas, liquid (fuel oil) and solid (coal) fuels are made in this study. Irreversibilities based on primary fuel consumption (primary irreversibility) and primary fuel consumption including irreversibility associated with mining (cumulative irreversibility) are considered. In the exergy analysis, the fuel type affects only the boiler region. The lowest cumulative irreversibility is calculated for the coal fired boiler system (297.5 kW for design temperature; 200.2 kW for average temperature). The natural gas system requires the smallest fuel mass flow rate (12.943 kg/h). Cost analyses show that the fuel oil system has larger capital cost (capital cost of existing natural gas system + 7093 YTL) and annual cost (11,649 YTL/year) than the natural gas system (10,137 YTL/year). The annual cost for the solid fuel system (13,421 YTL/year) is larger than the existing system. In addition, when the manpower requirement and air pollution rates are considered, solid fuel is not a good choice.

Four different heating water temperatures (90-70 ^{o}C, 80-60 ^{o}C, 75-65 ^{o}C, 50-35 ^{o}C) are analysed in the study. It is seen that decrease in heating water temperature reduces the irreversibility of the radiators but increases the irreversibility rate in the boiler.

The largest change in system irreversibility occurs when the heat generator changes. As alternative heat generators, an electric powered air source heat pump alternately powered using the grid and a cogeneration unit are investigated. For the grid powered air source heat pump system, the electricity that feeds the heat pump is assumed to be produced from coal in a thermal power station. Initially, the analyses are made for the heating water temperature of the existing system. The direct irreversibility in the grid powered heat pump system (79.9 kW) is found to be much lower than in the boiler system (223.2 kW). Conversely, the primary and cumulative irreversibility values are calculated higher than the boiler system (see Figure 22). The calculations are repeated for other heating water temperatures. It is seen that decreasing the regime temperature and increasing the outdoor temperature has a positive effect on heat pump performance. However, for both the design temperature and the average temperature, the grid powered heat pump system irreversibilities are larger than for the boiler system (see Figures 24 and 25). For all regimes, the lowest irreversibilities are determined for the cogeneration + heat pump system (see Figures 24 and 25). The cost analyses show that decreasing the regime temperature decreases the annual operating cost of the cogeneration + heat pump system but increases the initial cost because of an increase in the radiator lengths.

The results can be evaluated for selecting an optimal heating system. Replacing the existing window glass with 4+16+4 Low-E glass and not using insulation in floor decreases both the capital cost (5300 YTL) and the annual operating cost (355 YTL/year). The cogeneration + heat pump system (with 50-35^{o}C heating water temperature) has the lowest annual operating cost (5,946 YTL/year) but highest additional capital cost (179,733 YTL) and relative to the present system has a payback period of 43 years.

6.2 Recommendations for Future Works

In this study, it is seen that the largest irreversibility of a boiler system occurs in the boiler. A combustion reaction with 150% theoretical air is analysed and the water in the combustion products is taken as a vapor. The analyses can be improved by taking the water formed by combustion as a liquid and by changing the theoretical air value.

Electric powered air source heat pump alternately powered by the grid and a cogeneration unit is used as alternative to the existing boiler system. Research that is more detailed can be performed for COP of heat pumps to achieve experimental values for the heating water regimes considered in this study. In the study the waste heat of the cogeneration unit is used to drive a heat pump. As an alternative to this system, generated electricity by the cogeneration unit can be used for electricity requirement of the electrical equipments in the high school instead of driving a heat pump.

The COP of heat pumps increases with decreasing heating water temperature. However, decreasing the working temperature requires an increase in the heat transfer surface and lengths of the radiators. The radiator cost is 20330 YTL for 90-70^{o}C heating water temperature and 58555 YTL for 50-35^{o}C heating water temperature. The capital cost and payback period values for cogeneration + heat pump system with 50-35^{o}C heating water temperature may decrease by using wall or floor heating instead of radiators, which by design have very large heat transfer areas and are designed to operate with low heating water temperatures as 50-35^{o}C. To prove its advisability, the economic analysis should be performed for floor and wall heating.

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APPENDIX A

HEAT TRANSFER COEFFICIENT VALUES OF BUILDING STRUCTURE COMPONENTS

Table A.1 k values for components of composite structures of building [15]

Description	**k (W/mK)**
Plaster	0.7
Plaster clipboard	0.21
Cement plaster	1.4
Brick	0.5
Concrete	2.1
Filling concrete	1.74
Extruded polystrene insulation (XPS) (with rough surface)	0.31
Extruded polystrene insulation (XPS) (with smooth surface)	0.28
Polythene foil	0.19

Table A.2 U values for windows and doors [15]

Type	U values (W/m^{2}K)								
	Single glass	Double glass				Double glass Low-E Covered			
		Air gap (mm)				Air gap (mm)			
		6	9	12	16	6	9	12	16
Wooden window	5.1	3.3	3.1	3.0	2.8	2.8	2.3	2.2	2.0
PVC window	5.0	3.2	3.0	2.8	2.7	2.2	2.1	1.9	
Metal window	5.9	4.0	3.9	3.7	3.6	3.6	3.1	3.0	2.8
Metal window (Insulated frame)	5.2	3.4	3.2	3.0	2.9	2.9	2.4	2.3	2.1
Wooden door	3.5								
Metal door (insulated)	4.5								
Metal door	5.5								

Table A.3 Air convection coefficients [15]

Description	h (W/m^{2}K)
Indoor air film, still air, vertical surface, horizontal heat flow	7.7
Indoor air film, still air, horizontal surface, upward heat flow	7.7
Indoor air film, still air, horizontal surface, downward heat flow	5.8
Outdoor air film, 24 km/h wind (winter)	23.3
Outdoor air film, attic (winter)	13

APPENDIX B

INFILTRATION AND INCREMENT COEFFICIENTS OF HEAT LOSS CALCULATIONS

Table B.1 Z_D values [12]

Operating I: Process works all day, slowdowns at nights Operating II: Process stops 10 hours everyday Operating III: Process stops 14 hours or more everyday $D = Q_0 / A(T_{in}-T_{out})$ Q_0:Net total heat loss A:Total area heat transferred				
	D			
Operating Situation	0.1-0.29	0.30-0.69	0.7-1.49	>1.5
	Z_D%			
Operating I	7	7	7	7
Operating II	20	15	15	15
Operating III	30	25	20	15

Table B.2 Z_H values [12]

Direction	S	SW	W	NW	N	NE	E	SE
Z_H%	-5	-5	0	5	5	5	0	-5

Table B.3 Z_W values [12]

		Floors				
Total floor number of building	**4**	3,2,1	4			
	5	3,2,1	4	5		
	6	3,2,1	5,4	6		
	7	3,2,1	5,4	6	7	
	8	3,2,1	5,4	7,6	8	
	9	3,2,1	6,5,4	8,7	9	
	10	3,2,1	6,5,4	9,8,7	10	
	11	3,2,1	6,5,4	9,8,7	10	11
	12	3,2,1	6,5,4	9,8,7	11,10	12
	13	3,2,1	6,5,4	9,8,7	12,11,10	13
	14	4,3,2,1	7,6,5	10,9,8	13,12,11	14
	15	5,4,3,2,1	8,7,6	11,10,9	14,13,12	15
Z_W%		0	5	10	15	20

Table B.4 Air infiltration coefficients of window and doors [12]

Material	**Type of window or door**	**a**
Wood	Single glass	3
Wood	Double glass	2.5
PVC	Single glass	2
PVC	Double glass	1.5
Metal	Single glass	1.5
Metal	Double glass	1.5
Note: Doors behaves like windows		

Table B.5 R values [12]

Window frame type		Window area/Interior door area	R
Wooden or PVC	Intermittent	<3	0.9
	Contiguous	<1.5	
Metal	Intermittent	<6	
	Contiguous	<2.5	
Wooden or PVC	Intermittent	3-9	0.7
	Contiguous	1.5-3	
Metal	Intermittent	6-20	
	Contiguous	2.5-6	

Table B.6 Building situation coefficients [12]

Situation of Region	Situation of Building	H (kWh/m$^{3\circ}$C)	
		Contiguous	Detached
Normal	Sheltered	0.279x10^{-3}	0.396x10^{-3}
	Semi-sheltered	0.477x10^{-3}	0.675x10^{-3}
	Free	0.700x10^{-3}	0.977x10^{-3}
Windy	Sheltered	0.477x10^{-3}	0.675x10^{-3}
	Semi-sheltered	0.700x10^{-3}	0.977x10^{-3}
	Free	0.950x10^{-3}	1.314x10^{-3}

Table B.7 Room situation coefficients [12]

Room Situation	**Z$_e$**
Room with windows at two or more side	1.2
Room with windows at one side	1

APPENDIX C

RADIATOR HEAT TRANSFER CAPACITIES

Table C.1 Radiator heat transfer capacities for 90-70°C water regime [16]

Room Temperature (°C)	**15**	**18**	**20**	**22**	**24**	**26**
160/500	149	140	135	128	122	116
160/900	230	216	207	198	190	180
Note: The units of capacities are Watt.						

Table C.2 Radiator heat transfer capacities for 80-60°C and 75-65°C water regime

Room Temperature (°C)	**15**	**18**	**20**	**22**	**24**	**26**
160/500	116	108	102	97	92	86
160/900	177	165	156	148	140	132
Note: The units of capacities are Watt.						

Table C.3 Radiator heat transfer capacities for 50-35°C water regime

Room Temperature (°C)	**15**	**18**	**20**	**22**	**24**	**26**
160/500	55	50	44	42	39	35
160/900	81	74	67	62	56	52
Note: The units of capacities are Watt.						

APPENDIX D

CALCULATION ACCORDING TO DIFFERENT OUTDOOR TEMPERATURES

D.1 Heat Loss Calculations

Table D.1.1 Heat losses for 0^{o}C outdoor temperature

NO.	ROOM NAME	HEAT LOSS (Watts)	ROOM TEMP. (°C)	RAD. TYPE	PIECE	GROUP CAP.	GR. QTY	TOTAL HEAT SUPPLY CAP. (Watts)
201	CLASSROOM	3400	22	160/500	7	854	4	3416
202	CLASSROOM	2803	22	160/500	8	976	3	2928
203	CLASSROOM	3363	22	160/500	10	1220	3	3660
204	CLASSROOM	3618	22	160/500	8	976	4	3904
205	MEN WC	481	18	160/500	4	536	1	536
206	WOMEN WC	481	18	160/500	4	536	1	536
207	TEACHERS ROOM	694	22	160/500	6	732	1	732
208	CLASSROOM	3247	22	160/500	9	1098	3	3294
209	MEETING ROOM	4161	22	160/500	9	1098	4	4392
210	LIBRARY	6368	22	160/500	8	976	7	6832
211	MEN WC	262	18	160/500	3	402	1	402
212	WOMEN WC	241	18	160/500	3	402	1	402
213	WOMEN WC	481	18	160/500	4	536	1	536
214	MEN WC	481	18	160/500	4	536	1	536
215	CLASSROOM	3618	22	160/500	8	976	4	3904
216	COMPUTER ROOM	4596	22	160/500	8	976	5	4880
217	PREP.ROOM	692	18	160/500	6	804	1	804
218	LABORATORY	2835	18	160/500	6	804	4	3216
225	CORRIDOR	6022	18	160/500	6	804	8	6432
101	CLASSROOM	2835	22	160/500	6	732	4	2928
102	CLASSROOM	2239	22	160/500	7	854	3	2562
103	CLASSROOM	2799	22	160/500	8	976	3	2928

Table D.1.1 (continued)

NO.	ROOM NAME	HEAT LOSS (Watts)	ROOM TEMP. (°C)	RAD. TYPE	PIECE	GROUP CAP.	GR. QTY	TOTAL HEAT SUPPLY CAP. (Watts)
104	CLASSROOM	3053	22	160/500	7	854	4	3416
105	MEN WC	284	18	160/500	3	402	1	402
106	WOMEN WC	284	18	160/500	3	402	1	402
107	STORAGE	290	15	160/500	3	426	1	426
108	CLASSROOM	2895	22	160/500	8	976	3	2928
109	CANTEEN	2197	18	160/500	5	670	4	2680
110	OFFICIAL	1628	22	160/500	7	854	2	1708
111	MANAGER ROOM	2650	22	160/500	8	976	3	2928
112	PUBLICATION	1628	22	160/500	7	854	2	1708
113	MEN WC	174	18	160/500	3	402	1	402
114	WOMEN WC	174	18	160/500	3	402	1	402
115	WOMEN WC	284	18	160/500	3	402	1	402
116	MEN WC	284	18	160/500	3	402	1	402
117	CLASSROOM	3053	22	160/500	7	854	4	3416
118	MUSIC ROOM	4296	22	160/500	8	976	5	4880
119	STORAGE	448	15	160/500	4	568	1	568
120	MECHANICAL WS	2920	18	160/500	6	804	4	3216
124	CORRIDOR	2985	18	160/500	3	402	8	3216
Z01	CLASSROOM	3612	22	160/500	8	976	4	3904
Z02	CLASSROOM	2979	22	160/500	9	1098	3	3294
Z03	CLASSROOM	3590	22	160/500	10	1220	3	3660
Z04	CLASSROOM	3854	22	160/500	8	976	4	3904
Z05	MEN WC	300	18	160/500	3	402	1	402
Z06	WOMEN WC	300	18	160/500	3	402	1	402
Z07	EQUIPMENT ROOM	303	15	160/500	3	426	1	426
Z08	MEETING ROOM	959	22	160/500	8	976	1	976
Z09	GUIDANCE	1991	22	160/500	9	1098	2	2196
Z10	ARCHIVE	466	15	160/500	4	568	1	568
Z11	INFIRMARY	3647	24	160/500	16	1872	2	3744
Z12	MANAGER ASSISTANT	1956	22	160/500	9	1098	2	2196
Z13	SOCIAL ROOM	1543	22	160/500	7	854	2	1708
Z14	MEN WC	182	18	160/500	3	402	1	402
Z15	WOMEN WC	182	18	160/500	3	402	1	402
Z16	WOMEN WC	300	18	160/500	3	402	1	402
Z17	MEN WC	300	18	160/500	3	402	1	402
Z18	ACTIVITY ROOM	3159	22	160/500	7	854	4	3416
Z19	OFFICE	548	18	160/500	5	670	1	670
Z20	ACTIVITY ROOM	3249	22	160/500	9	1098	3	3294
Z21	CLASSROOM	4372	22	160/500	9	1098	4	4392
Z22	CORRIDOR	5436	18	160/500	5	670	10	6700

Table D.1.1 (continued)

NO.	ROOM NAME	HEAT LOSS (Watts)	ROOM TEMP. (°C)	RAD. TYPE	PIECE	GROUP CAP.	GR. QTY	TOTAL HEAT SUPPLY CAP. (Watts)
B01	SHELTER	4280	18	160/900	4	864	5	4320
B03	STORAGE	353	15	160/900	3	690	1	690
B05	WORKER DRESSING ROOM	1223	24	160/900	7	1330	1	1330
B06	WORKER ROOM	1823	22	160/900	10	1980	1	1980
B08	MEN WC	208	18	160/900	3	648	1	648
B09	WOMEN WC	198	18	160/900	3	648	1	648
B10	WOMEN WC	320	18	160/900	3	648	1	648
B11	MEN WC	292	18	160/900	3	648	1	648
B12	MEN DRESSING ROOM	1364	24	160/900	8	1520	1	1520
B13	SPOR EQ.ROOM	216	15	160/900	3	690	1	690
B14	WOMEN DRESSING ROOM	1344	24	160/900	8	1520	1	1520
B15	PHYSICAL TRAINING HALL	2087	18	160/900	4	864	3	2592
B17	MEN TEACH.DRESS.ROOM	1364	24	160/900	8	1520	1	1520
B18	WOMEN TEACH.DRES.	1401	24	160/900	8	1520	1	1520
B19	CORRIDOR	1116	18	160/900	3	648	2	1296
	TOTAL	**146,060**		**160/500**	**1127**		**189**	**162,292**
				160/900	**105**			

Table D.1.2 Heat losses for -6°C outdoor temperature

NO.	ROOM NAME	HEAT LOSS (Watts)	ROOM TEMP. (°C)	RAD. TYPE	PIECE	GROUP CAP.	GR. QTY	TOTAL HEAT CAP. (Watts)
201	CLASSROOM	4247	22	160/500	9	1098	4	4392
202	CLASSROOM	3495	22	160/500	10	1220	3	3660
203	CLASSROOM	4335	22	160/500	12	1464	3	4392
204	CLASSROOM	4465	22	160/500	10	1220	4	4880
205	MEN WC	641	18	160/500	5	670	1	670
206	WOMEN WC	641	18	160/500	5	670	1	670
207	TEACHERS ROOM	883	22	160/500	8	976	1	976
208	CLASSROOM	3956	22	160/500	11	1342	3	4026
209	MEETING ROOM	5107	22	160/500	11	1342	4	5368
210	LIBRARY	7918	22	160/500	10	1220	7	8540
211	MEN WC	349	18	160/500	3	402	1	402
212	WOMEN WC	322	18	160/500	3	402	1	402
213	WOMEN WC	641	18	160/500	5	670	1	670
214	MEN WC	641	18	160/500	5	670	1	670
215	CLASSROOM	4465	22	160/500	10	1220	4	4880
216	COMPUTER ROOM	5690	22	160/500	10	1220	5	6100
217	PREP.ROOM	922	18	160/500	7	938	1	938
218	LABORATORY	3967	18	160/500	8	1072	4	4288
225	CORRIDOR	8092	18	160/500	8	1072	8	8576
101	CLASSROOM	3528	22	160/500	8	976	4	3904
102	CLASSROOM	2776	22	160/500	8	976	3	2928
103	CLASSROOM	3617	22	160/500	10	1220	3	3660
104	CLASSROOM	3746	22	160/500	8	976	4	3904
105	MEN WC	379	18	160/500	3	402	1	402
106	WOMEN WC	379	18	160/500	3	402	1	402
107	STORAGE	405	15	160/500	3	426	1	426
108	CLASSROOM	3444	22	160/500	10	1220	3	3660
109	CANTEEN	2930	18	160/500	6	804	4	3216
110	OFFICIAL	2014	22	160/500	9	1098	2	2196
111	MANAGER ROOM	3176	22	160/500	9	1098	3	3294
112	PUBLICATION	2014	22	160/500	9	1098	2	2196
113	MEN WC	232	18	160/500	3	402	1	402
114	WOMEN WC	232	18	160/500	3	402	1	402
115	WOMEN WC	379	18	160/500	3	402	1	402
116	MEN WC	379	18	160/500	3	402	1	402
117	CLASSROOM	3746	22	160/500	8	976	4	3904
118	MUSIC ROOM	5185	22	160/500	9	1098	5	5490
119	STORAGE	627	15	160/500	5	710	1	710
120	MECHANICAL WORKSHOP	3706	18	160/500	7	938	4	3752
124	CORRIDOR	4043	18	160/500	4	536	8	4288
Z01	CLASSROOM	4324	22	160/500	9	1098	4	4392

Table D.1.2 (continued)

NO.	**ROOM NAME**	**HEAT LOSS (Watts)**	**ROOM TEMP. (°C)**	**RAD. TYPE**	**PIECE**	**GROUP CAP.**	**GR. QTY**	**TOTAL HEAT CAP. (Watts)**
Z02	CLASSROOM	3526	22	160/500	10	1220	3	3660
Z03	CLASSROOM	4443	22	160/500	13	1586	3	4758
Z04	CLASSROOM	4567	22	160/500	10	1220	4	4880
Z05	MEN WC	400	18	160/500	3	402	1	402
Z06	WOMEN WC	400	18	160/500	3	402	1	402
Z07	EQUIPMENT ROOM	424	15	160/500	3	426	1	426
Z08	MEETING ROOM	1060	22	160/500	9	1098	1	1098
Z09	GUIDANCE	2364	22	160/500	10	1220	2	2440
Z10	ARCHIVE	653	15	160/500	5	710	1	710
Z11	INFIRMARY	4099	24	160/500	18	2106	2	4212
Z12	MANAGER ASSISTANT	2322	22	160/500	10	1220	2	2440
Z13	SOCIAL ROOM	1908	22	160/500	8	976	2	1952
Z14	MEN WC	242	18	160/500	3	402	1	402
Z15	WOMEN WC	242	18	160/500	3	402	1	402
Z16	WOMEN WC	400	18	160/500	3	402	1	402
Z17	MEN WC	400	18	160/500	3	402	1	402
Z18	ACTIVITY ROOM	3872	22	160/500	8	976	4	3904
Z19	OFFICE	730	18	160/500	6	804	1	804
Z20	ACTIVITY ROOM	3797	22	160/500	11	1342	3	4026
Z21	CLASSROOM	5408	22	160/500	12	1464	4	5856
Z22	CORRIDOR	7199	18	160/500	6	804	10	8040
B01	SHELTER	5123	18	160/900	5	1080	5	5400
B03	STORAGE	448	15	160/900	3	690	1	690
B05	WORKER DRESSING ROOM	1347	24	160/900	8	1520	1	1520
B06	WORKER ROOM	1929	22	160/900	10	1980	1	1980
B08	MEN WC	266	18	160/900	3	648	1	648
B09	WOMEN WC	253	18	160/900	3	648	1	648
B10	WOMEN WC	405	18	160/900	3	648	1	648
B11	MEN WC	373	18	160/900	3	648	1	648
B12	MEN DRESSING ROOM	1446	24	160/900	8	1520	1	1520
B13	SPOR EQ.ROOM	297	15	160/900	3	690	1	690
B14	WOMEN DRESSING ROOM	1468	24	160/900	8	1520	1	1520
B15	PHYSICAL TRAINING HALL	2630	18	160/900	5	1080	3	3240
B17	MEN TEACH.DRESS.ROOM	1446	24	160/900	8	1520	1	1520
B18	WOMEN TEACH.DRES.	1788	24	160/900	10	1900	1	1900
B19	CORRIDOR	1442	18	160/900	4	864	2	1728
	TOTAL	**181,156**		**160/500**	**1365**		**189**	**194,750**
				160/900	**118**			

Table D.1.3 Heat losses for -18°C outdoor temperature

NO.	ROOM NAME	HEAT LOSS (Watts)	ROOM TEMP. (°C)	RAD. TYPE	PIECE	GROUP CAP.	GR. QTY	TOTAL HEAT CAP. (Watts)
201	CLASSROOM	5940	22	160/500	13	1586	4	6344
202	CLASSROOM	4878	22	160/500	14	1708	3	5124
203	CLASSROOM	6209	22	160/500	17	2074	3	6222
204	CLASSROOM	6159	22	160/500	13	1586	4	6344
205	MEN WC	961	18	160/500	8	1072	1	1072
206	WOMEN WC	961	18	160/500	8	1072	1	1072
207	TEACHERS ROOM	1262	22	160/500	11	1342	1	1342
208	CLASSROOM	5375	22	160/500	15	1830	3	5490
209	MEETING ROOM	6999	22	160/500	15	1830	4	7320
210	LIBRARY	11019	22	160/500	13	1586	7	11102
211	MEN WC	523	18	160/500	4	536	1	536
212	WOMEN WC	483	18	160/500	4	536	1	536
213	WOMEN WC	961	18	160/500	8	1072	1	1072
214	MEN WC	961	18	160/500	8	1072	1	1072
215	CLASSROOM	6159	22	160/500	13	1586	4	6344
216	COMPUTER ROOM	7878	22	160/500	13	1586	5	7930
217	PREP.ROOM	1383	18	160/500	11	1474	1	1474
218	LABORATORY	6160	18	160/500	12	1608	4	6432
225	CORRIDOR	12208	18	160/500	12	1608	8	12864
101	CLASSROOM	4914	22	160/500	11	1342	4	5368
102	CLASSROOM	3852	22	160/500	11	1342	3	4026
103	CLASSROOM	5182	22	160/500	15	1830	3	5490
104	CLASSROOM	5132	22	160/500	11	1342	4	5368
105	MEN WC	569	18	160/500	5	670	1	670
106	WOMEN WC	569	18	160/500	5	670	1	670
107	STORAGE	637	15	160/500	5	710	1	710
108	CLASSROOM	4543	22	160/500	13	1586	3	4758
109	CANTEEN	4394	18	160/500	9	1206	4	4824
110	OFFICIAL	2786	22	160/500	12	1464	2	2928
111	MANAGER ROOM	4228	22	160/500	12	1464	3	4392
112	PUBLICATION	2786	22	160/500	12	1464	2	2928
113	MEN WC	348	18	160/500	3	402	1	402
114	WOMEN WC	348	18	160/500	3	402	1	402
115	WOMEN WC	569	18	160/500	5	670	1	670
116	MEN WC	569	18	160/500	5	670	1	670
117	CLASSROOM	5132	22	160/500	11	1342	4	5368
118	MUSIC ROOM	6962	22	160/500	12	1464	5	7320
119	STORAGE	986	15	160/500	7	994	1	994
120	MECHANICAL WORKSHOP	5279	18	160/500	10	1340	4	5360
124	CORRIDOR	6135	18	160/500	6	804	8	6432
Z01	CLASSROOM	5750	22	160/500	12	1464	4	5856
Z02	CLASSROOM	4622	22	160/500	13	1586	3	4758

Table D.1.3 (continued)

NO.	ROOM NAME	HEAT LOSS (Watts)	ROOM TEMP. (°C)	RAD. TYPE	PIECE	GROUP CAP.	GR. QTY	TOTAL HEAT CAP. (Watts)
Z03	CLASSROOM	6074	22	160/500	17	2074	3	6222
Z04	CLASSROOM	5992	22	160/500	13	1586	4	6344
Z05	MEN WC	599	18	160/500	5	670	1	670
Z06	WOMEN WC	599	18	160/500	5	670	1	670
Z07	EQUIPMENT ROOM	666	15	160/500	5	710	1	710
Z08	MEETING ROOM	1263	22	160/500	11	1342	1	1342
Z09	GUIDANCE	3110	22	160/500	13	1586	2	3172
Z10	ARCHIVE	1026	15	160/500	8	1136	1	1136
Z11	INFIRMARY	5003	24	160/500	22	2574	2	5148
Z12	MANAGER ASSISTANT	3053	22	160/500	13	1586	2	3172
Z13	SOCIAL ROOM	2639	22	160/500	11	1342	2	2684
Z14	MEN WC	364	18	160/500	3	402	1	402
Z15	WOMEN WC	364	18	160/500	3	402	1	402
Z16	WOMEN WC	599	18	160/500	5	670	1	670
Z17	MEN WC	599	18	160/500	5	670	1	670
Z18	ACTIVITY ROOM	5298	22	160/500	11	1342	4	5368
Z19	OFFICE	1096	18	160/500	9	1206	1	1206
Z20	ACTIVITY ROOM	4892	22	160/500	14	1708	3	5124
Z21	CLASSROOM	7404	22	160/500	16	1952	4	7808
Z22	CORRIDOR	10698	18	160/500	8	1072	10	10720
B01	SHELTER	6807	18	160/900	7	1512	5	7560
B03	STORAGE	638	15	160/900	3	690	1	690
B05	WORKER DRESSING ROOM	1597	24	160/900	9	1710	1	1710
B06	WORKER ROOM	2142	22	160/900	11	2178	1	2178
B08	MEN WC	380	18	160/900	3	648	1	648
B09	WOMEN WC	362	18	160/900	3	648	1	648
B10	WOMEN WC	575	18	160/900	3	648	1	648
B11	MEN WC	535	18	160/900	3	648	1	648
B12	MEN DRESSING ROOM	1610	24	160/900	9	1710	1	1710
B13	SPOR EQ.ROOM	460	15	160/900	3	690	1	690
B14	WOMEN DRESSING ROOM	1716	24	160/900	10	1900	1	1900
B15	PHYSICAL TRAINING HALL	3716	18	160/900	6	1296	3	3888
B17	MEN TEACH.DRESS.ROOM	1610	24	160/900	9	1710	1	1710
B18	WOMEN TEACH.DRES.	2487	24	160/900	14	2660	1	2660
B19	CORRIDOR	2079	18	160/900	5	1080	2	2160
	TOTAL	**250,824**		**160/350**	**0**		**189**	**263,144**
				160/500	**1868**			
				160/900	**143**			

Table D.1.4 Heat losses for -24°C outdoor temperature

NO.	ROOM NAME	HEAT LOSS (Watts)	ROOM TEMP. (°C)	RAD. TYPE	PIECE	GROUP CAP.	GR. QTY	TOTAL HEAT SUPPLY CAP. (Watts)
201	CLASSROOM	6787	22	160/500	14	1708	4	6832
202	CLASSROOM	5570	22	160/500	16	1952	3	5856
203	CLASSROOM	7110	22	160/500	20	2440	3	7320
204	CLASSROOM	7005	22	160/500	15	1830	4	7320
205	MEN WC	1121	18	160/500	9	1206	1	1206
206	WOMEN WC	1121	18	160/500	9	1206	1	1206
207	TEACHERS ROOM	1451	22	160/500	12	1464	1	1464
208	CLASSROOM	6084	22	160/500	17	2074	3	6222
209	MEETING ROOM	7944	22	160/500	17	2074	4	8296
210	LIBRARY	12570	22	160/500	15	1830	7	12810
211	MEN WC	611	18	160/500	5	670	1	670
212	WOMEN WC	563	18	160/500	5	670	1	670
213	WOMEN WC	1121	18	160/500	9	1206	1	1206
214	MEN WC	1121	18	160/500	9	1206	1	1206
215	CLASSROOM	7005	22	160/500	15	1830	4	7320
216	COMPUTER ROOM	8972	22	160/500	15	1830	5	9150
217	PREP.ROOM	1614	18	160/500	13	1742	1	1742
218	LABORATORY	7222	18	160/500	14	1876	4	7504
225	CORRIDOR	14254	18	160/500	14	1876	8	15008
101	CLASSROOM	5607	22	160/500	12	1464	4	5856
102	CLASSROOM	4390	22	160/500	12	1464	3	4392
103	CLASSROOM	5930	22	160/500	17	2074	3	6222
104	CLASSROOM	5825	22	160/500	12	1464	4	5856
105	MEN WC	664	18	160/500	5	670	1	670
106	WOMEN WC	664	18	160/500	5	670	1	670
107	STORAGE	753	15	160/500	6	852	1	852
108	CLASSROOM	5092	22	160/500	14	1708	3	5124
109	CANTEEN	5127	18	160/500	10	1340	4	5360
110	OFFICIAL	3172	22	160/500	13	1586	2	3172
111	MANAGER ROOM	4754	22	160/500	13	1586	3	4758
112	PUBLICATION	3172	22	160/500	13	1586	2	3172
113	MEN WC	406	18	160/500	4	536	1	536
114	WOMEN WC	406	18	160/500	4	536	1	536
115	WOMEN WC	664	18	160/500	5	670	1	670
116	MEN WC	664	18	160/500	5	670	1	670
117	CLASSROOM	5825	22	160/500	12	1464	4	5856
118	MUSIC ROOM	7851	22	160/500	13	1586	5	7930
119	STORAGE	1165	15	160/500	9	1278	1	1278
120	MECHANICAL WORKSHOP	6065	18	160/500	12	1608	4	6432
124	CORRIDOR	7169	18	160/500	7	938	8	7504
Z01	CLASSROOM	6463	22	160/500	14	1708	4	6832

Table D.1.4 (continued)

NO.	ROOM NAME	HEAT LOSS (Watts)	ROOM TEMP. (°C)	RAD. TYPE	PIECE	GROUP CAP.	GR. QTY	TOTAL HEAT SUPPLY CAP. (Watts)
Z02	CLASSROOM	5170	22	160/500	15	1830	3	5490
Z03	CLASSROOM	6851	22	160/500	19	2318	3	6954
Z04	CLASSROOM	6705	22	160/500	14	1708	4	6832
Z05	MEN WC	699	18	160/500	6	804	1	804
Z06	WOMEN WC	699	18	160/500	6	804	1	804
Z07	EQUIPMENT ROOM	787	15	160/500	6	852	1	852
Z08	MEETING ROOM	1364	22	160/500	12	1464	1	1464
Z09	GUIDANCE	3483	22	160/500	15	1830	2	3660
Z10	ARCHIVE	1213	15	160/500	9	1278	1	1278
Z11	INFIRMARY	5454	24	160/500	24	2808	2	5616
Z12	MANAGER ASSISTANT	3419	22	160/500	15	1830	2	3660
Z13	SOCIAL ROOM	3005	22	160/500	13	1586	2	3172
Z14	MEN WC	424	18	160/500	4	536	1	536
Z15	WOMEN WC	424	18	160/500	4	536	1	536
Z16	WOMEN WC	699	18	160/500	6	804	1	804
Z17	MEN WC	699	18	160/500	6	804	1	804
Z18	ACTIVITY ROOM	6010	22	160/500	13	1586	4	6344
Z19	OFFICE	1278	18	160/500	10	1340	1	1340
Z20	ACTIVITY ROOM	5440	22	160/500	15	1830	3	5490
Z21	CLASSROOM	8364	22	160/500	18	2196	4	8784
Z22	CORRIDOR	12435	18	160/500	10	1340	10	13400
B01	SHELTER	7650	18	160/900	8	1728	5	8640
B03	STORAGE	733	15	160/900	4	920	1	920
B05	WORKER DRESSING ROOM	1721	24	160/900	10	1900	1	1900
B06	WORKER ROOM	2249	22	160/900	12	2376	1	2376
B08	MEN WC	438	18	160/900	3	648	1	648
B09	WOMEN WC	417	18	160/900	3	648	1	648
B10	WOMEN WC	660	18	160/900	4	864	1	864
B11	MEN WC	616	18	160/900	3	648	1	648
B12	MEN DRESSING ROOM	1692	24	160/900	9	1710	1	1710
B13	SPOR EQ.ROOM	542	15	160/900	3	690	1	690
B14	WOMEN DRESSING ROOM	1840	24	160/900	10	1900	1	1900
B15	PHYSICAL TRAINING HALL	4258	18	160/900	7	1512	3	4536
B17	MEN TEACH.DRESS.ROOM	1692	24	160/900	9	1710	1	1710
B18	WOMEN TEACH.DRES.	2798	24	160/900	15	2850	1	2850
B19	CORRIDOR	2390	18	160/900	6	1296	2	2592
	TOTAL	**285,395**		**160/500**	**2124**		**189**	**298,612**
				160/900	**158**			

D.2 Irreversibility of Boiler and Fuel Mass Flow Rate Calculations

D.2.1 Calculation of Combustion Heat for Different Outdoor Temperatures

The input air to the boiler changes with outdoor temperature and this situation affects the combustion heat in the boiler. The combustion heat calculations for different air temperatures are given below.

for T_0=0

	n	**h_f**	**h(273K)**	**h(450K)**	**h_0(298K)**	**n. (h_f+h-h_0)**
CH4	1	-74850				-74850
O2	3	0	7946		8682	-2208
N2	11.3	0	7937		8669	-8256.96
CO2	1	-393520		15483	9364	-387401
H2O	2	-241820		15080	9904	-473288
N2	11.3	0		12811	8669	46721.76
O2	1	0		13228	8682	4546

$\bar{q}_{combustion}$:	724106.280	kJ/kmol CH4
$q_{combustion}$:	45138.155	kJ/kg CH4

for T_0=-6

	n	**h_f**	**h(267K)**	**h(450K)**	**h_0(298K)**	**n. (h_f+h-h_0)**
CH4	1	-74850				-74850
O2	3	0	7770		8682	-2736
N2	11.3	0	7761		8669	-10242.24
CO2	1	-393520		15483	9364	-387401
H2O	2	-241820		15080	9904	-473288
N2	11.3	0		12811	8669	46721.76
O2	1	0		13228	8682	4546

$\bar{q}_{combustion}$:	721593.000	kJ/kmol CH4
$q_{combustion}$:	44981.486	kJ/kg CH4

for T_0=-12

	n	h_f	h(261K)	h(450K)	h_0(298K)	n. (h_f+h-h_0)
CH4	1	-74850				-74850
O2	3	0	7595		8682	-3261
N2	11.3	0	7587		8669	-12204.96
CO2	1	-393520		15483	9364	-387401
H2O	2	-241820		15080	9904	-473288
N2	11.3	0		12811	8669	46721.76
O2	1	0		13228	8682	4546

$\overline{q}_{combustion}$:	719105.280	kJ/kmol CH4
$q_{combustion}$:	44826.411	kJ/kg CH4

for T_0=-18

	n	h_f	h(255K)	h(450K)	h_0(298K)	n. (h_f+h-h_0)
CH4	1	-74850				-74850
O2	3	0	7421		8682	-3783
N2	11.3	0	7412		8669	-14178.96
CO2	1	-393520		15483	9364	-387401
H2O	2	-241820		15080	9904	-473288
N2	11.3	0		12811	8669	46721.76
O2	1	0		13228	8682	4546

$\overline{q}_{combustion}$:	716609.280	kJ/kmol CH4
$q_{combustion}$:	44670.819	kJ/kg CH4

for T_0=-24

	n	h_f	h(249K)	h(450K)	h_0(298K)	n. (h_f+h-h_0)
CH4	1	-74850				-74850
O2	3	0	7246		8682	-4308
N2	11.3	0	7237		8669	-16152.96
CO2	1	-393520		15483	9364	-387401
H2O	2	-241820		15080	9904	-473288
N2	11.3	0		12811	8669	46721.76
O2	1	0		13228	8682	4546

$\overline{q}_{combustion}$:	714110.280	kJ/kmol CH4
$q_{combustion}$:	44515.041	kJ/kg CH4

D.2.2 MathCAD Calculation for $0^{o}C$ Outdoor Temperature

$\text{Qbuilding} := 146.060$ $\text{qcombustion} := 45138.155$ $\text{LHV} := 50010$

$\eta := 0.9$ $a := 1.04$

$\text{Cp} := 2.254$ $T := 298.15$ $\text{T0} := 273.15$

$R := 0.5183$ $P := 600$ $\text{P0} := 101$

$\text{h70} := 292.98$ $\text{s70} := 0.9549$

$\text{h90} := 376.92$ $\text{s90} := 1.1925$

$$\text{Qcombustion} := \frac{\text{Qbuilding}}{\eta}$$

$\text{Qcombustion} = 162.28889$

$$\text{mf} := \frac{\text{Qcombustion}}{\text{qcombustion}}$$

$\text{mf} = 3.59538 \times 10^{-3}$

$\text{mfh} := \text{mf} \cdot 3600$

$\text{mfh} = 12.94337$

$\text{Efchemical} := a \cdot \text{LHV} \cdot \text{mf}$

$\text{Efchemical} = 186.99723$

$$\text{efphysical} := \text{Cp} \cdot \left(T - \text{T0} - \text{T0} \cdot \ln\left(\frac{T}{\text{T0}} \right) \right) + R \cdot \text{T0} \cdot \ln\left(\frac{P}{\text{P0}} \right)$$

$\text{efphysical} = 254.68865$

$\text{Efphysical} := \text{mf} \cdot \text{efphysical}$

$\text{Efphysical} = 0.9157$

$\text{Ef} := \text{Efchemical} + \text{Efphysical}$

$\text{Ef} = 187.91293$

$$\text{mw} := \frac{\text{Qbuilding}}{(\text{h90} - \text{h70})}$$

$\text{mw} = 1.74005$

$I := \text{Ef} + \text{mw} \cdot [\, \text{h70} - \text{h90} - \text{T0} \cdot (\text{s70} - \text{s90}) \,]$

$I = 154.7831$

D.2.3 MathCAD Calculation for -6^{o}C Outdoor Temperature

$\mathrm{Qbuilding} := 181.156$ $\mathrm{qcombustion} := 44981.486$ $\mathrm{LHV} := 50010$

$\eta := 0.9$ $a := 1.04$

$\mathrm{Cp} := 2.254$ $T := 298.15$ $T0 := 267.15$

$R := 0.5183$ $P := 600$ $P0 := 101$

$h70 := 292.98$ $s70 := 0.9549$

$h90 := 376.92$ $s90 := 1.1925$

$$\mathrm{Qcombustion} := \frac{\mathrm{Qbuilding}}{\eta}$$

$\mathrm{Qcombustion} = 201.28444$

$$\mathrm{mf} := \frac{\mathrm{Qcombustion}}{\mathrm{qcombustion}}$$

$\mathrm{mf} = 4.47483\times 10^{-3}$

$\mathrm{mfh} := \mathrm{mf}\cdot 3600$

$\mathrm{mfh} = 16.10938$

$\mathrm{Efchemical} := a\cdot \mathrm{LHV}\cdot \mathrm{mf}$

$\mathrm{Efchemical} = 232.73763$

$$\mathrm{efphysical} := \mathrm{Cp}\cdot\left(T - T0 - T0\cdot\ln\left(\frac{T}{T0}\right)\right) + R\cdot T0\cdot\ln\left(\frac{P}{P0}\right)$$

$\mathrm{efphysical} = 250.48158$

$\mathrm{Efphysical} := \mathrm{mf}\cdot \mathrm{efphysical}$

$\mathrm{Efphysical} = 1.12086$

$\mathrm{Ef} := \mathrm{Efchemical} + \mathrm{Efphysical}$

$\mathrm{Ef} = 233.85849$

$$\mathrm{mw} := \frac{\mathrm{Qbuilding}}{(h90 - h70)}$$

$\mathrm{mw} = 2.15816$

$I := \mathrm{Ef} + \mathrm{mw}\cdot[\,h70 - h90 - T0\cdot(s70 - s90)\,]$

$I = 189.69139$

D.2.4 MathCAD Calculation for -12^{o}C Outdoor Temperature

$\text{Qbuilding} := 215.727 \qquad \text{qcombustion} := 44826.411 \qquad \text{LHV} := 50010$

$\eta := 0.9 \qquad a := 1.04$

$\text{Cp} := 2.254 \qquad T := 298.15 \qquad T0 := 261.15$

$R := 0.5183 \qquad P := 600 \qquad P0 := 101$

$h70 := 292.98 \qquad s70 := 0.9549$

$h90 := 376.92 \qquad s90 := 1.1925$

$$\text{Qcombustion} := \frac{\text{Qbuilding}}{\eta}$$

$\text{Qcombustion} = 239.69667$

$$\text{mf} := \frac{\text{Qcombustion}}{\text{qcombustion}}$$

$\text{mf} = 5.34722 \times 10^{-3}$

$\text{mfh} := \text{mf} \cdot 3600$

$\text{mfh} = 19.24999$

$\text{Efchemical} := a \cdot \text{LHV} \cdot \text{mf}$

$\text{Efchemical} = 278.11103$

$$\text{efphysical} := \text{Cp} \cdot \left(T - T0 - T0 \cdot \ln\left(\frac{T}{T0}\right)\right) + R \cdot T0 \cdot \ln\left(\frac{P}{P0}\right)$$

$\text{efphysical} = 246.57828$

$\text{Efphysical} := \text{mf} \cdot \text{efphysical}$

$\text{Efphysical} = 1.31851$

$\text{Ef} := \text{Efchemical} + \text{Efphysical}$

$\text{Ef} = 279.42954$

$$\text{mw} := \frac{\text{Qbuilding}}{(h90 - h70)}$$

$\text{mw} = 2.57001$

$I := \text{Ef} + \text{mw} \cdot [\, h70 - h90 - T0 \cdot (s70 - s90)\,]$

$I = 223.16998$

D.2.5 MathCAD Calculation for -18^{o}C Outdoor Temperature

$\text{Qbuilding} := 250.824$ $\text{qcombustion} := 44670.819$ $\text{LHV} := 50010$

$\eta := 0.9$ $a := 1.04$

$\text{Cp} := 2.254$ $T := 298.15$ $T0 := 255.15$

$R := 0.5183$ $P := 600$ $P0 := 101$

$h70 := 292.98$ $s70 := 0.9549$

$h90 := 376.92$ $s90 := 1.1925$

$$\text{Qcombustion} := \frac{\text{Qbuilding}}{\eta}$$

$\text{Qcombustion} = 278.69333$

$$\text{mf} := \frac{\text{Qcombustion}}{\text{qcombustion}}$$

$\text{mf} = 6.23882 \times 10^{-3}$

$\text{mfh} := \text{mf} \cdot 3600$

$\text{mfh} = 22.45976$

$\text{Efchemical} := a \cdot \text{LHV} \cdot \text{mf}$

$\text{Efchemical} = 324.48368$

$$\text{efphysical} := \text{Cp} \cdot \left(T - T0 - T0 \cdot \ln\left(\frac{T}{T0}\right)\right) + R \cdot T0 \cdot \ln\left(\frac{P}{P0}\right)$$

$\text{efphysical} = 242.98573$

$\text{Efphysical} := \text{mf} \cdot \text{efphysical}$

$\text{Efphysical} = 1.51594$

$\text{Ef} := \text{Efchemical} + \text{Efphysical}$

$\text{Ef} = 325.99963$

$$\text{mw} := \frac{\text{Qbuilding}}{(h90 - h70)}$$

$\text{mw} = 2.98813$

$I := \text{Ef} + \text{mw} \cdot [\, h70 - h90 - T0 \cdot (s70 - s90)\,]$

$I = 256.32721$

D.2.6 MathCAD Calculation for -24^{o}C Outdoor Temperature

$Qbuilding := 285.395$ $qcombustion := 44515.041$ $LHV := 50010$

$\eta := 0.9$ $a := 1.04$

$Cp := 2.254$ $T := 298.15$ $T0 := 249.15$

$R := 0.5183$ $P := 600$ $P0 := 101$

$h70 := 292.98$ $s70 := 0.9549$

$h90 := 376.92$ $s90 := 1.1925$

$$Qcombustion := \frac{Qbuilding}{\eta}$$

$Qcombustion = 317.10556$

$$mf := \frac{Qcombustion}{qcombustion}$$

$mf = 7.12356 \times 10^{-3}$

$mfh := mf \cdot 3600$

$mfh = 25.64482$

$Efchemical := a \cdot LHV \cdot mf$

$Efchemical = 370.49919$

$$efphysical := Cp \cdot \left(T - T0 - T0 \cdot \ln\left(\frac{T}{T0}\right)\right) + R \cdot T0 \cdot \ln\left(\frac{P}{P0}\right)$$

$efphysical = 239.71123$

$Efphysical := mf \cdot efphysical$

$Efphysical = 1.7076$

$Ef := Efchemical + Efphysical$

$Ef = 372.20679$

$$mw := \frac{Qbuilding}{(h90 - h70)}$$

$mw = 3.39999$

$I := Ef + mw \cdot [\, h70 - h90 - T0 \cdot (s70 - s90) \,]$

$I = 288.08442$

D.3 Irreversibility Because of Heat Transfer From Radiators and Rooms

Table D.3.1 Irreversibilities of rooms and radiators for 0^{o}C outdoor temperature

ROOM NO.	ROOM NAME	HEAT LOSS (Watt)	ROOM TEMP. (°C)	REQ. WATER FLOW (kg/h)	IRREV. RATES OF RAD. (Watt)	EXERGY LOSS IN ROOMS (Watt)
201	CLASSROOM	3400	22	145.81	517.72	253.41
202	CLASSROOM	2803	22	120.22	426.89	208.95
203	CLASSROOM	3363	22	144.25	512.20	250.71
204	CLASSROOM	3618	22	155.16	550.93	269.66
205	MEN WC	481	18	20.61	79.30	29.71
206	WOMEN WC	481	18	20.61	79.30	29.71
207	TEACHERS ROOM	694	22	29.77	105.70	51.74
208	CLASSROOM	3247	22	139.24	494.41	242.00
209	MEETING ROOM	4161	22	178.46	633.67	310.16
210	LIBRARY	6368	22	273.11	969.77	474.67
211	MEN WC	262	18	11.22	43.18	16.18
212	WOMEN WC	241	18	10.35	39.84	14.93
213	WOMEN WC	481	18	20.61	79.30	29.71
214	MEN WC	481	18	20.61	79.30	29.71
215	CLASSROOM	3618	22	155.16	550.93	269.66
216	COMPUTER ROOM	4596	22	197.13	699.96	342.60
217	PREP.ROOM	692	18	29.66	114.12	42.76
218	LABORATORY	2835	18	121.59	467.78	175.27
225	CORRIDOR	6022	18	258.26	993.61	372.29
101	CLASSROOM	2835	22	121.60	431.77	211.34
102	CLASSROOM	2239	22	96.02	340.93	166.88
103	CLASSROOM	2799	22	120.04	426.25	208.63
104	CLASSROOM	3053	22	130.95	464.98	227.59
105	MEN WC	284	18	12.20	46.94	17.59
106	WOMEN WC	284	18	12.20	46.94	17.59
107	STORAGE	290	15	12.42	50.61	15.07
108	CLASSROOM	2895	22	124.15	440.84	215.78
109	CANTEEN	2197	18	94.23	362.53	135.84
110	OFFICIAL	1628	22	69.82	247.92	121.35
111	MANAGER ROOM	2650	22	113.64	403.50	197.50
112	PUBLICATION	1628	22	69.82	247.92	121.35
113	MEN WC	174	18	7.46	28.70	10.75
114	WOMEN WC	174	18	7.46	28.70	10.75
115	WOMEN WC	284	18	12.20	46.94	17.59
116	MEN WC	284	18	12.20	46.94	17.59

Table D.3.1 (continued)

ROOM NO.	ROOM NAME	HEAT LOSS (Watt)	ROOM TEMP. (°C)	REQ. WATER FLOW (kg/h)	IRREV. RATES OF RAD. (Watt)	EXERGY LOSS IN ROOMS (Watt)
117	CLASSROOM	3053	22	130.95	464.98	227.59
118	MUSIC ROOM	4296	22	184.25	654.25	320.23
119	STORAGE	448	15	19.22	78.31	23.33
120	MECHANICAL WORKSHOP	2920	18	125.21	481.73	180.50
124	CORRIDOR	2985	18	128.03	492.57	184.56
Z01	CLASSROOM	3612	22	154.90	550.00	269.21
Z02	CLASSROOM	2979	22	127.75	453.60	222.02
Z03	CLASSROOM	3590	22	153.96	546.67	267.58
Z04	CLASSROOM	3854	22	165.29	586.89	287.26
Z05	MEN WC	300	18	12.85	49.45	18.53
Z06	WOMEN WC	300	18	12.85	49.45	18.53
Z07	EQUIPMENT ROOM	303	15	12.98	52.89	15.75
Z08	MEETING ROOM	959	22	41.13	146.05	71.49
Z09	GUIDANCE	1991	22	85.38	303.16	148.38
Z10	ARCHIVE	466	15	20.01	81.53	24.28
Z11	INFIRMARY	3647	24	156.41	532.67	294.56
Z12	MANAGER ASSISTANT	1956	22	83.91	297.95	145.83
Z13	SOCIAL ROOM	1543	22	66.16	234.92	114.98
Z14	MEN WC	182	18	7.80	30.00	11.24
Z15	WOMEN WC	182	18	7.80	30.00	11.24
Z16	WOMEN WC	300	18	12.85	49.45	18.53
Z17	MEN WC	300	18	12.85	49.45	18.53
Z18	ACTIVITY ROOM	3159	22	135.49	481.10	235.48
Z19	OFFICE	548	18	23.49	90.39	33.87
Z20	ACTIVITY ROOM	3249	22	139.34	494.77	242.17
Z21	CLASSROOM	4372	22	187.52	665.86	325.91
Z22	CORRIDOR	5436	18	233.15	896.99	336.09
B01	SHELTER	4280	18	183.58	706.28	264.64
B03	STORAGE	353	15	15.13	61.65	18.36
B05	WORKER DRESSING ROOM	1223	24	52.45	178.62	98.77
B06	WORKER ROOM	1823	22	78.18	277.61	135.88
B08	MEN WC	208	18	8.93	34.37	12.88
B09	WOMEN WC	198	18	8.48	32.64	12.23
B10	WOMEN WC	320	18	13.74	52.86	19.81
B11	MEN WC	292	18	12.54	48.25	18.08
B12	MEN DRESSING ROOM	1364	24	58.48	199.17	110.14
B13	SPOR EQ.ROOM	216	15	9.26	37.72	11.23
B14	WOMEN DRESSING ROOM	1344	24	57.66	196.36	108.58

Table D.3.1 (continued)

ROOM NO.	ROOM NAME	HEAT LOSS (Watt)	ROOM TEMP. (°C)	REQ. WATER FLOW (kg/h)	IRREV. RATES OF RAD. (Watt)	EXERGY LOSS IN ROOMS (Watt)
B15	PHYSICAL TRAINING HALL	2087	18	89.50	344.32	129.01
B17	MEN TEACH.DRESS.ROOM	1364	24	58.48	199.17	110.14
B18	WOMEN TEACH.DRES.	1401	24	60.08	204.60	113.14
B19	CORRIDOR	1116	18	47.88	184.20	69.02
	TOTAL	**146060**		**6264.18**	**22703**	**10427**

Table D.3.2 Irreversibilities of rooms and radiators for -6°C outdoor temperature

ROOM NO.	ROOM NAME	HEAT LOSS (Watt)	ROOM TEMP. (°C)	REQ. WATER FLOW (kg/h)	IRREV. RATES OF RAD. (Watt)	EXERGY LOSS IN ROOMS (Watt)
201	CLASSROOM	4247	22	182.13	632.49	402.86
202	CLASSROOM	3495	22	149.89	520.52	331.55
203	CLASSROOM	4335	22	185.93	645.69	411.27
204	CLASSROOM	4465	22	191.48	664.97	423.55
205	MEN WC	641	18	27.48	103.41	52.82
206	WOMEN WC	641	18	27.48	103.41	52.82
207	TEACHERS ROOM	883	22	37.89	131.57	83.80
208	CLASSROOM	3956	22	169.66	589.21	375.29
209	MEETING ROOM	5107	22	219.02	760.62	484.48
210	LIBRARY	7918	22	339.61	1179.38	751.20
211	MEN WC	349	18	14.96	56.31	28.76
212	WOMEN WC	322	18	13.81	51.95	26.54
213	WOMEN WC	641	18	27.48	103.41	52.82
214	MEN WC	641	18	27.48	103.41	52.82
215	CLASSROOM	4465	22	191.48	664.97	423.55
216	COMPUTER ROOM	5690	22	244.05	847.52	539.83
217	PREP.ROOM	922	18	39.55	148.82	76.02
218	LABORATORY	3967	18	170.13	640.14	326.99
225	CORRIDOR	8092	18	347.04	1305.81	667.02
101	CLASSROOM	3528	22	151.32	525.50	334.71
102	CLASSROOM	2776	22	119.08	413.53	263.40
103	CLASSROOM	3617	22	155.12	538.69	343.12
104	CLASSROOM	3746	22	160.67	557.98	355.40
105	MEN WC	379	18	16.27	61.21	31.27
106	WOMEN WC	379	18	16.27	61.21	31.27
107	STORAGE	405	15	17.39	69.29	29.54
108	CLASSROOM	3444	22	147.71	512.97	326.74
109	CANTEEN	2930	18	125.64	472.76	241.49
110	OFFICIAL	2014	22	86.38	299.97	191.06
111	MANAGER ROOM	3176	22	136.20	473.00	301.27
112	PUBLICATION	2014	22	86.38	299.97	191.06
113	MEN WC	232	18	9.95	37.43	19.12
114	WOMEN WC	232	18	9.95	37.43	19.12
115	WOMEN WC	379	18	16.27	61.21	31.27
116	MEN WC	379	18	16.27	61.21	31.27
117	CLASSROOM	3746	22	160.67	557.98	355.40
118	MUSIC ROOM	5185	22	222.37	772.25	491.88
119	STORAGE	627	15	26.90	107.23	45.72
120	MECHANICAL WORKSHOP	3706	18	158.94	598.06	305.50
124	CORRIDOR	4043	18	173.39	652.44	333.27
Z01	CLASSROOM	4324	22	185.46	644.08	410.24
Z02	CLASSROOM	3526	22	151.24	525.23	334.54
Z03	CLASSROOM	4443	22	190.56	661.77	421.51

Table D.3.2 (continued)

ROOM NO.	ROOM NAME	HEAT LOSS (Watt)	ROOM TEMP. (°C)	REQ. WATER FLOW (kg/h)	IRREV. RATES OF RAD. (Watt)	EXERGY LOSS IN ROOMS (Watt)
Z04	CLASSROOM	4567	22	195.85	680.16	433.23
Z05	MEN WC	400	18	17.14	64.48	32.94
Z06	WOMEN WC	400	18	17.14	64.48	32.94
Z07	EQUIPMENT ROOM	424	15	18.17	72.42	30.88
Z08	MEETING ROOM	1060	22	45.47	157.92	100.59
Z09	GUIDANCE	2364	22	101.38	352.08	224.26
Z10	ARCHIVE	653	15	28.01	111.63	47.60
Z11	INFIRMARY	4099	24	175.79	585.52	413.82
Z12	MANAGER ASSISTANT	2322	22	99.59	345.85	220.29
Z13	SOCIAL ROOM	1908	22	81.84	284.20	181.02
Z14	MEN WC	242	18	10.40	39.12	19.98
Z15	WOMEN WC	242	18	10.40	39.12	19.98
Z16	WOMEN WC	400	18	17.14	64.48	32.94
Z17	MEN WC	400	18	17.14	64.48	32.94
Z18	ACTIVITY ROOM	3872	22	166.06	576.69	367.32
Z19	OFFICE	730	18	31.32	117.87	60.21
Z20	ACTIVITY ROOM	3797	22	162.84	565.49	360.19
Z21	CLASSROOM	5408	22	231.95	805.53	513.08
Z22	CORRIDOR	7199	18	308.74	1161.72	593.41
B01	SHELTER	5123	18	219.70	826.69	422.28
B03	STORAGE	448	15	19.21	76.56	32.64
B05	WORKER DRESSING ROOM	1347	24	57.79	192.48	136.04
B06	WORKER ROOM	1929	22	82.75	287.36	183.03
B08	MEN WC	266	18	11.39	42.87	21.90
B09	WOMEN WC	253	18	10.83	40.76	20.82
B10	WOMEN WC	405	18	17.38	65.38	33.40
B11	MEN WC	373	18	16.01	60.23	30.77
B12	MEN DRESSING ROOM	1446	24	62.00	206.50	145.95
B13	SPOR EQ.ROOM	297	15	12.75	50.83	21.67
B14	WOMEN DRESSING ROOM	1468	24	62.97	209.74	148.23
B15	PHYSICAL TRAINING HALL	2630	18	112.78	424.37	216.77
B17	MEN TEACH.DRESS.ROOM	1446	24	62.00	206.50	145.95
B18	WOMEN TEACH.DRES.	1788	24	76.70	255.46	180.55
B19	CORRIDOR	1442	18	61.84	232.68	118.86
	TOTAL	**181156**		**7769.40**	**27588**	**16580**

Table D.3.3 Irreversibilities of rooms and radiators for -18^{o}C outdoor temperature

ROOM NO.	ROOM NAME	HEAT LOSS (Watt)	ROOM TEMP. (°C)	REQ. WATER FLOW (kg/h)	IRREV. RATES OF RAD. (Watt)	EXERGY LOSS IN ROOMS (Watt)
201	CLASSROOM	5940	22	254.77	845.03	805.08
202	CLASSROOM	4878	22	209.21	693.91	661.10
203	CLASSROOM	6209	22	266.28	883.18	841.43
204	CLASSROOM	6159	22	264.13	876.05	834.63
205	MEN WC	961	18	41.22	148.14	118.85
206	WOMEN WC	961	18	41.22	148.14	118.85
207	TEACHERS ROOM	1262	22	54.12	179.51	171.03
208	CLASSROOM	5375	22	230.51	764.56	728.41
209	MEETING ROOM	6999	22	300.16	995.55	948.48
210	LIBRARY	11019	22	472.59	1567.48	1493.37
211	MEN WC	523	18	22.45	80.66	64.71
212	WOMEN WC	483	18	20.71	74.42	59.71
213	WOMEN WC	961	18	41.22	148.14	118.85
214	MEN WC	961	18	41.22	148.14	118.85
215	CLASSROOM	6159	22	264.13	876.05	834.63
216	COMPUTER ROOM	7878	22	337.88	1120.69	1067.70
217	PREP.ROOM	1383	18	59.33	213.20	171.04
218	LABORATORY	6160	18	264.20	949.46	761.71
225	CORRIDOR	12208	18	523.57	1881.58	1509.49
101	CLASSROOM	4914	22	210.76	699.05	666.00
102	CLASSROOM	3852	22	165.20	547.93	522.02
103	CLASSROOM	5182	22	222.26	737.20	702.35
104	CLASSROOM	5132	22	220.11	730.07	695.55
105	MEN WC	569	18	24.40	87.69	70.35
106	WOMEN WC	569	18	24.40	87.69	70.35
107	STORAGE	637	15	27.32	104.00	72.96
108	CLASSROOM	4543	22	194.83	646.20	615.65
109	CANTEEN	4394	18	188.46	677.28	543.35
110	OFFICIAL	2786	22	119.48	396.30	377.57
111	MANAGER ROOM	4228	22	181.33	601.43	572.99
112	PUBLICATION	2786	22	119.48	396.30	377.57
113	MEN WC	348	18	14.92	53.62	43.02
114	WOMEN WC	348	18	14.92	53.62	43.02
115	WOMEN WC	569	18	24.40	87.69	70.35
116	MEN WC	569	18	24.40	87.69	70.35
117	CLASSROOM	5132	22	220.11	730.07	695.55
118	MUSIC ROOM	6962	22	298.60	990.40	943.58
119	STORAGE	986	15	42.28	160.93	112.89
120	MECHANICAL WORKSHOP	5279	18	226.40	813.63	652.73
124	CORRIDOR	6135	18	263.11	945.55	758.56
Z01	CLASSROOM	5750	22	246.60	817.93	779.26
Z02	CLASSROOM	4622	22	198.23	657.48	626.40
Z03	CLASSROOM	6074	22	260.48	863.96	823.11

Table D.3.3 (continued)

ROOM NO.	ROOM NAME	HEAT LOSS (Watt)	ROOM TEMP. (°C)	REQ. WATER FLOW (kg/h)	IRREV. RATES OF RAD. (Watt)	EXERGY LOSS IN ROOMS (Watt)
Z04	CLASSROOM	5992	22	256.99	852.39	812.09
Z05	MEN WC	599	18	25.71	92.38	74.11
Z06	WOMEN WC	599	18	25.71	92.38	74.11
Z07	EQUIPMENT ROOM	666	15	28.55	108.69	76.25
Z08	MEETING ROOM	1263	22	54.16	179.62	171.13
Z09	GUIDANCE	3110	22	133.39	442.44	421.52
Z10	ARCHIVE	1026	15	44.01	167.54	117.53
Z11	INFIRMARY	5003	24	214.55	682.51	707.08
Z12	MANAGER ASSISTANT	3053	22	130.94	434.31	413.78
Z13	SOCIAL ROOM	2639	22	113.19	375.44	357.69
Z14	MEN WC	364	18	15.59	56.04	44.96
Z15	WOMEN WC	364	18	15.59	56.04	44.96
Z16	WOMEN WC	599	18	25.71	92.38	74.11
Z17	MEN WC	599	18	25.71	92.38	74.11
Z18	ACTIVITY ROOM	5298	22	227.20	753.57	717.94
Z19	OFFICE	1096	18	46.99	168.86	135.47
Z20	ACTIVITY ROOM	4892	22	209.82	695.94	663.03
Z21	CLASSROOM	7404	22	317.54	1053.21	1003.41
Z22	CORRIDOR	10698	18	458.83	1648.91	1322.83
B01	SHELTER	6807	18	291.95	1049.19	841.71
B03	STORAGE	638	15	27.37	104.19	73.09
B05	WORKER DRESSING ROOM	1597	24	68.47	217.81	225.65
B06	WORKER ROOM	2142	22	91.87	304.73	290.32
B08	MEN WC	380	18	16.31	58.62	47.03
B09	WOMEN WC	362	18	15.53	55.80	44.77
B10	WOMEN WC	575	18	24.65	88.58	71.06
B11	MEN WC	535	18	22.94	82.43	66.13
B12	MEN DRESSING ROOM	1610	24	69.03	219.60	227.50
B13	SPOR EQ.ROOM	460	15	19.75	75.16	52.73
B14	WOMEN DRESSING ROOM	1716	24	73.59	234.11	242.54
B15	PHYSICAL TRAINING HALL	3716	18	159.35	572.66	459.42
B17	MEN TEACH.DRESS.ROOM	1610	24	69.03	219.60	227.50
B18	WOMEN TEACH.DRES.	2487	24	106.66	339.31	351.53
B19	CORRIDOR	2079	18	89.15	320.39	257.03
	TOTAL	**250,824**		**10757.28**	**36554.84**	**33117.55**

Table D.3.4 Irreversibilities of rooms and radiators for -24°C outdoor temperature

ROOM NO.	ROOM NAME	HEAT LOSS (Watt)	ROOM TEMP. (°C)	REQ. WATER FLOW (kg/h)	IRREV. RATES OF RAD. (Watt)	EXERGY LOSS IN ROOMS (Watt)
201	CLASSROOM	6787	22	291.10	942.80	1057.83
202	CLASSROOM	5570	22	238.87	773.67	868.06
203	CLASSROOM	7110	22	304.95	987.67	1108.18
204	CLASSROOM	7005	22	300.45	973.09	1091.82
205	MEN WC	1121	18	48.09	168.77	161.76
206	WOMEN WC	1121	18	48.09	168.77	161.76
207	TEACHERS ROOM	1451	22	62.24	201.59	226.18
208	CLASSROOM	6084	22	260.94	845.12	948.23
209	MEETING ROOM	7944	22	340.72	1103.52	1238.17
210	LIBRARY	12570	22	539.08	1745.97	1959.00
211	MEN WC	611	18	26.19	91.90	88.08
212	WOMEN WC	563	18	24.16	84.79	81.27
213	WOMEN WC	1121	18	48.09	168.77	161.76
214	MEN WC	1121	18	48.09	168.77	161.76
215	CLASSROOM	7005	22	300.45	973.09	1091.82
216	COMPUTER ROOM	8972	22	384.80	1246.30	1398.36
217	PREP.ROOM	1614	18	69.21	242.88	232.80
218	LABORATORY	7222	18	309.74	1086.93	1041.82
225	CORRIDOR	14254	18	611.34	2145.32	2056.28
101	CLASSROOM	5607	22	240.48	778.87	873.90
102	CLASSROOM	4390	22	188.26	609.73	684.13
103	CLASSROOM	5930	22	254.33	823.73	924.24
104	CLASSROOM	5825	22	249.83	809.16	907.89
105	MEN WC	664	18	28.47	99.90	95.75
106	WOMEN WC	664	18	28.47	99.90	95.75
107	STORAGE	753	15	32.29	120.02	101.90
108	CLASSROOM	5092	22	218.39	707.31	793.61
109	CANTEEN	5127	18	219.87	771.58	739.56
110	OFFICIAL	3172	22	136.04	440.60	494.36
111	MANAGER ROOM	4754	22	203.89	660.36	740.93
112	PUBLICATION	3172	22	136.04	440.60	494.36
113	MEN WC	406	18	17.41	61.09	58.55
114	WOMEN WC	406	18	17.41	61.09	58.55
115	WOMEN WC	664	18	28.47	99.90	95.75
116	MEN WC	664	18	28.47	99.90	95.75
117	CLASSROOM	5825	22	249.83	809.16	907.89
118	MUSIC ROOM	7851	22	336.72	1090.56	1223.63
119	STORAGE	1165	15	49.96	185.72	157.68
120	MECHANICAL WORKSHOP	6065	18	260.13	912.85	874.97
124	CORRIDOR	7169	18	307.47	1078.97	1034.18
Z01	CLASSROOM	6463	22	277.17	897.70	1007.23
Z02	CLASSROOM	5170	22	221.72	718.11	805.73
Z03	CLASSROOM	6851	22	293.80	951.57	1067.67

Table D.3.4 (continued)

ROOM NO.	ROOM NAME	HEAT LOSS (Watt)	ROOM TEMP. (°C)	REQ. WATER FLOW (kg/h)	IRREV. RATES OF RAD. (Watt)	EXERGY LOSS IN ROOMS (Watt)
Z04	CLASSROOM	6705	22	287.56	931.35	1044.99
Z05	MEN WC	699	18	29.99	105.24	100.87
Z06	WOMEN WC	699	18	29.99	105.24	100.87
Z07	EQUIPMENT ROOM	787	15	33.74	125.43	106.49
Z08	MEETING ROOM	1364	22	58.50	189.46	212.58
Z09	GUIDANCE	3483	22	149.40	483.87	542.91
Z10	ARCHIVE	1213	15	52.02	193.35	164.16
Z11	INFIRMARY	5454	24	233.93	726.66	881.08
Z12	MANAGER ASSISTANT	3419	22	146.62	474.88	532.82
Z13	SOCIAL ROOM	3005	22	128.87	417.39	468.32
Z14	MEN WC	424	18	18.19	63.84	61.19
Z15	WOMEN WC	424	18	18.19	63.84	61.19
Z16	WOMEN WC	699	18	29.99	105.24	100.87
Z17	MEN WC	699	18	29.99	105.24	100.87
Z18	ACTIVITY ROOM	6010	22	257.77	834.86	936.72
Z19	OFFICE	1278	18	54.82	192.37	184.38
Z20	ACTIVITY ROOM	5440	22	233.32	755.66	847.86
Z21	CLASSROOM	8364	22	358.69	1161.73	1303.48
Z22	CORRIDOR	12435	18	533.33	1871.56	1793.88
B01	SHELTER	7650	18	328.08	1151.29	1103.50
B03	STORAGE	733	15	31.45	116.90	99.25
B05	WORKER DRESSING ROOM	1721	24	73.81	229.28	278.01
B06	WORKER ROOM	2249	22	96.44	312.35	350.46
B08	MEN WC	438	18	18.77	65.87	63.14
B09	WOMEN WC	417	18	17.87	62.73	60.12
B10	WOMEN WC	660	18	28.29	99.26	95.14
B11	MEN WC	616	18	26.40	92.65	88.81
B12	MEN DRESSING ROOM	1692	24	72.55	225.35	273.24
B13	SPOR EQ.ROOM	542	15	23.24	86.39	73.35
B14	WOMEN DRESSING ROOM	1840	24	78.91	245.11	297.20
B15	PHYSICAL TRAINING HALL	4258	18	182.64	640.91	614.30
B17	MEN TEACH.DRESS.ROOM	1692	24	72.55	225.35	273.24
B18	WOMEN TEACH.DRES.	2798	24	120.01	372.79	452.01
B19	CORRIDOR	2390	18	102.51	359.72	344.79
	TOTAL	**285,395**		**12239.94**	**40641.23**	**43481.04**

APPENDIX E

COSTS OF EQUIPMENT AND COMPONENTS

E.1 Costs of Building Structure Components

Description		**Cost** [20]
XPS (rugged) heat insulation		217 YTL/m3
XPS (smooth) heat insulation		230 YTL/m3
Rock wool heat insulation	3 cm	6 YTL/m2
	5 cm	9.56 YTL/m2
	8 cm	15.85 YTL/m2
	10 cm	19.25 YTL/m2
Window frame (PVC)		0.8 YTL/kg
Glass (4+9+4)		35.78 YTL/m2
Glass (4+12+4)		37.59 YTL/m2
Glass (4+16+4)		38.71 YTL/m2
Glass (4+9+4) Low-E		46.78 YTL/m2
Glass (4+12+4) Low-E		48.72 YTL/m2
Glass (4+16+4) Low-E		49.76 YTL/m2

E.2 Costs of Heating Equipments

Description		**Cost** [20][25][27]
Cast iron radiator 160/500		44.7 YTL/m2
Cast iron radiator 160/900		46.4 YTL/m2
Boiler	Natural gas	5491.2 YTL
	Fuel oil	9346.7 YTL
	Coal	7058.7 YTL
Fuel tank (13000 liter)		3237.3 YTL
Closed type expansion tank (500 liter)		870.87 YTL
Open type expansion tank (500 liter)		500 YTL
Heat pump (125 kW heating capacity)		31000 €
Heat pump (215 kW heating capacity)		53500 €
Cogeneration Unit (90 kW heating cap.)		49000 €

E.3 Costs of Fuels and Electricity

Description	**Cost** [23][24][26]
Natural gas	0.439393 YTL/m3
Fuel oil	0.53176 YTL/kg
Coal	0.28YTL/kg
Electricity	0.11673 YTL/kWh

APPENDIX F

CALCULATIONS FOR DIFFERENT TYPES OF FUEL

F.1 Calculation of Heat Output During Combustion for Fuel Oil

LHV for Fuel oil

	n	**h_f**	**n. (h_f+h-h_0)**
C10H22	1	-249659	-249659
O2	15.5	0	0
N2	58.28	0	0
CO2	10	-393520	-3935200
H2O	11	-241820	-2660020
N2	58.28	0	0
O2	0	0	0

$\bar{q}_{combustion}$: **6345561** **kJ/kmol CH4**

$q_{combustion}$: **44598** **kJ/kg CH4**

for T=0

	n	**h_f**	**h(273K)**	**h(450K)**	**h_0(298K)**	**n. (h_f+h-h_0)**
C10H22	1	-249659				-249659
O2	23.25	0	7946		8682	-17112
N2	87.42	0	7937		8669	-63991.44
CO2	10	-393520		15483	9364	-3874010
H2O	11	-241820		15080	9904	-2603084
N2	87.42	0		12811	8669	362093.64
O2	7.75	0		13228	8682	35231.5

$\bar{q}_{combustion}$: 5,749,006 kJ/kmol CH4

$q_{combustion}$: 40,405 kJ/kg CH4

for T=-12

	n	**h_f**	**h(261K)**	**h(450K)**	**h_0(298K)**	**n. (h_f+h-h_0)**
C10H22	1	-249659				-249659
O2	23.25	0	7595		8682	-25272.75
N2	87.42	0	7587		8669	-94588.44
CO2	10	-393520		15483	9364	-3874010
H2O	11	-241820		15080	9904	-2603084
N2	87.42	0		12811	8669	362093.64
O2	7.75	0		13228	8682	35231.5

$\bar{q}_{combustion}$: 5,710,249 kJ/kmol CH4

$q_{combustion}$: 40,133 kJ/kg CH4

F.2 Calculation of Heat Output During Combustion for Coal

LHV of Coal

	n	**h_f**	**n. (h_f+h-h_0)**
S	0.0156	0	0
H2	1.75	0	0
C	4.05	0	0
O2	0.375	0	0
N2	0.025	0	0
O2	4.5656	0	0
N2	17.17	0	0
CO2	4.05	-393520	-1593756
H2O	1.75	-241820	-423185
SO2	0.0156	-296842	-4630.7352
N2	17.19	0	0
O2	0	0	0

$q_{combustion}$: **20216** **kJ/kg**

for T=0

	n	h_f	h(273K)	h(450K)	h_0(298K)	n. (h_f+h-h_0)
S	0.0156	0				0
H2	1.75	0				0
C	4.05	0				0
O2	0.375	0				0
N2	0.025	0				0
O2	6.8484	0	7946		8682	-5040
N2	25.75	0	7937		8669	-18848
CO2	4.05	-393520		15483	9364	-1568974
H2O	1.75	-241820		15080	9904	-414127
SO2	0.0156	-296842		15080	9904	-4549
N2	25.77	0		12811	8669	106759
O2	2.2828	0		13228	8682	10377

$q_{combustion}$: **18466** **kJ/kg**

for T=-12

	n	h_f	h(261K)	h(450K)	h_0(298K)	n. (h_f+h-h_0)
S	0.0156	0				0
H2	1.75	0				0
C	4.05	0				0
O2	0.375	0				0
N2	0.025	0				0
O2	6.8484	0	7595		8682	-7444
N2	25.75	0	7587		8669	-27861
CO2	4.05	-393520		15483	9364	-1568974
H2O	1.75	-241820		15080	9904	-414127
SO2	0.0156	-296842		15080	9904	-4549
N2	25.77	0		12811	8669	106759
O2	2.2828	0		13228	8682	10377

$q_{combustion}$: **18352** **kJ/kg**

F.3 MathCAD Calculation for Natural Gas

$Qbuilding := 215.727$ $\quad qcombustion := 44826.41$ $\quad LHV := 50010$

$\eta := 0.9$ $\quad a := 1.04$

$Cp := 2.254$ $\quad T := 298.15$ $\quad T0 := 261.15$

$R := 0.5183$ $\quad P := 600$ $\quad P0 := 101$

$h70 := 292.98$ $\quad s70 := 0.9549$

$h90 := 376.92$ $\quad s90 := 1.1925$

$$Qcombustion := \frac{Qbuilding}{\eta}$$

$Qcombustion = 239.69667$

$$mf := \frac{Qcombustion}{qcombustion}$$

$mf = 5.34722 \times 10^{-3}$

$mfh := mf \cdot 3600$

$mfh = 19.24999$

$Efchemical := a \cdot LHV \cdot mf$

$Efchemical = 278.11104$

$$efphysical := Cp \cdot \left(T - T0 - T0 \cdot \ln\left(\frac{T}{T0} \right) \right) + R \cdot T0 \cdot \ln\left(\frac{P}{P0} \right)$$

$efphysical = 246.57828$

$Efphysical := mf \cdot efphysical$

$Efphysical = 1.31851$

$Ef := Efchemical + Efphysical$

$Ef = 279.42955$

$$mw := \frac{Qbuilding}{(h90 - h70)}$$

$mw = 2.57001$

$I := Ef + mw \cdot [h70 - h90 - T0 \cdot (s70 - s90)]$

$I = 223.16998$

F.4 MathCAD Calculation for Fuel Oil

$Qbuilding := 215.727$ $qcombustion := 40133$ $LHV := 44600$

$\eta := 0.9$ $a := 1.04$

$C := 1.9$ $T := 298.15$ $T0 := 261.15$

$R := 0.5183$

$h70 := 292.98$ $s70 := 0.9549$

$h90 := 376.92$ $s90 := 1.1925$

$$Qcombustion := \frac{Qbuilding}{\eta}$$

$Qcombustion = 239.69667$

$$mf := \frac{Qcombustion}{qcombustion}$$

$mf = 5.97256\times 10^{-3}$

$mfh := mf\cdot 3600$

$mfh = 21.50121$

$Efchemical := a\cdot mf\cdot LHV$

$Efchemical = 277.03113$

$$efphysical := C\cdot\left(T - T0 - T0\cdot\ln\left(\frac{T}{T0}\right)\right)$$

$Efphysical := mf\cdot efphysical$

$Efphysical = 0.0272$

$Ef := Efchemical + Efphysical$

$Ef = 277.05833$

$$mw := \frac{Qbuilding}{(h90 - h70)}$$

$mw = 2.57001$

$I := Ef + mw\cdot[\,h70 - h90 - T0\cdot(s70 - s90)\,]$

$I = 220.79876$

F.5 MathCAD Calculation for Coal

$Qbuilding := 215.727$ $\quad qcombustion := 18352$ $\quad LHV := 20215$

$\eta := 0.9$ $\quad a := 1.05$

$C := 1.26$ $\quad T := 298.15$ $\quad T0 := 261.15$

$h70 := 292.98$ $\quad s70 := 0.9549$

$h90 := 376.92$ $\quad s90 := 1.1925$

$$Qcombustion := \frac{Qbuilding}{\eta}$$

$Qcombustion = 239.69667$

$$mf := \frac{Qcombustion}{qcombustion}$$

$mf = 0.01306$

$mfh := mf \cdot 3600$

$mfh = 47.01983$

$Efchemical := a \cdot mf \cdot LHV$

$Efchemical = 277.2309$

$$efphysical := C \cdot \left(T - T0 - T0 \cdot \ln\left(\frac{T}{T0} \right) \right)$$

$Efphysical := mf \cdot efphysical$

$Efphysical = 0.03945$

$Ef := Efchemical + Efphysical$

$Ef = 277.27035$

$$mw := \frac{Qbuilding}{(h90 - h70)}$$

$mw = 2.57001$

$I := Ef + mw \cdot [\, h70 - h90 - T0 \cdot (s70 - s90) \,]$

$I = 221.01079$

APPENDIX G

CALCULATIONS FOR DIFFERENT HEATING WATER TEMPERATURES

G.1 Irreversibility of the Boiler

G.1.1 MathCAD Calculation for 80-60^{O}C Heating Water Temperature

$\mathrm{Qbuilding} := 215.727 \quad \mathrm{qcombustion} := 44826.41 \quad \mathrm{LHV} := 5001$

$\eta := 0.9 \quad a := 1.04$

$\mathrm{Cp} := 2.254 \quad T := 298.15 \quad \mathrm{T0} := 261.15$

$R := 0.5183 \quad P := 600 \quad \mathrm{P0} := 101$

$\mathrm{h60} := 251.11 \quad \mathrm{s60} := 0.8311$

$\mathrm{h80} := 334.88 \quad \mathrm{s80} := 1.0752$

$$\mathrm{Qcombustion} := \frac{\mathrm{Qbuilding}}{\eta}$$

$\mathrm{Qcombustion} = 239.69667$

$$\mathrm{mf} := \frac{\mathrm{Qcombustion}}{\mathrm{qcombustion}}$$

$\mathrm{mf} = 5.34722\times 10^{-3}$

$\mathrm{mfh} := \mathrm{mf}\cdot 3600$

$\mathrm{mfh} = 19.24999$

$\mathrm{Efchemical} := a\cdot \mathrm{LHV}\cdot \mathrm{mf}$

$\mathrm{Efchemical} = 278.11104$

$$\mathrm{efphysical} := \mathrm{Cp}\cdot\left(T - \mathrm{T0} - \mathrm{T0}\cdot\ln\left(\frac{T}{\mathrm{T0}}\right)\right) + R\cdot \mathrm{T0}\cdot\ln\left(\frac{P}{\mathrm{P0}}\right)$$

$\mathrm{Efphysical} := \mathrm{mf}\cdot \mathrm{efphysical}$

$\mathrm{Efphysical} = 1.31851$

$\mathrm{Ef} := \mathrm{Efchemical} + \mathrm{Efphysical}$

$$\mathrm{mw} := \frac{\mathrm{Qbuilding}}{(\mathrm{h80} - \mathrm{h60})}$$

$\mathrm{mw} = 2.57523$

$\mathrm{I} := \mathrm{Ef} + \mathrm{mw}\cdot[\,\mathrm{h60} - \mathrm{h80} - \mathrm{T0}\cdot(\mathrm{s60} - \mathrm{s80})\,]$

$\mathrm{I} = 227.86499$

G.1.2 MathCAD Calculation for 75-65^{O}C Heating Water Temperature

$Qbuilding := 215.727$ $\quad$ $qcombustion := 44826.41$ $\quad$ $LHV := 50010$

$\eta := 0.9$ $\quad$ $a := 1.04$

$Cp := 2.254$ $\quad$ $T := 298.15$ $\quad$ $T0 := 261.15$

$R := 0.5183$ $\quad$ $P := 600$ $\quad$ $P0 := 101$

$h65 := 272.03$ $\quad$ $s65 := 0.8934$

$h75 := 313.91$ $\quad$ $s75 := 1.0154$

$$Qcombustion := \frac{Qbuilding}{\eta}$$

$Qcombustion = 239.69667$

$$mf := \frac{Qcombustion}{qcombustion}$$

$mf = 5.34722 \times 10^{-3}$

$mfh := mf \cdot 3600$

$mfh = 19.24999$

$Efchemical := a \cdot LHV \cdot mf$

$Efchemical = 278.11104$

$$efphysical := Cp \cdot \left(T - T0 - T0 \cdot \ln\left(\frac{T}{T0}\right)\right) + R \cdot T0 \cdot \ln\left(\frac{P}{P0}\right)$$

$efphysical = 246.57828$

$Efphysical := mf \cdot efphysical$

$Efphysical = 1.31851$

$Ef := Efchemical + Efphysical$

$Ef = 279.42955$

$$mw := \frac{Qbuilding}{(h75 - h65)}$$

$mw = 5.15107$

$I := Ef + mw \cdot [\, h65 - h75 - T0 \cdot (s65 - s75)\,]$

$I = 227.81733$

G.1.3 MathCAD Calculation for 50-35^{O}C Heating Water Temperature

$Qbuilding := 215.727$ $\quad qcombustion := 44826.41$ $\quad LHV := 50010$

$\eta := 0.9$ $\quad a := 1.04$

$Cp := 2.254$ $\quad T := 298.15$ $\quad T0 := 261.15$

$R := 0.5183$ $\quad P := 600$ $\quad P0 := 101$

$h35 := 146.66$ $\quad s35 := 0.5052$

$h50 := 209.31$ $\quad s50 := 0.7037$

$$Qcombustion := \frac{Qbuilding}{\eta}$$

$Qcombustion = 239.69667$

$$mf := \frac{Qcombustion}{qcombustion}$$

$mf = 5.34722 \times 10^{-3}$

$mfh := mf \cdot 3600$

$mfh = 19.24999$

$Efchemical := a \cdot LHV \cdot mf$

$Efchemical = 278.11104$

$$efphysical := Cp \cdot \left(T - T0 - T0 \cdot \ln\left(\frac{T}{T0}\right)\right) + R \cdot T0 \cdot \ln\left(\frac{P}{P0}\right)$$

$efphysical = 246.57828$

$Efphysical := mf \cdot efphysical$

$Efphysical = 1.31851$

$Ef := Efchemical + Efphysical$

$Ef = 279.42955$

$$mw := \frac{Qbuilding}{(h50 - h35)}$$

$mw = 3.44337$

$I := Ef + mw \cdot [\, h35 - h50 - T0 \cdot (s35 - s50)\,]$

$I = 242.2008$

G.2 Irreversibility of the Radiators

Table G.2.1 Irreversibilities of radiators for 75-65 ^{O}C heating water temperature

ROOM NO.	ROOM NAME	HEAT LOSS (Watt)	ROOM TEMP. (°C)	REQ. WATER FLOW (kg/h)	IRREV. RATES OF RAD. (Watt)
201	CLASSROOM	5094	22	437.84	631.87
202	CLASSROOM	4186	22	359.87	519.34
203	CLASSROOM	5237	22	450.17	649.65
204	CLASSROOM	5312	22	456.59	658.92
205	MEN WC	801	18	68.85	109.10
206	WOMEN WC	801	18	68.85	109.10
207	TEACHERS ROOM	1073	22	92.21	133.07
208	CLASSROOM	4665	22	401.04	578.75
209	MEETING ROOM	6053	22	520.30	750.86
210	LIBRARY	9469	22	813.94	1174.63
211	MEN WC	436	18	37.49	59.41
212	WOMEN WC	402	18	34.59	54.81
213	WOMEN WC	801	18	68.85	109.10
214	MEN WC	801	18	68.85	109.10
215	CLASSROOM	5312	22	456.59	658.92
216	COMPUTER ROOM	6784	22	583.18	841.61
217	PREP.ROOM	1153	18	99.09	157.01
218	LABORATORY	5029	18	432.25	684.93
225	CORRIDOR	10138	18	871.47	1380.90
101	CLASSROOM	4221	22	362.86	523.65
102	CLASSROOM	3314	22	284.89	411.13
103	CLASSROOM	4365	22	375.18	541.44
104	CLASSROOM	4439	22	381.60	550.71
105	MEN WC	474	18	40.76	64.58
106	WOMEN WC	474	18	40.76	64.58
107	STORAGE	521	15	44.80	75.86
108	CLASSROOM	3993	22	343.28	495.40
109	CANTEEN	3662	18	314.78	498.79
110	OFFICIAL	2400	22	206.30	297.72
111	MANAGER ROOM	3702	22	318.21	459.22
112	PUBLICATION	2400	22	206.30	297.72
113	MEN WC	290	18	24.92	39.49
114	WOMEN WC	290	18	24.92	39.49
115	WOMEN WC	474	18	40.76	64.58
116	MEN WC	474	18	40.76	64.58
117	CLASSROOM	4439	22	381.60	550.71
118	MUSIC ROOM	6074	22	522.09	753.45
119	STORAGE	807	15	69.33	117.39
120	MECHANICAL WORKSHOP	4492	18	386.17	611.91
124	CORRIDOR	5077	18	436.44	691.56
Z01	CLASSROOM	5037	22	433.00	624.87
Z02	CLASSROOM	4074	22	350.22	505.42

Table G.2.1 (continued)

ROOM NO.	ROOM NAME	HEAT LOSS (Watt)	ROOM TEMP. (°C)	REQ. WATER FLOW (kg/h)	IRREV. RATES OF RAD. (Watt)
Z03	CLASSROOM	5220	22	448.72	647.57
Z04	CLASSROOM	5279	22	453.82	654.93
Z05	MEN WC	499	18	42.93	68.03
Z06	WOMEN WC	499	18	42.93	68.03
Z07	EQUIPMENT ROOM	545	15	46.82	79.28
Z08	MEETING ROOM	1162	22	99.84	144.09
Z09	GUIDANCE	2737	22	235.28	339.54
Z10	ARCHIVE	840	15	72.18	122.21
Z11	INFIRMARY	4551	24	391.18	537.43
Z12	MANAGER ASSISTANT	2688	22	231.03	333.40
Z13	SOCIAL ROOM	2274	22	195.45	282.06
Z14	MEN WC	303	18	26.05	41.27
Z15	WOMEN WC	303	18	26.05	41.27
Z16	WOMEN WC	499	18	42.93	68.03
Z17	MEN WC	499	18	42.93	68.03
Z18	ACTIVITY ROOM	4585	22	394.10	568.75
Z19	OFFICE	913	18	78.48	124.36
Z20	ACTIVITY ROOM	4345	22	373.46	538.95
Z21	CLASSROOM	6368	22	547.39	789.96
Z22	CORRIDOR	8936	18	768.13	1217.14
B01	SHELTER	5965	18	512.76	812.49
B03	STORAGE	543	15	46.68	79.04
B05	WORKER DRESSING ROOM	1472	24	126.53	173.84
B06	WORKER ROOM	2036	22	175.00	252.54
B08	MEN WC	323	18	27.76	43.99
B09	WOMEN WC	307	18	26.42	41.86
B10	WOMEN WC	490	18	42.12	66.74
B11	MEN WC	454	18	39.03	61.84
B12	MEN DRESSING ROOM	1528	24	131.31	180.40
B13	SPOR EQ.ROOM	379	15	32.57	55.15
B14	WOMEN DRESSING ROOM	1592	24	136.86	188.02
B15	PHYSICAL TRAINING HALL	3173	18	272.72	432.14
B17	MEN TEACH.DRESS.ROOM	1528	24	131.31	180.40
B18	WOMEN TEACH.DRES.	2100	24	180.47	247.95
B19	CORRIDOR	1753	18	150.71	238.80
	TOTAL	**215,727**		**18543.89**	**27504.87**

Table G.2.2 Irreversibilities of radiators for 80-60 ^{O}C heating water temperature

ROOM NO.	ROOM NAME	HEAT LOSS (Watt)	ROOM TEMP. (°C)	REQ. WATER FLOW (kg/h)	IRREV. RATES OF RAD. (Watt)
201	CLASSROOM	5094	22	218.89	630.74
202	CLASSROOM	4186	22	179.91	518.42
203	CLASSROOM	5237	22	225.06	648.49
204	CLASSROOM	5312	22	228.27	657.74
205	MEN WC	801	18	34.42	108.92
206	WOMEN WC	801	18	34.42	108.92
207	TEACHERS ROOM	1073	22	46.10	132.83
208	CLASSROOM	4665	22	200.49	577.72
209	MEETING ROOM	6053	22	260.12	749.52
210	LIBRARY	9469	22	406.92	1172.54
211	MEN WC	436	18	18.74	59.31
212	WOMEN WC	402	18	17.29	54.72
213	WOMEN WC	801	18	34.42	108.92
214	MEN WC	801	18	34.42	108.92
215	CLASSROOM	5312	22	228.27	657.74
216	COMPUTER ROOM	6784	22	291.56	840.11
217	PREP.ROOM	1153	18	49.54	156.76
218	LABORATORY	5029	18	216.10	683.82
225	CORRIDOR	10138	18	435.68	1378.66
101	CLASSROOM	4221	22	181.41	522.72
102	CLASSROOM	3314	22	142.43	410.40
103	CLASSROOM	4365	22	187.57	540.48
104	CLASSROOM	4439	22	190.78	549.72
105	MEN WC	474	18	20.38	64.48
106	WOMEN WC	474	18	20.38	64.48
107	STORAGE	521	15	22.40	75.75
108	CLASSROOM	3993	22	171.62	494.51
109	CANTEEN	3662	18	157.37	497.98
110	OFFICIAL	2400	22	103.14	297.19
111	MANAGER ROOM	3702	22	159.09	458.41
112	PUBLICATION	2400	22	103.14	297.19
113	MEN WC	290	18	12.46	39.43
114	WOMEN WC	290	18	12.46	39.43
115	WOMEN WC	474	18	20.38	64.48
116	MEN WC	474	18	20.38	64.48
117	CLASSROOM	4439	22	190.78	549.72
118	MUSIC ROOM	6074	22	261.02	752.11
119	STORAGE	807	15	34.66	117.21
120	MECHANICAL WORKSHOP	4492	18	193.06	610.92
124	CORRIDOR	5077	18	218.19	690.43
Z01	CLASSROOM	5037	22	216.47	623.76
Z02	CLASSROOM	4074	22	175.09	504.52
Z03	CLASSROOM	5220	22	224.34	646.42
Z04	CLASSROOM	5279	22	226.88	653.76
Z05	MEN WC	499	18	21.46	67.92

Table G.2.2 (continued)

ROOM NO.	ROOM NAME	HEAT LOSS (Watt)	ROOM TEMP. (°C)	REQ. WATER FLOW (kg/h)	IRREV. RATES OF RAD. (Watt)
Z06	WOMEN WC	499	18	21.46	67.92
Z07	EQUIPMENT ROOM	545	15	23.41	79.16
Z08	MEETING ROOM	1162	22	49.92	143.83
Z09	GUIDANCE	2737	22	117.63	338.94
Z10	ARCHIVE	840	15	36.09	122.03
Z11	INFIRMARY	4551	24	195.57	536.42
Z12	MANAGER ASSISTANT	2688	22	115.50	332.81
Z13	SOCIAL ROOM	2274	22	97.71	281.56
Z14	MEN WC	303	18	13.02	41.20
Z15	WOMEN WC	303	18	13.02	41.20
Z16	WOMEN WC	499	18	21.46	67.92
Z17	MEN WC	499	18	21.46	67.92
Z18	ACTIVITY ROOM	4585	22	197.03	567.74
Z19	OFFICE	913	18	39.24	124.15
Z20	ACTIVITY ROOM	4345	22	186.71	537.99
Z21	CLASSROOM	6368	22	273.66	788.55
Z22	CORRIDOR	8936	18	384.02	1215.16
B01	SHELTER	5965	18	256.35	811.17
B03	STORAGE	543	15	23.34	78.92
B05	WORKER DRESSING ROOM	1472	24	63.26	173.51
B06	WORKER ROOM	2036	22	87.49	252.09
B08	MEN WC	323	18	13.88	43.92
B09	WOMEN WC	307	18	13.21	41.79
B10	WOMEN WC	490	18	21.06	66.63
B11	MEN WC	454	18	19.51	61.74
B12	MEN DRESSING ROOM	1528	24	65.65	180.07
B13	SPOR EQ.ROOM	379	15	16.28	55.06
B14	WOMEN DRESSING ROOM	1592	24	68.42	187.67
B15	PHYSICAL TRAINING HALL	3173	18	136.34	431.44
B17	MEN TEACH.DRESS.ROOM	1528	24	65.65	180.07
B18	WOMEN TEACH.DRES.	2100	24	90.23	247.48
B19	CORRIDOR	1753	18	75.34	238.42
	TOTAL	**215,727**		**9270.84**	**27457.19**

Table G.2.3 Irreversibilities of radiators for 50-35^{O}C heating water temperature

ROOM NO.	ROOM NAME	HEAT LOSS (Watt)	ROOM TEMP. (°C)	REQ. WATER FLOW (kg/h)	IRREV. RATES OF RAD. (Watt)
201	CLASSROOM	5094	22	292.69	292.26
202	CLASSROOM	4186	22	240.56	240.21
203	CLASSROOM	5237	22	300.92	300.48
204	CLASSROOM	5312	22	305.22	304.77
205	MEN WC	801	18	46.03	55.70
206	WOMEN WC	801	18	46.03	55.70
207	TEACHERS ROOM	1073	22	61.64	61.55
208	CLASSROOM	4665	22	268.08	267.69
209	MEETING ROOM	6053	22	347.80	347.29
210	LIBRARY	9469	22	544.10	543.30
211	MEN WC	436	18	25.06	30.33
212	WOMEN WC	402	18	23.12	27.98
213	WOMEN WC	801	18	46.03	55.70
214	MEN WC	801	18	46.03	55.70
215	CLASSROOM	5312	22	305.22	304.77
216	COMPUTER ROOM	6784	22	389.84	389.27
217	PREP.ROOM	1153	18	66.24	80.15
218	LABORATORY	5029	18	288.95	349.65
225	CORRIDOR	10138	18	582.56	704.94
101	CLASSROOM	4221	22	242.56	242.21
102	CLASSROOM	3314	22	190.44	190.16
103	CLASSROOM	4365	22	250.80	250.43
104	CLASSROOM	4439	22	255.09	254.72
105	MEN WC	474	18	27.24	32.97
106	WOMEN WC	474	18	27.24	32.97
107	STORAGE	521	15	29.95	41.11
108	CLASSROOM	3993	22	229.47	229.14
109	CANTEEN	3662	18	210.42	254.63
110	OFFICIAL	2400	22	137.91	137.71
111	MANAGER ROOM	3702	22	212.72	212.40
112	PUBLICATION	2400	22	137.91	137.71
113	MEN WC	290	18	16.66	20.16
114	WOMEN WC	290	18	16.66	20.16
115	WOMEN WC	474	18	27.24	32.97
116	MEN WC	474	18	27.24	32.97
117	CLASSROOM	4439	22	255.09	254.72
118	MUSIC ROOM	6074	22	349.01	348.49
119	STORAGE	807	15	46.35	63.61
120	MECHANICAL WORKSHOP	4492	18	258.15	312.38
124	CORRIDOR	5077	18	291.75	353.04
Z01	CLASSROOM	5037	22	289.45	289.02
Z02	CLASSROOM	4074	22	234.11	233.77
Z03	CLASSROOM	5220	22	299.96	299.52
Z04	CLASSROOM	5279	22	303.37	302.92
Z05	MEN WC	499	18	28.70	34.73

Table G.2.3 (continued)

ROOM NO.	ROOM NAME	HEAT LOSS (Watt)	ROOM TEMP. (°C)	REQ. WATER FLOW (kg/h)	IRREV. RATES OF RAD. (Watt)
Z06	WOMEN WC	499	18	28.70	34.73
Z07	EQUIPMENT ROOM	545	15	31.30	42.96
Z08	MEETING ROOM	1162	22	66.74	66.64
Z09	GUIDANCE	2737	22	157.28	157.05
Z10	ARCHIVE	840	15	48.25	66.23
Z11	INFIRMARY	4551	24	261.49	234.01
Z12	MANAGER ASSISTANT	2688	22	154.44	154.21
Z13	SOCIAL ROOM	2274	22	130.65	130.46
Z14	MEN WC	303	18	17.41	21.07
Z15	WOMEN WC	303	18	17.41	21.07
Z16	WOMEN WC	499	18	28.70	34.73
Z17	MEN WC	499	18	28.70	34.73
Z18	ACTIVITY ROOM	4585	22	263.45	263.06
Z19	OFFICE	913	18	52.46	63.48
Z20	ACTIVITY ROOM	4345	22	249.65	249.28
Z21	CLASSROOM	6368	22	365.92	365.38
Z22	CORRIDOR	8936	18	513.47	621.34
B01	SHELTER	5965	18	342.76	414.77
B03	STORAGE	543	15	31.21	42.83
B05	WORKER DRESSING ROOM	1472	24	84.58	75.69
B06	WORKER ROOM	2036	22	116.98	116.81
B08	MEN WC	323	18	18.56	22.46
B09	WOMEN WC	307	18	17.66	21.37
B10	WOMEN WC	490	18	28.15	34.07
B11	MEN WC	454	18	26.09	31.57
B12	MEN DRESSING ROOM	1528	24	87.78	78.55
B13	SPOR EQ.ROOM	379	15	21.77	29.88
B14	WOMEN DRESSING ROOM	1592	24	91.49	81.87
B15	PHYSICAL TRAINING HALL	3173	18	182.31	220.61
B17	MEN TEACH.DRESS.ROOM	1528	24	87.78	78.55
B18	WOMEN TEACH.DRES.	2100	24	120.64	107.96
B19	CORRIDOR	1753	18	100.74	121.91
	TOTAL	**215,727**		**12396.14**	**13121.40**