Analysis of Carbon Dioxide (CO_2) Emission by Heat Recovery Steam Generator (HRSG)

By

Muhammad Syahmi Bin Aminudin

12763

A dissertation report submitted for partial fulfillment of requirements for the Bachelor of Engineering (Hons) (Mechanical Engineering)

Bachelor of Engineering (Hons)

(Mechanical Engineering)

MAY 2013

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CERTIFICATION OF APPROVAL

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Approved by,

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(AP Dr. M Amin A Majid)

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TRONOH PERAK

May 2013

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project that the original work is my own concept except as specified in the references and acknowledgements and that the original work contained herein have not been undone or done by unspecified source or persons.

MUHAMMAD SYAHMI BIN AMINUDIN

ABSTRACT

This research is about to analyze the carbon dioxide (CO_2) emission of the Heat Recovery Steam Generator (HRSG). The exhaust heat from the Gas Turbine (GT) released to the environment consists of CO_2 and other air pollutant emission, which contribute to the global warming and the greenhouse effect. The main objective of this project is to study the carbon dioxide (CO_2) emission by HRSG, which is fueled by exhaust gas heat from the GT and when 100% of exhaust gas heat from the GT is emitted to the environment. Block diagram energy models are develop based on the principle of First Law of Thermodynamics, mass and energy models. Using mass and energy balances for each subcomponent of HRSG and for the exhaust gas heat from GT, computations of energy contents and flow are possible for thermodynamics analysis. THREE (3) assumptions are used for CO_2 analysis; i. The flow rate of flue gas is kept constant as 19.22 kg/s, ii. The inlet and outlet temperature of evaporator is set as 95^{o}C and 180^{o}C respectively and iii. The temperature of hot gases at economizer is set to 182^{o}C. The result of 100% of waste heat emitted to the environment is compared with the waste heat used by the HRSG for the conversion of steam. It is noted that the amount of CO_2 emission by HRSG is inversely proportional with the amount of CO_2 emission by the exhaust heat from GT because at 8am, the maximum amount of CO_2 emission by HRSG is the minimum amount of CO_2 emission by the exhaust heat from GT. By comparing these values, it is noted that HRSG contributes about 32.21% of CO_2 emission at UTP GDC in comparison to the exhaust heat from GT when it is 100% emitted to the environment. Moreover, it is noted that the amount of CO_2 emission by HRSG is less than when 100% of exhaust heat is emitted to the environment by approximately 35.59%.

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This project would not been in any possible way to accomplish without the guidance and the help from the many individuals in many ways that contributed in stimulating suggestions and encouragement.

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Last but not least, thank you so much to my parents and friends for giving me endless support.

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ABBREVIATIONS AND NOMENCLATURES

GDC	Gas District Cooling
UTP	Universiti Teknologi Petronas
GT	Gas Turbines
HRSG	Heat Recovery Steam Generator
SAC	Steam Absorption Chiller
CO_2	Carbon dioxide
GWP	Global warming potential
CCPP	Combined cycle power plant
CHP	Combined heat and power production
GHG	Greenhouse gases
CO_2/PEC	The carbon intensity of primary supply
GDP	Gross Domestic Product
DCS	Distributed Control System

CHAPTER 1: INTRODUCTION

1.1 Background of Study

Gas turbines (GT) are widely installed at the gas fuelled power plant to generate electricity. It is integrated to the power generation systems either as open cycle system, combined cycle system or cogeneration system. Besides generating electricity, the GT generate exhaust heat. The exhaust heat released to the environment consists of carbon dioxide (CO_2) and other air pollutant emission. Studies on CO_2 emission have been undertaken by a number of authors. (Graus & Worrell, 2011) reported that the amount of CO_2 intensity released using power and heat method by gas-fuelled power generating system is 404 g/kWh. (Harrison *et al*, 1997) found that CO_2 accounts for 99 wt% of all air emissions. The contributions from CO_2 gas is considered in the assessment of the global warming potential (GWP) of natural gas combined-cycle system. The GWP for this system is 499.1 g CO_2-equivalent/kWh (Houghton, *et al*, 1996). The following table (Table 1.1) contains the emission rates for CO_2 gas and its contribution to the total GWP.

TABLE 1-1: Emissions of CO_2 Gas and Contribution to GWP (IEA Greenhouse Gas Programme. (1999), “Greenhouse Gas Emissions from Power Stations”, United Kingdom, Website: www.ieagreen.org.uk.)

Emissions of Greenhouse Gases and Contribution to GWP

	Emission amount (g/kWh)	Percent of greenhouse gases in this table (%)	GWP relative to CO_2 (100 year IPCC values)	GWP value (g CO_2-equivalent /kWh)	Percent contribution to GWP (%)
CO_2	439.7	99.4	1	439.7	88.1
CH_4	2.8	0.6	21	59.2	11.9
N_2O	0.00073	0.0002	310	0.2	0.04

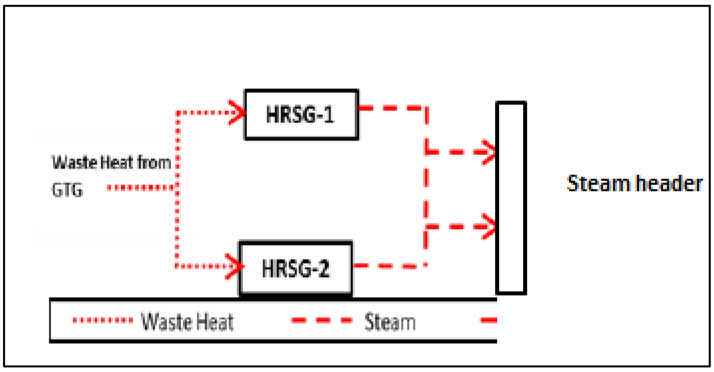


FIGURE 1.1: Steam Generations by HRSG

Source: S. Amear *et.al*. (2013) [5]

For the district cooling plant at Universiti Teknologi Petronas (UTP), the exhaust heat from GT is used to generate steam by Heat Recovery Steam Generator (HRSG). During peak periods, it is operated with full load capacity. The waste heat from GTG is used to generate steam by HRSG. As shown in Figure 1.1 & Figure 1.2, the waste heat from the GTG is diverted to HRSG to generate steam. The steam is then transferred to the steam header. For the analysis, only 66.6% of exhaust heat is captured to produce the steam while the remaining 33.4% is emitted to the environment [5].

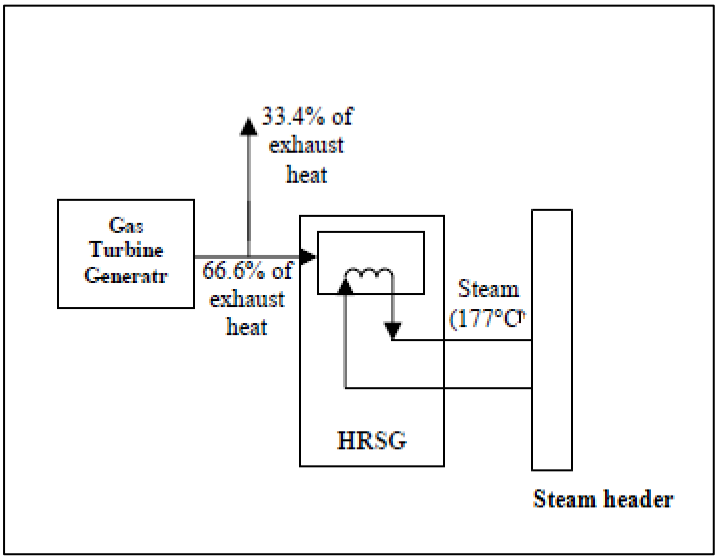


FIGURE 1.2: Energy System Circulation

Source: S. Amear *et.al*. (2013) [5]

1.2 Problem Statement

Carbon dioxide comprises about 0.03% of the earth's atmospheric volume but because of combustion of fossil fuels and deforestation, this percentage has increased by about 25% since pre-industrial times. Scientists estimate that excessive CO_2 emissions into the atmosphere will increase the earth's surface temperature approximately by 1.5-4^{o}C in the next 30-40 years [6]. Due to climate change the worldwide consensus is to make every effort to limit the global average increasing temperature to 2^{o}C compared to pre-industrial times [7].

Waste heat from GT is normally emitted to the environment. This contributes to CO_2 emission to the surrounding where it leads to the environmental hazard. CO_2 is considered to be responsible for the greenhouse effect and global warming. Concentrations of 3-6% can cause headaches; larger concentration can lead to unconsciousness and possibly death. One option to overcome this is to use the exhaust heat to generate steam using HRSG.

Many authors have done analyses of cogeneration system at Universiti Teknologi Petronas (UTP) covering Gas Turbine [8], Electric Chillers and Steam Absorption Chillers [9] and Thermal Energy Storage [10]. However, there is no specific study on the evaluation of the amount of carbon dioxide (CO_2) emitted from steam generation process by HRSG.

1.3 Objective and Scope of Study

1.3.1 Objective

The main objective of this study is to study the carbon dioxide (CO_2) emission by HRSG, which is fueled by exhaust gas heat from the GT and when 100% of exhaust gas heat from the GT is emitted to the environment.

1.3.2 Scope of Study

The scope of study covers the following:

i) The gas turbines and HRSG at UTP GDC available are taken as case study
ii) For the analysis, the CO_2 analysis will cover two scope, namely:
   - 100% of exhaust gas heat from the GT emitted to the environment
   - only 66.6% of exhaust heat captured by HRSG to produce the steam while the remaining 33.4% is emitted to the environment

CHAPTER 2: LITERATURE REVIEW

2.1 HEAT RECOVERY STEAM GENERATOR

Heat Recovery Steam Generators (HRSGs) are widely used in process and refineries, power plants and in several cogeneration/combined cycle systems. HRSG is a steam boiler that recovers heat from the hot exhaust gases of gas turbine engine for steam generation.

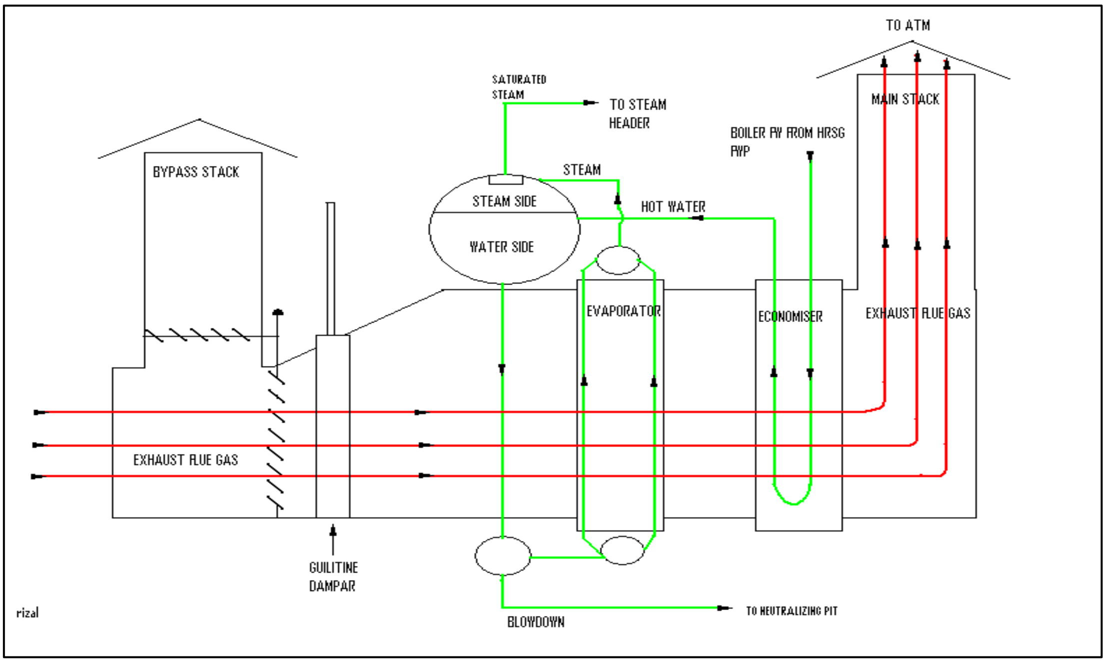


FIGURE 2.1: Heat Recovery Steam Generator

(Sources: Gas District Cooling Plant, UTP, 2001) [11]

From Figure 2.1, the exhaust gases from the GT enter the evaporator where steam is generated. The hot gases leaving the evaporator pass through the economizer unit. After a pre-heating step in the economizer, water enters into the drum, slightly sub cooled. From the drum, the water flows to the evaporator and returns as a water/steam mixture to the drum where water and steam are separated.

The saturated steam leaves the drum to the superheater where it reaches the maximum temperature (J.Y. Shin, Y.J. Jeon, D.J. Maeng, J.S. Kin, S.T. Ro, 2002).[12]

Some HRSGs are single-pressure units, but much more common are multi-pressure systems, as they offer improved efficiency. P.R Kumar and V.D Raju (2012) [13] clarify that HRSGs are categorized into single, dual, and triple pressure types depending on the number of drums in the boiler. With a single-pressure HRSG about 30% of the total plant output is generated in the steam turbine. A dual-pressure arrangement can increase the power output of the steam cycle by up to 10%, and an additional 3% can result with a triple-pressure cycle.

Deschamps P.J. (1998) [14] states “in a combined cycle power plant (CCPP), the HRSG represents the interface element between the gas turbine and the steam cycle”. The process is known as combined-cycle power generation when the steam drives a turbine for electricity production. When steam is used for industrial purposes, the process is known as co-generation (Buecker, B. 2002). The quality of steam generated by the HRSG depends on the flow and temperature of the exhaust gases entering it.

The overall efficiency of the plant increases due to the harnessing of energy from the gas turbine exhaust gas which would be otherwise wasted. Efficiencies of combined-cycle units may approach 60% as compared to a conventional steam turbine only power generation plant without a combined steam and gas turbine (US Patent No. 6367258, 2002)[15].

2.1.1 Fundamental Part of HRSG

The fundamental part of HRSG is explained by P.R Kumar and V.D Raju (2012) [13]. HRSG consists of steam drum, evaporator, economizer and superheater.

Steam Drum

The steam drum is the boiler shell that is connected by short tubes with the uptake riser and by longer tubes to the down take header. The water level in the drum is slightly above the center. The water tubes are connected to the top and bottom header and are kept inclined at an angle of 15^o to the horizontal.

Evaporator

Evaporator is the portion of HRSG in which water is boiling to form steam. Typically a mixture of water and steam exists of this portion. It acts to vaporize water and produce steam in one component, like kettle in the kitchen.

Economizer

The economizer is placed at the end of side flues before exhausting the hot gases to the chimney. The water before being fed into the boiler through the valve is passed through the economizer.

In single pressure HRSG, the economizer will be located directly downstream (with respect to gas flow) of the evaporator section. In a multi-pressure unit the various economizer sections may be split and be located in several locations both upstream and downstream of the various evaporators.

Superheater

The superhater is the portion of HRSG in which saturated steam is heated to higher temperatures. While the evaporator produces dry-saturated steam, this is rarely acceptable for large steam turbines and is frequently not appropriate condition for process applications.

In these cases, the saturated steam produced in the evaporator is sent to superheater. This component adds sensible heat to the dry steam, superheating it beyond the saturation temperature.

2.2 THE FIRST LAW OF THERMODYNAMICS

Energy is a fundamental concept of thermodynamics and one of the most significant aspects of engineering analysis. Energy has number of different basic forms: kinetic energy, gravitational potential energy and internal energy, all of which measure the ability of an object or system to do work on another subject or system. Energy can also be transformed from one form to another and transformed from one form to another and transferred between systems. For closed systems, energy can be transferred by work and heat transfer. The total amount of energy is conserved in all transformations and transfers.

2.2.1 Work

In thermodynamics, the term work denotes a means for transferring energy. Work is an effect of one system on another which is identified and measured as follows: Work is done by a system on its surrounding if the sole effect on everything external to the system could have been rising of a weight. Notice that the raising of a weight is in effect a force acting ever, the sole effect could be the change in elevation of a mass. The magnitude of the work is measured by the number of standard weights that could have been raised.

Work done by a system in considered positive in value; work done on a system is considered negative. Using the symbol *W* to denote work, we have

$W > 0$: work done by the system

$W < 0$: work done on the system

The time rate of doing work or power is symbolized by W

2.2.2 Energy

A closed system undergoing a process that involves only work interactions with its surroundings experiences an adiabatic process. On the basis altered adiabatically, the amount of work W_{ad} is fixed by the end states of the system and is independent of the details of the process. Regardless of the type of work interaction involved the type of process or the nature of the system; this is proved as one way the first law of thermodynamics can be stated.

As the work in an adiabatic process depends on the initial and final states only, it can be concluded that an extensive property can be defined for a system such that its change in value between two states is equal to the work in an adiabatic process that has these as the end states. This property is called energy.

According to Moran, MJ., (1999a) [16]

In engineering thermodynamics the change in the energy of a system is considered to be made up of three macroscopic contributions. One is the change in kinetic energy (KE) associated with the motion of the system as a whole relative to an external coordinate frame. Another is the change in gravitational potential energy (PE) associated with the position of the system as a whole in Earth's gravitational field. All other energy changes are lumped together in the internal energy (U) of the system. Like kinetic energy and gravitational potential energy, internal energy is an extensive property.(p.p 5)

Bejan, Adrian., et.al (1996a) [17] further describes that the change in energy between two states in terms of the work in an adiabatic process between these states is

$$(KE_2 - KE_1) + (PE_2 - PE_1) + (U_2 - U_1) = -W_{ad} \tag{2.1}$$

where 1 and 2 denote the initial and final states respectively and the minus sig n before the work term is in accordance with the previously stated sign convention for work.

Meanwhile, internal energy is a state function of a system and can has intensive thermodynamic property called specific internal energy. The specific internal is symbolized by u or $\bar{u}$, respectively. The specific internal is expressed on a unit mass or per mole basis.

According to Moran, MJ., (1999b) [16]

The specific energy (energy per unit mass) is the sum of the specific internal energy u, the specific kinetic energy $V^2/2$ and the specific gravitational potential energy gz. That is,

$$\text{Specific energy} = u + \frac{1}{2}V^2 + gz \tag{2.2}$$

where V is the velocity and z is the elevation, each relative to a specified datum and g is the acceleration of gravity.

2.2.3 Energy balance

Closed systems can also interact with their surroundings in a way that cannot be categorized as work. This type of interaction is called a heat interaction and the process can be referred to as a non-adiabatic process.

A fundamental aspect of the energy concept is the energy is conserved. According to Bejan, Adrian., et.al (1996b) [17],

Since a closed system experiences precisely the same energy change during a non-adiabatic process as during an adiabatic process between the same end states, it can be concluded that the net energy transfer to the system in each of these processes must be the same. It follows that heat interactions also involve energy transfer. Further, the amount of energy Q transferred to a closed system in such interactions must equal the sum of the energy change of the system and the amount of energy transferred from the system by work. That is,

$$Q = [(KE_2 - KE_1) + (PE_2 - PE_1) + (U_2 - U_1)] + W$$

This expression can be rewritten as

$$(U_2 – U_1) + (KE_2 – KE_1) + (PE_2 – PE_1) = Q – W \quad (2.3)$$

Equation 2.4, called the closed system energy balance, summarizes the conservation of energy principle for closed systems of all kinds.

2.3 PREVIOUS STUDY ON EVALUATION OF CO_2 EMISSION

There are many researchers studied about evaluation of CO_2 intensity such as Graus, WHJ. *et al* (2011) [1] studied the five methods to calculate CO_2 intensity (g/kWh) of power generation, based on difference ways to take into account combined heat and power generation. They reveal that heat correction method has large impact on CO_2 intensity of CHP plant. In addition, they reported that CO_2 intensity electricity consumption is 8-14% higher than electricity generation and they concluded that CO_2 emission from power generation can be reduced by implementing best practice technology for fossil power generation.

Wu, L., Zeng W. (2013) [18] reported that based on the use of the long-mean Divasia Index Decomposition Method (LMDI) the carbon dioxide emissions intensity is decomposed into the contribution from four components: industry structure effect, industrial intensity effect, energy structure effect and emission coefficient effect. In their paper, it is found that the contribution of industry and energy structure effect into the decrease of carbon dioxide emissions intensity is 53-98% and 26.84% respectively. NA Odeh, TT Cockerill (2007) [19] investigates the global warming potential (GWP, g CO_2–e/kWh) and energy balance of three generation technologies; supercritical pulverized coal (super-PC), natural gas combined cycle (NGCC) and integrated gasification combine cycle (IGCC) using life cycle approach. In their paper, results show that for 90% CO_2 capture efficiency, life cycle GHG emissions are reduced by 75-84% depending on what technology is used. Meanwhile, S.P. Raghuvanshi *et al.* (2005) [20] provide a brief investigation of CO_2 emission from coal based power generation in India. Energy indicators, trends in energy consumption and CO_2 emissions have been thoroughly investigated. They decomposed CO_2 emissions as the product of the primary energy consumption and the carbon intensity of primary supply (CO_2/PEC). The growth rate can thus, be approximated as the sum of the growth rates in energy and carbon intensity. Kaya Y. (1989) [21] given CO_2 emissions equation known as Kaya identity also relates the carbon dioxide per GDP with the improvement in energy intensity for GDP (process efficiency improvement) and carbon intensity (energy conversion efficiency) of power conversion devices. G. Chicco and P. Mancarella (2008) [22] noted that, to assess the emission reduction of CO_2 and other Greenhouse Gas (GHG) from cogeneration system, it should be broken up to subsystems which are represented with block diagram models. From the experience M. Kanoglu *et al.*,[23] on the evaluation of energy systems; the assessment of the cogeneration system should be based on the thermodynamic principles.

2.3.1 Evaluation of Carbon Dioxide Emission using Energy Analysis Approach: A Case Study of a District Cooling Plant

This study was done by S. Amear, *et al.* (2013) [5] at district cooling plant at Universiti Teknologi Petronas (UTP). The focus of their study was to analyze the amount of heat loss and CO_2 released to the environment. Using the First Law of Thermodynamics, the emission reduction of CO_2 is assessed by broken up the cogeneration system to subsystem using block diagram models.

Block diagram energy model

The block diagram energy model is developed from the past research based on the principle of first law of thermodynamics, mass and energy balance models. Using principles developed thus far, a detailed thermodynamic model is developed and presented for heat recovery steam generator (HRSG) system as illustrated in Figure 2.2.

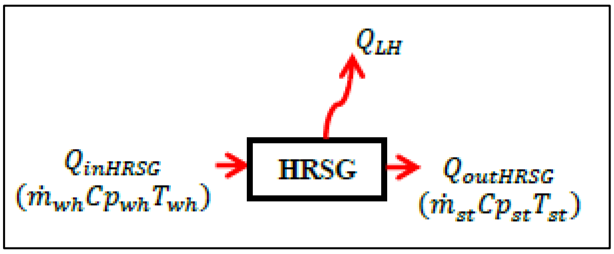


FIGURE 2.2: Energy Model of HRSG [5]

Where;

Q_{inHRSG} = energy in to HRSG (kWh)

$Q_{outHRSG}$ = energy out from HRSG (kWh)

Q_{LH} = energy loss from HRSG (kWh)

$\dot{m}_{wh}$ = flow rate of waste heat (kg/s)

$\dot{m}_{st}$ = flow rate of steam (kg/s)

Cp_{wh} = enthalpy of waste heat

Cp_{st} = enthalpy of steam

T_{wh} = temperature of waste heat

T_{st} = temperature of steam

Thermodynamic analysis [First Law of Thermodynamics]

Thermodynamic First Law states that energy can neither be created nor destroyed but can only alter the form. The thermodynamics models are based on fundamental mass and energy balances. Using the mass and energy balance equations for each component in the power plant model, it is possible to compute energy contents and flows at each device of the plants and efficiency of the plants [24]. Energy balance equations used for the analysis as shown by Equation (2.4) [25].

Energy balance equations:

$$\dot{Q} - \dot{W} + \sum \dot{m} \left[(h_i - h_o) + \left(\frac{{v_i}^2 - {v_0}^2}{2} \right) + g(z_i - z_o) \right] = 0 \tag{2.4}$$

Where;

$\dot{Q}$ = heat rate into the system

$\dot{W}$ = rate of work done by the system

$\dot{m}$ = mass flow rate

h_i = specific enthalpy of the working fluid entering the system

h_o = specific enthalpy of the working fluid leaving the system

v_i = velocity of mass inlet

v_0 = velocity of mass outlet

g = acceleration due to mass

z_i = elevation of mass inlet

z_o = elevation of mass outlet

Notes: For the analysis, the velocity and elevation components are assumed zero.

For the case of HRSG, it generates steam by utilizing the energy in the exhaust heat from the gas turbine. The energy balance equations model with reference to Figure 2.2 is formulated as follows;

$$Energy_{in}\ of\ HRSG(Q_{inHRSG}) = \dot{m}_{wh}Cp_{wh}T_{wh} \qquad (2.5)$$

While the produced steam out from HRSG is shown below;

$$Energy_{out}\ of\ HRSG\ (Q_{outHRSG}) = \dot{m}_{st}Cp_{st}T_{st} \qquad (2.6)$$

Therefore, the difference between the energy in the exhaust heat from the gas turbine and the produced steam out from HRSG is denoted as;

$$\boldsymbol{Energy_{loss}\ for\ HRSG\ (Q_{LH}) = Energy_{in} - Energy_{out}} \qquad (2.7)$$

Results

In this paper, the historical data for August 2011 is used. The plots of the result are shown in Figure 2.3 and Figure 2.4.

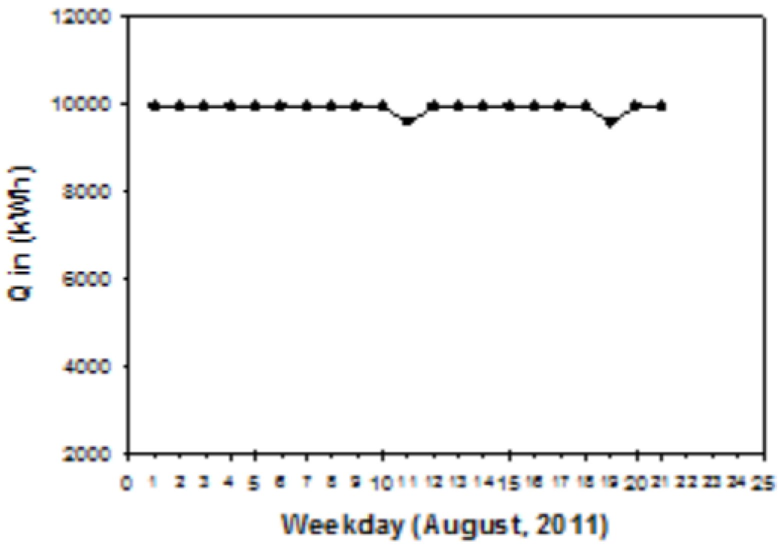


FIGURE 2.3: $Energy_{in}$ of HRSG for August 2011

Source: S. Amear *et.al*. (2013) [5]

Figure 2.3 shows the total energy that was supplied to HRSG. It assumed the input energy to the HRSG is constants which is around 10 000 kWh. However, the output energy is about 5500 kWh as shown in Figure 2.4. Thus, energy loss during the process within HRSG is about 57%.

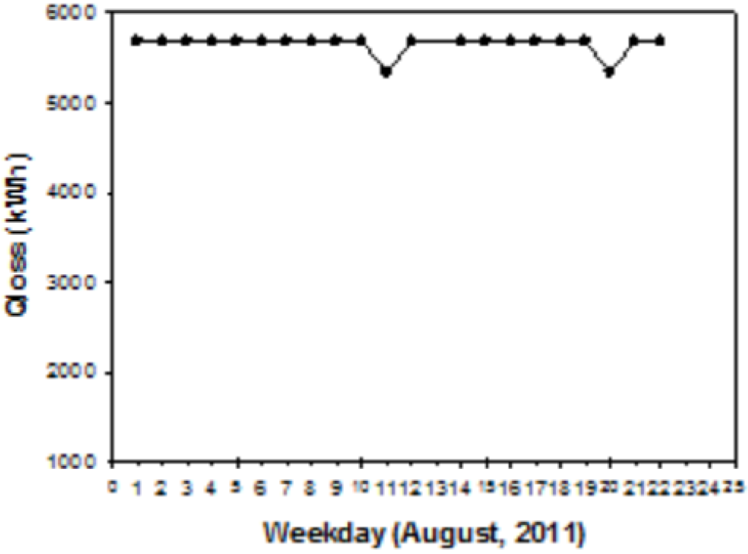


FIGURE 2.4 $Energy_{loss}$ of HRSG for August 2011

Source: S. Amear *et.al*. (2013) [5]

The results are summarized in Table 2-1.

TABLE 2-1: Results from Energy Analysis for HRSG

HRSG				
	Q_{in} (kWh)	Q_{out} (kWh)	Q_{loss} (kWh)	Eff. (%)
Min	9582	4245	5607	0.59
Max	9926	4245	5681	0.57
Mean	9893	4245	5648	0.57
SD	104	N/A	104	0.02

Source: S. Amear *et.al*. (2013) [5]

From Table 2-1, it is noted that the minimum of $Energy_{in}$ for HRSG is 9582 kWh; the maximum of $Energy_{in}$ to HRSG is 9926 kWh while $Energy_{out}$ for HRSG is constant (4245 kWh).

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter explains research methodology beginning with flow chart, block diagram energy model, thermodynamic analysis and the development of spreadsheet template.

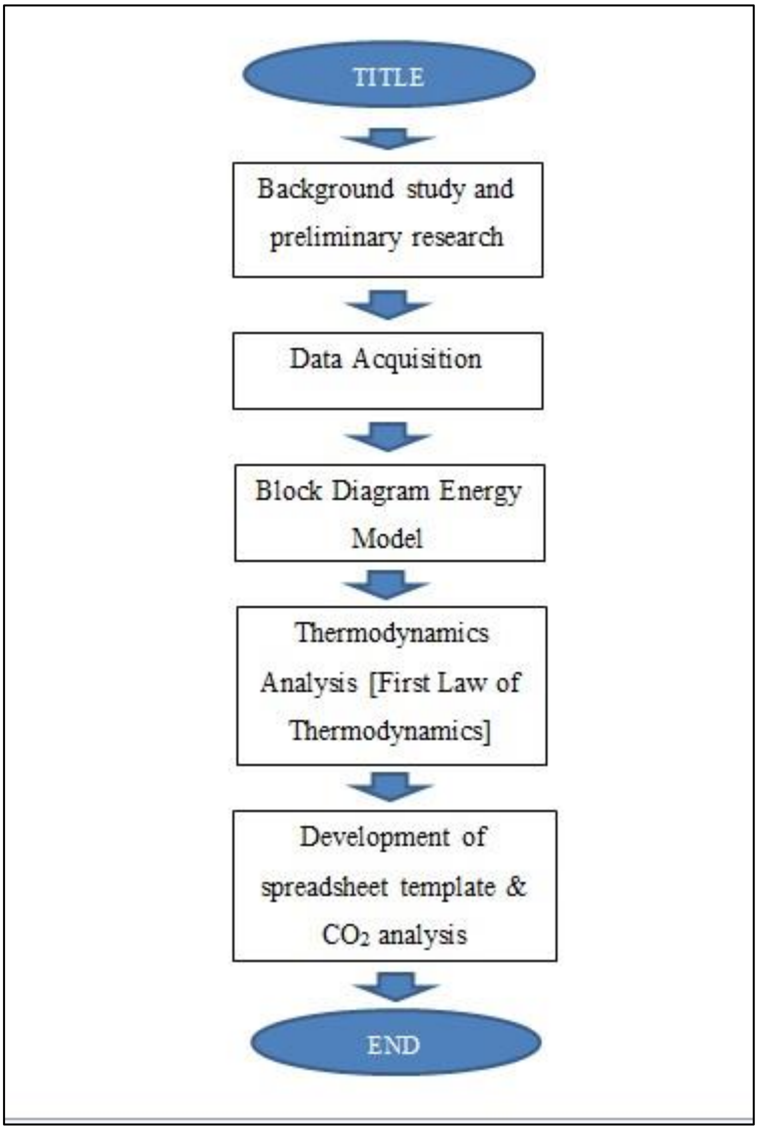


FIGURE 3.1: Project Flow Chart

3.2 RESEARCH METHODOLOGY

Overall the project is following the flow chart with the beginning of received and clarification of title from the supervisor. Literature review starts from finding journals that related to the project as references to study. After that, the HRSG daily checklist from UTP GDC (APPENDIX 3-1) is acquired. The date chosen is on 25th July 2013. The data includes steam line pressure (kPa), steam flowrate (ton/hour) and boiler steam pressure (bar). The schematic diagram of HRSG comprising evaporator and economizer is created based on the operation of UTP GDC.as shown below.

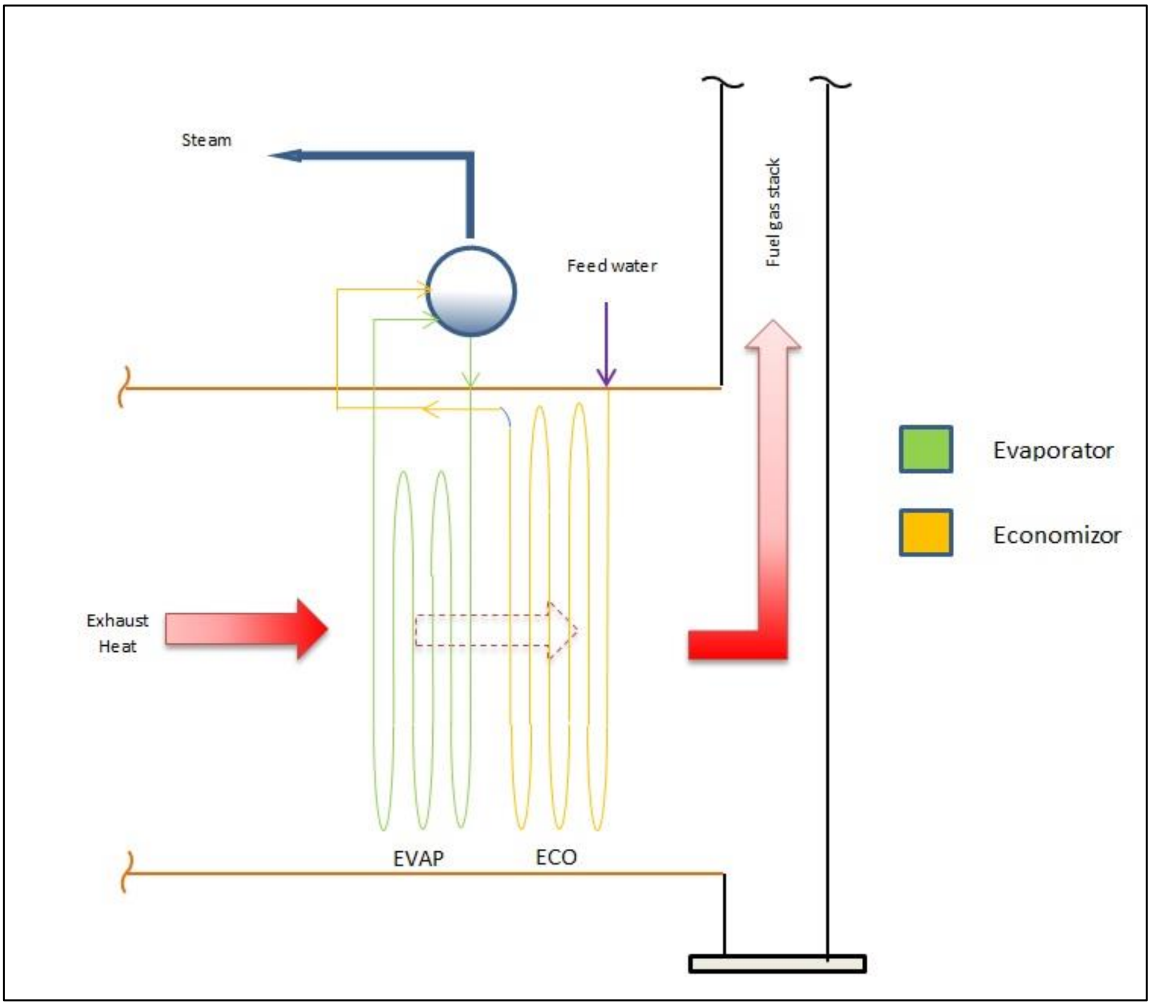


FIGURE 3.2: The Schematic Diagram of HRSG

(Based on UTP GDC HRSG)

3.2.1 BLOCK DIAGRAM ENERGY MODELS

Block diagram energy models are develop based on the principle of First Law of Thermodynamics, mass and energy models. Based on the principle developed thus far, detailed thermodynamic models for subcomponents of HRSG; evaporator and economizer are presented and illustrated.

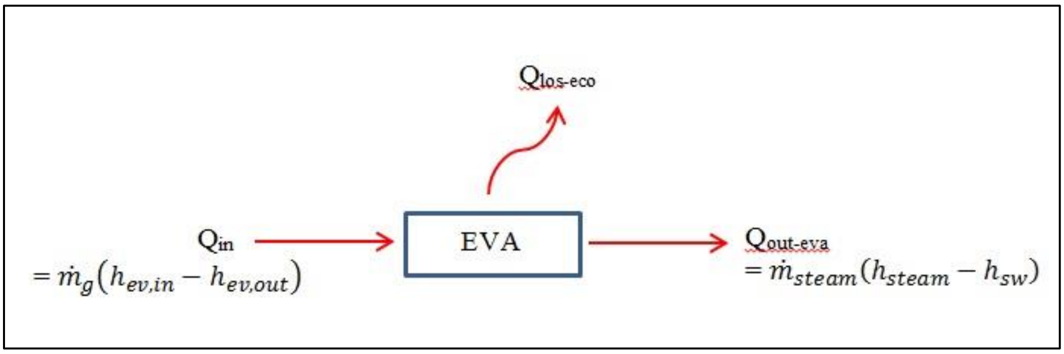


FIGURE 3.3: Evaporator Block Diagram Energy Model

(Based on UTP GDC HRSG)

Where

$Q_{in\text{-}eva}$ = energy input from evaporator (kWh)

$Q_{out\text{-}eva}$ = energy output from evaporator (kWh)

$Q_{los\text{-}eva}$ = energy loss from evaporator (kWh)

$\dot{m}_g$ = flow rate of flue gas (kg/s)

$\dot{m}_{steam}$ = flow rate of steam (kg/s)

$h_{ev,in}$ = enthalpy inlet from evaporator (kJ/kg)

$h_{ev,out}$ = enthalpy outlet from evaporator (kJ/kg)

h_{steam} = enthalpy of steam (kJ/kg)

h_{sw} = enthalpy of saturated water (kJ/kg)

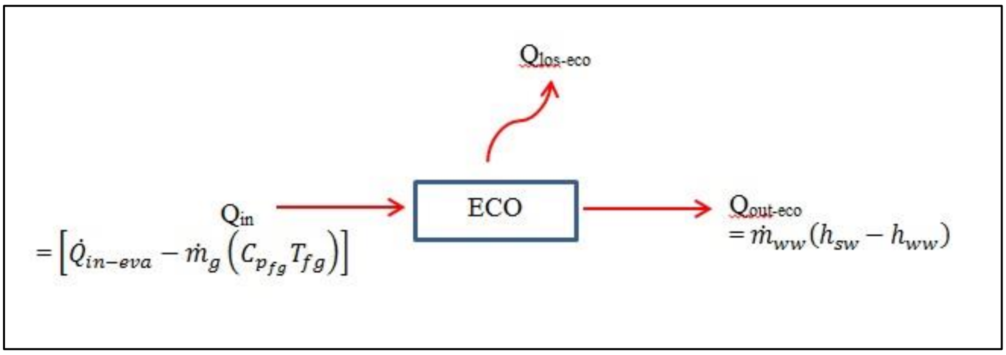


FIGURE 3.4: Economizer Block Diagram Energy Model

(Based on UTP GDC HRSG)

Where

Q_{in-eva} = energy input from economizer (kWh)

Q_{in-eco} = energy input from economizer (kWh)

$Q_{out-eco}$ = energy output from economizer (kWh)

$Q_{los-eco}$ = energy loss from economizer (kWh)

$\dot{m}_g$ = flow rate of flue gas (kg/s)

$\dot{m}_{ww}$ = flow rate of warm water (kg/s)

$C_{p_{fg}} T_{fg}$ = enthalpy from the economizer (kJ/kg)

h_{sw} = enthalpy of saturated water (kJ/kg)

h_{ww} = enthalpy of feed water (kJ/kg)

3.2.2 THERMODYNAMICS ANALYSIS [FIRST LAW OF THERMODYNAMICS]

The thermodynamics models are developed based on mass and energy balances for each subcomponent of HRSG and when 100% of exhaust gas heat from the GT is emitted. Using mass and energy balances for each subcomponent of HRSG and for the exhaust heat, computations of energy contents and flow are possible.

For the case of evaporator, the energy balance in the evaporator is the energy supplied by the flue gas which must be equal to energy gained by steam and energy lost in the evaporator. The energy balance equations model with reference to evaporator energy model is formulated as follows;

The energy supplied by hot gases at evaporator is denoted as:

$$\dot{Q}_{in-eva} = \dot{Q}_{ev,in} - \dot{Q}_{ev,out} = \dot{m}_g\left(h_{ev,in} - h_{ev,out}\right) \tag{2.7}$$

While the energy gained by steam is shown below;

$$\dot{Q}_{out-eva} = \dot{Q}_{steam} - \dot{Q}_{sw} = \dot{m}_{steam}(h_{steam} - h_{sw}) \tag{2.8}$$

For economizer, energy supplied by hot gases at economizer is less than at evaporator due to energy lost. So, the energy supplied by hot gases at evaporator is subtracted with the energy lost at economizer. The energy balance equations model with reference to economizer energy model is formulated as follows;

The energy supplied by hot gases at economizer is denoted as:

$$\dot{\mathrm{Q}}_{\mathrm{in-eco}} = \left[\dot{\mathrm{Q}}_{\mathrm{in-eva}} - \dot{\mathrm{m}}_{\mathrm{g}}\left(\mathrm{C}_{\mathrm{p}_{\mathrm{fg}}}\mathrm{T}_{\mathrm{fg}}\right)\right] \tag{2.9}$$

While the energy gained by warm water is shown below:

$$\dot{Q}_{out-eco} = \dot{m}_{ww}(h_{sw} - h_{ww}) \quad (2.10)$$

The energy loss at evaporator is the difference between the energy supplied by hot gases at evaporator and the energy gained by steam. Therefore, balance equation model of the energy loss at evaporator with reference to evaporator energy model is formulated as follows;

$$\dot{Q}_{los-eva} = \dot{m}_g\left(h_{ev,in} - h_{ev,out}\right) - \dot{m}_{steam}(h_{steam} - h_{sw}) \quad (2.11)$$

Meanwhile, the energy lost in the economizer is the difference between the energy supplied by hot gases at economizer and the energy gained by warm water. Thus, balance equation model of the energy loss at economizer with reference to economizer energy mode is denoted as:

$$\dot{Q}_{loss-eco} = \left[\dot{Q}_{in-eva} - \dot{m}_g\left(C_{p_{fg}}T_{fg}\right)\right] - \dot{m}_{ww}(h_{sw} - h_{ww}) \quad (2.12)$$

Then, the total energy loss by HRSG with reference to balance equation model is the sum of the energy loss at the evaporator and the energy loss at the economizer. Thus, the total energy loss by HRSG is then denoted as:

$$\dot{Q}_{losHRSG} = \dot{Q}_{los-eva} + \dot{Q}_{loss-eco}$$

(2.13)

For analysis, the percentage of energy loss by HRSG is computed below;

$$The\ percentage\ of\ energy\ loss\ (\%) = \frac{Energy\ loss, Qlos}{Energy\ in, Qin} \times 100 \quad (2.14)$$

Lastly, when 100% of waste heat emitted to the environment, the energy supplied by exhaust heat is shown below;

$$\dot{Q}_{ex} = \dot{m}_g C_{p_g} T_{fg} \quad (2.15)$$

These equations will be used in the spreadsheet to obtain energy contents and flow, CO_2 analysis by HRSG, CO2 analysis by exhaust heat from GT and comparison of both CO_2 analysis data.

3.2.3 DEVELOPMENT OF SPREADSHEET TEMPLATE & CO_2 ANALYSIS

The development of spreadsheet template cover the subcomponent of HRSG; evaporator and economizer as well as the exhaust heat generated by GT when 100% of waste heat emitted to the environment. THREE (3) assumptions are used to develop the spreadsheet template & analyze the CO_2 emission by HRSG (66.6%).

i. The flow rate of flue gas is kept constant as 19.22 kg/s
ii. The inlet and outlet temperature of evaporator is set as 95^{o}C and 180^{o}C respectively
iii. The temperature of hot gases at economizer is set to 182^{o}C and the specific heat capacity of the flue gas is 1.068 kJ/kg.^{o}C.

For evaporator, the inlet and outlet enthalpy of evaporator is gained from the thermodynamics property tables [APPENDIX 4-1]. Setting the inlet and outlet temperature of evaporator as 95^{o}C and 180^{o}C respectively, the inlet enthalpy of evaporator is 2270.2kJ/kg and the outlet enthalpy of evaporator is 2015 kJ/kg. The steam flow supplied to steam header ($\dot{m}_{steam}$) in which the unit of ton/hour acquired from the HRSG daily checklist on 25th July 2013 is first changed to kg/s. Furthermore, the steam and saturated water pressure from that HRSG daily checklist is used in the thermodynamics property tables [APPENDIX 4-2] to find the enthalpy of steam and saturated water. The pressure unit is altered from kPa to bar. Noted that 1 bar =10^3 kPa. Now, the energy supplied by hot gases at evaporator, the energy gained by steam and the energy lost in the evaporator is calculated and recorded in the spreadsheet.

The warm water flow ($\dot{m}_{ww}$) in which the unit of ton/hour picked up from the HRSG daily checklist on 25th July 2013 is changed to kg/s. Likewise, the temperature of warm water from that HRSG daily checklist is used in the thermodynamics property tables [TABLE A-2] to find the enthalpy of warm water. Now, the energy supplied by hot gases (Q_{in}) at the economizer, the energy gained by warm water ($Q_{out-eco}$) and the energy lost in the economizer is calculated and developed in the spreadsheet.

CO_2 analysis is started when the total energy loss and the amount of CO_2 emission by HRSG (66.6%) and the energy supplied by hot gases and the amount of CO_2 emission from GT (100%) are acquired. The total energy loss by HRSG is formulated in Equation (2.13) while energy supplied by hot gases from GT is in Equation (2.15).

To analyze the amount of CO_2 emission, the total energy loss by HRSG and the energy supplied by hot gases from GT which are in kWh are then converted to the amount of CO_2 emission. The amount of CO_2 emission is termed in kg of CO_2. The conversion is made by using the CO_2 emission factor as reported by R.Kannan *et al* [27], which is 0.474 kg/kWh for gas fired combined cycle.

The amount of CO_2 emission can be summarized as below;

$$= energy\ loss\ [kWh] \times CO_2\ emission\ factor\ \left[0.474 \frac{kg}{kWh}\right] \qquad (2.16)$$

Finally, the CO_2 released to the environment by HRSG and the amount of CO_2 released from GT is compared. The contribution of the amount of CO_2 emission by HRSG is compared in terms of percentage with the amount of CO_2 emission by exhaust heat from GT. Comparison is done in graphical form.

The percentage of the amount of CO_2 emission by HRSG (%) is shown below;

$$= \frac{The\ amount\ of\ CO_2\ emission\ by\ HRSG}{(The\ amount\ of\ CO_2\ by\ exhaust\ heat\ from\ GT)} \times 100\% \qquad (2.17)$$

TABLE 3-1: Evaporator Spreadsheet

EVAPORATOR									
TIME	GAS FLOW,ṁg	ENTHALPY INLET, hev,in	ENTHALPY OUTLET, hev,out	STEAM FLOW, ṁsteam	ENTHALPY STEAM,hsteam	ENTHALPY SATURATED WATER	ENERGY SUPPLIED BY HOT GASES, Qin	ENERGY GAINED BY STEAM,Qout	ENERGY LOST, Qlos
8:00	19.22	2270.2	2015	1.1222	2770.4	736.314	4904.944	2282.651	2622.293
9:00	19.22	2270.2	2015	1.2583	2770.3	736.314	4904.944	2559.365	2345.579
10:00	19.22	2270.2	2015	1.2417	2770.3	736.314	4904.944	2525.600	2379.344
11:00	19.22	2270.2	2015	1.25	2770.3	736.314	4904.944	2542.483	2362.462
12:00	19.22	2270.2	2015	1.25	2770.3	736.314	4904.944	2542.483	2362.462
13:00	19.22	2270.2	2015	1.2528	2770.3	736.314	4904.944	2548.178	2356.766
14:00	19.22	2270.2	2015	1.25	2770.3	736.314	4904.944	2542.483	2362.462
15:00	19.22	2270.2	2015	1.2583	2770.3	736.314	4904.944	2559.365	2345.579
16:00	19.22	2270.2	2015	1.2472	2770.3	736.314	4904.944	2536.787	2368.157
17:00	19.22	2270.2	2015	1.25	2770.2	736.097	4904.944	2542.629	2362.315
18:00	19.22	2270.2	2015	1.2417	2770.3	736.097	4904.944	2525.870	2379.074
19:00	19.22	2270.2	2015	1.2611	2770.3	736.314	4904.944	2565.060	2339.884
20:00	19.22	2270.2	2015	1.256	2770.3	736.097	4904.944	2554.959	2349.985

TABLE 3-2 Economizer Spreadsheet

TIME	ECONOMIZER										
	GAS FLOW, ṁg	SPECIFIC HEAT CAPACITY ,fg	TEMPERATURE FLUE GAS	ENERGY LOST BY FLUE GAS	WARM WATER FLOW, ṁww	ENTHALPY SATURATED WATER	TEMPERATURE WARM WATER	ENTHALPY WARM WATER	ENERGY SUPPLIED BY HOT GASES, Qin	ENERGY GAINED BY WARM WATER, Qout-eco	ENERGY LOST, Qlos
8:00	19.22	1.068	182	3735.9067	1.2	736.314	90.1	376.92	1169.0373	431.2728	737.76448
9:00	19.22	1.068	182	3735.9067	1.325	736.314	83.6	350	1169.0373	511.86605	657.17123
10:00	19.22	1.068	182	3735.9067	1.3944	736.314	86.3	361.3574	1169.0373	522.83948	646.1978
11:00	19.22	1.068	182	3735.9067	1.3305	736.314	87	364.296	1169.0373	494.96995	674.06733
12:00	19.22	1.068	182	3735.9067	1.4361	736.314	87.2	365.1356	1169.0373	533.0493	635.98798
13:00	19.22	1.068	182	3735.9067	1.3944	736.314	86.9	363.8762	1169.0373	519.32727	649.71001
14:00	19.22	1.068	182	3735.9067	1.4056	736.314	87.2	365.1356	1169.0373	521.72836	647.30892
15:00	19.22	1.068	182	3735.9067	1.3278	736.314	87.7	367.2346	1169.0373	490.06363	678.97365
16:00	19.22	1.068	182	3735.9067	1.3278	736.314	84.3	352.9614	1169.0373	509.01558	660.0217
17:00	19.22	1.068	182	3735.9067	1.2667	736.097	86.4	361.7772	1169.0373	474.15089	694.88639
18:00	19.22	1.068	182	3735.9067	1.3278	736.097	86.6	362.6168	1169.0373	495.90701	673.13027
19:00	19.22	1.068	182	3735.9067	1.3361	736.314	86.8	363.4564	1169.0373	498.17504	670.86224
20:00	19.22	1.068	182	3735.9067	1.3361	736.097	86.8	363.4564	1169.0373	497.88511	671.15217

TABLE 3-3: The Energy Supplied By Hot Gases from GT Spreadsheet

TIME	GAS FLOW,ṁg	EXHAUST GAS TEMPERATURE,Tfg	SPECIFIC HEAT CAPACITY, Cpg	THE ENERGY SUPPLIED BY HOT GASES, Qex
8:00	19.22	448	1.135	9775.052
9:00	19.22	434	1.129	9418.198
10:00	19.22	427	1.126	9241.014
11:00	19.22	422	1.124	9113.34
12:00	19.22	430	1.127	9316.849
13:00	19.22	425	1.125	9189.889
14:00	19.22	432	1.128	9367.49
15:00	19.22	433	1.129	9392.836
16:00	19.22	434	1.129	9418.198
17:00	19.22	426	1.126	9215.443
18:00	19.22	423	1.124	9138.838
19:00	19.22	448	1.135	9775.052
20:00	19.22	459	1.140	10057.76

3.3 Key Milestones

Each of the activities is considered a milestone, in a sense that the first activity is finished before being able to continue to the next.

TABLE 3-4: Key Milestones

Activities (FYP1)	**Week**
Confirmation of project supervisor	**1**
Confirmation of research title	**2**
Completion of first stage of literature study	**4 & 5**
Completion of extended research proposal submission	**6**
Completion of second stage literature review	**7**
Outlining detailed methodology and project activities	**8**
Activities (FYP2)	**Week**
Completion of data acquisition	**2**
Formulation of Equation & Energy Models Development	**5**
Configuring Spreadsheet template	**9**
Configuring results of energy analysis	**10**
CO_2 Evaluation	**12**

3.4 Gantt Charts

Study Plan for Final Year Project (FYP1)

Action / Event		***Number of Weeks***														
		1	**2**	**3**	**4**	**5**	**6**	**7**	**MID SEMESTER BREAK**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Initial Studies and Title Selection																
1	FYP registration															
2	Title selection on FYP1															
3	Study on HRSG and its subsystem															
Preparation on completing extended proposal and proposal defense																
5	Submission of extended proposal															
6	Study methodology for project in detailed															
7	Study on governing equations related to HRSG															
8	Proposal defense for FYP1															
Details of study and final report for FYP1																
9	Study on basic concepts and definitions															
10	Outlining the steps in result and discussion															

11	Submission of interim report															

Study Plans for Final Year Project (FYP2)

No	**Task / Activities**	Weeks														
		1	2	3	4	5	6	7	**MID SEMESTER BREAK**	8	9	10	11	12	13	14
Project Work Continues																
1	Data Acquisition															
2	Formulate equation, energy models and developed into spreadsheet															
3	Analyze data and provide graphical illustration															
4	Analyze result, discussion, and modification															
5	Progress report submission							●								
Project finalization																
6	Review spreadsheet template															
7	Review result and data obtain. Modification if necessary															
8	CO_2 Evaluation															
9	Submission of Draft Report												●			

10	Submission of Dissertation													•		
11	Submission of Technical Paper														•	
12	Oral Presentation														•	
13	Submission of Project Dissertation (hard Bound)															•

3.5 Software and Tools

Microsoft Office Word & Excel 2007 is used in order to draw the schematic diagram of HRSG, develop block diagram energy models, thermodynamics analysis as well as the development of spreadsheet template. Data and mathematical equation is developed and used in this software to compute the energy contents and flows at HRSG and the exhaust heat from GT for CO_2 evaluation.

CHAPTER 4: RESULTS AND DISCUSSION

Graph of the amount of heat loss & CO_2 released to the environment for subcomponents of HRSG; evaporator & economizer and for the exhaust heat from GT on 25th July 2013 will be provided. Before that, the amount of heat loss & CO_2 released to the environment by HRSG and exhaust heat are computed. Comparison of the amount of heat loss & CO_2 released to the environment for subcomponents of HRSG; evaporator & economizer and energy supplied by the exhaust heat and the CO_2 released from GT are done and illustrated in graphical form.

4.1 THE ENERGY CONTENT AND FLOW AT HRSG

4.1.1 The Energy of Flue Gas Supplied To HRSG

FIGURE 4.1: The Energy of Flue Gas Supplied to HRSG Spreadsheet

TIME	EVAPORATOR	ECONOMIZER	HRSG
	ENERGY SUPPLIED BY HOT GASES, Qin	ENERGY SUPPLIED BY HOT GASES, Qin	ENERGY IN, Qin
8:00	4904.94	1169.04	6073.98
9:00	4904.94	1169.04	6073.98
10:00	4904.94	1169.04	6073.98
11:00	4904.94	1169.04	6073.98
12:00	4904.94	1169.04	6073.98
13:00	4904.94	1169.04	6073.98
14:00	4904.94	1169.04	6073.98
15:00	4904.94	1169.04	6073.98
16:00	4904.94	1169.04	6073.98
17:00	4904.94	1169.04	6073.98
18:00	4904.94	1169.04	6073.98
19:00	4904.94	1169.04	6073.98
20:00	4904.94	1169.04	6073.98

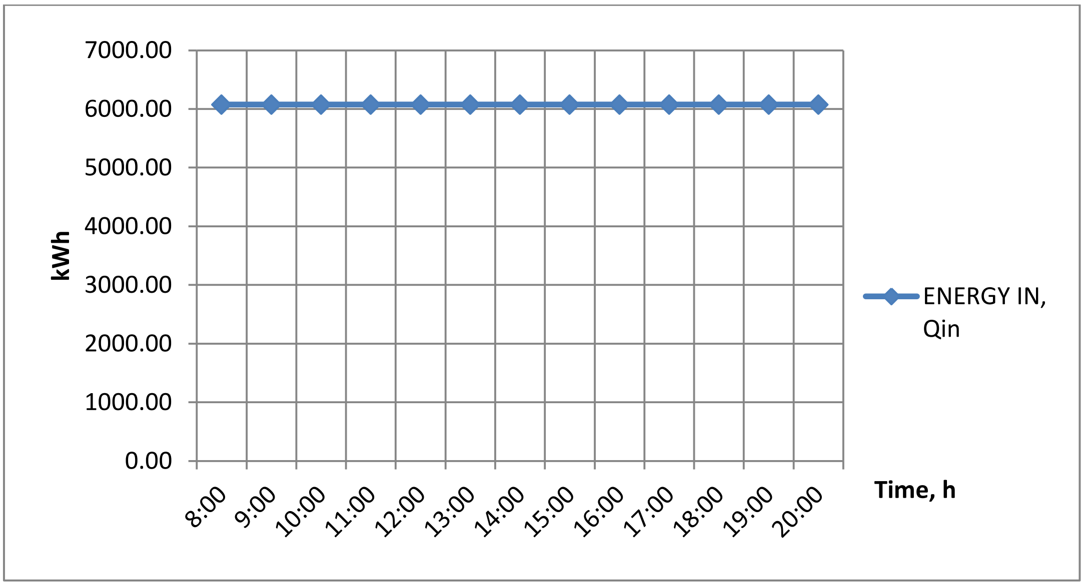


FIGURE 4.2: The Graph of the Energy of Flue Gas Supplied to HRSG against Time

From the spreadsheet above, for the case study of evaporator, the energy supplied by hot gases has a constant value of 4904.944 kWh. For the case study of economizer, the energy supplied by hot gases has a constant value of 1169.04 kWh. However, it is found that the energy supplied by hot gases at the economizer is lower than at the evaporator since there is energy lost by the flue gas from the economizer.

From the graph above, the energy supplied by hot gases to HRSG has a constant value of 6073.98 kWh. The constant energy supplies by hot gases to HRSG are due to the energy equality from the flue gas as it enters the HRSG.

4.1.2 The Energy of Steam Generated By HRSG

From the spreadsheet, for the case of the evaporator, the value of minimum energy gained by steam is 2282.65 kWh and it is happened at 8 am. Meanwhile, the maximum energy gained by steam is happened at 7 pm and the value is 2565.06 kWh. For the case of the economizer, the value of maximum energy gained by warm water is 533.05 kWh and it is happened at 12 pm. Meanwhile, the minimum energy gained by warm water is happened at 8 am and the value is 431.27 kWh.

TABLE 4-1: The Energy of Steam Generated by HRSG Spreadsheet

TIME	EVAPORATOR	ECONOMIZER	HRSG
	ENERGY GAINED BY STEAM,Qout-eva	ENERGY GAINED BY WARM WATER,Qout-eco	ENERGY OUT, Qout
8:00	2282.65	431.27	1851.38
9:00	2559.36	511.87	2047.50
10:00	2525.60	522.84	2002.76
11:00	2542.48	494.97	2047.51
12:00	2542.48	533.05	2009.43
13:00	2548.18	519.33	2028.85
14:00	2542.48	521.73	2020.75
15:00	2559.36	490.06	2069.30
16:00	2536.79	509.02	2027.77
17:00	2542.63	474.15	2068.48
18:00	2525.87	495.91	2029.96
19:00	2565.06	498.18	2066.88
20:00	2554.96	497.89	2057.07

MINIMUM

MAXIMUM

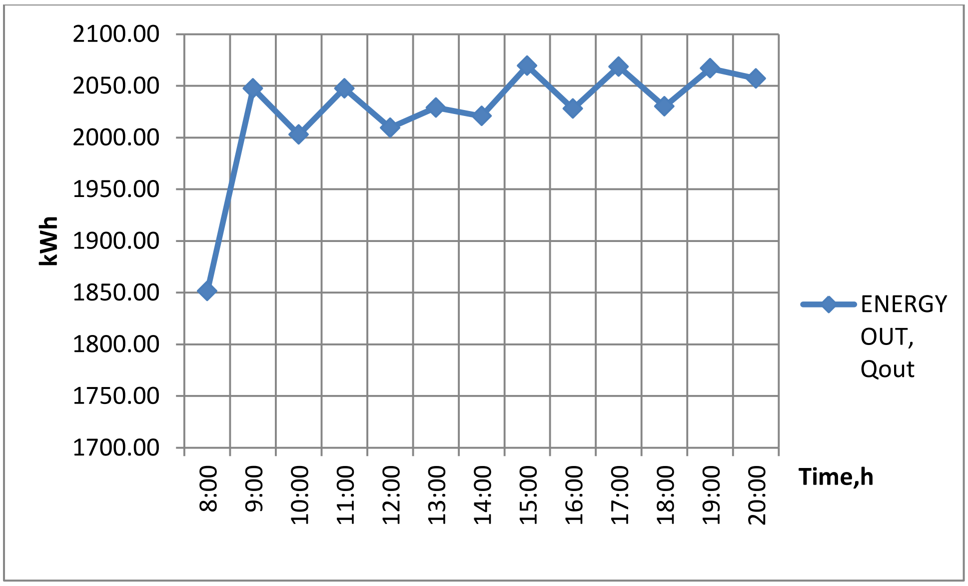


FIGURE 4.3: The Graph of Energy of Steam Generated by HRSG against Time

From the graph, the minimum energy of steam generated by HRSG is 1851.38 kWh and it is happened at 8 am. Meanwhile, the maximum energy of steam generated by HRSG is happened at 7 pm and the value is 2069.30 kWh.

Then, the energy of steam generated by HRSG is checked with the steam flow at the evaporator.

TABLE 4-2: The Energy of Steam Generated by HRSG & Steam Flow at the Evaporator Spreadsheet

TIME	EVAPORATOR	HRSG
	STEAM FLOW, $\dot{m}steam$	ENERGY OUT, Qout
8:00	1.12	1851.38
9:00	1.26	2047.50
10:00	1.24	2002.76
11:00	1.25	2047.51
12:00	1.25	2009.43
13:00	1.25	2028.85
14:00	1.25	2020.75
15:00	1.26	2069.30
16:00	1.25	2027.77
17:00	1.25	2068.48
18:00	1.24	2029.96
19:00	1.26	2066.88
20:00	1.26	2057.07

MINIMUM (yellow)
MAXIMUM (red)

At 8 am, the steam flow at the evaporator is the lowest and the steam flow at the evaporator is the highest at 12 pm. This concludes that the energy of steam generated by HRSG depends on the steam flow at the evaporator.

The steam is generated by HRSG at the evaporator and the amount of steam generated to be supplied to steam header depends on the steam flow at evaporator.

As the steam flow increases, the amount of exhaust heat used to generate steam supplied to steam header increases.

4.2 CO_2 ANALYSIS BY HRSG (66.6%)

4.2.1 The Percentage of the Total Energy Loss by HRSG

TABLE 4-3: The Percentage of the Total Energy Loss by HRSG Spreadsheet

TIME	HRSG		
	ENERGY IN, Qin	ENERGY LOSS,Qlos	PERCENTAGE OF ENERGY LOSS, %
8:00	6073.98	3360.0572	55.32
9:00	6073.98	3002.7506	49.44
10:00	6073.98	3025.5414	49.81
11:00	6073.98	3036.5288	49.99
12:00	6073.98	2998.4495	49.37
13:00	6073.98	3006.4764	49.50
14:00	6073.98	3009.7704	49.55
15:00	6073.98	3024.5531	49.80
16:00	6073.98	3028.1784	49.85
17:00	6073.98	3057.2016	50.33
18:00	6073.98	3052.2044	50.25
19:00	6073.98	3010.7465	49.57
20:00	6073.98	3021.1372	49.74

MINIMUM
MAXIMUM

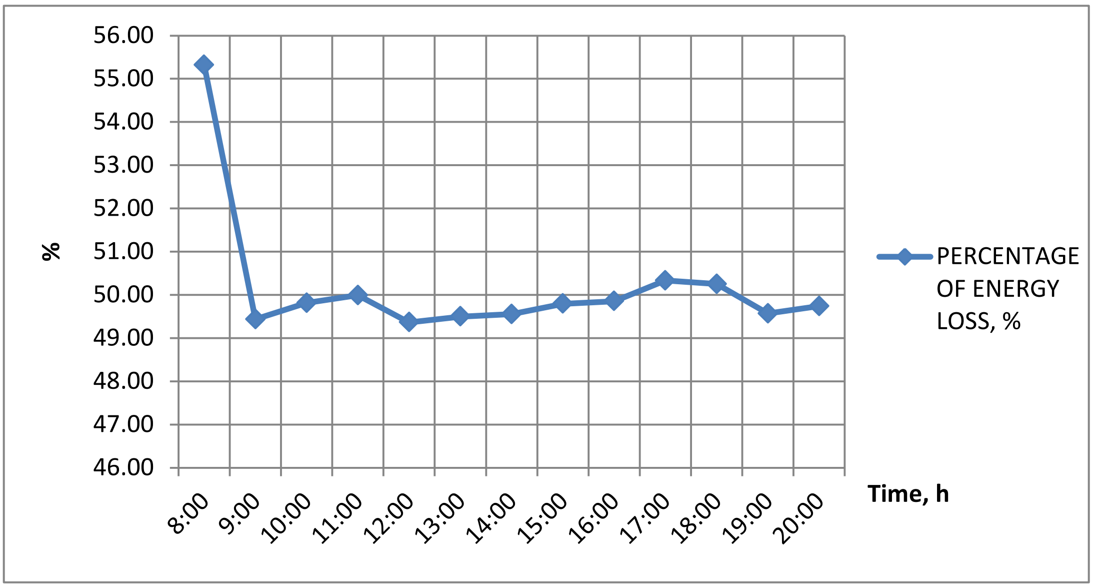


FIGURE 4.4: The Graph of the Percentage of Energy Loss by HRSG against Time

From the result above, the minimum percentage of energy loss by HRSG is 49.37 % while the maximum percentage of energy loss by HRSG is 55.32 %. From these values, it is detected that the lowest percentage of energy loss by HRSG occur at 12 pm and the peak value of percentage of energy loss by HRSG is at 8 am. The percentage of the energy loss by HRSG is then checked with the steam flow at the evaporator and the warm water flow at the economizer.

TABLE 4-4: The Percentage of the Energy Loss by HRSG, the Steam Flow at the Evaporator & the Warm Water Flow at the Economizer

TIME	ECONOMIZER	HRSG
	WARM WATER FLOW, $\dot{m}ww$	PERCENTAGE OF ENERGY LOSS, %
8:00	1.20	55.32
9:00	1.33	49.44
10:00	1.39	49.81
11:00	1.33	49.99
12:00	1.44	49.37
13:00	1.39	49.50
14:00	1.41	49.55
15:00	1.33	49.80
16:00	1.33	49.85
17:00	1.27	50.33
18:00	1.33	50.25
19:00	1.34	49.57
20:00	1.34	49.74

MINIMUM
MAXIMUM

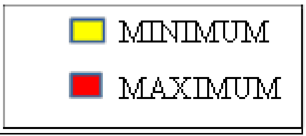
From the result above, it is noticed that the maximum percentage of energy loss by HRSG is the minimum flow of warm water at 8am and vice versa at 12pm. The minimum and maximum percentage of energy loss by HRSG is recorded as 49.37% and 55.32% respectively while the minimum and maximum flow of warm water is recorded as 1.20 kg/s and 1.44 kg/s respectively. Thereby, the percentage of energy loss by HRSG is inversely proportional with flow of warm water in a time.

4.2.2 The Total Energy Loss & Amount of CO_2 Emission by HRSG

The total energy loss by HRSG is converted to the amount of CO_2 emission by HRSG. The conversion is made by using the CO_2 emission factor 0.474 kg/kWh. The total energy loss by HRSG and the amount of CO_2 emission by HRSG are developed in the spreadsheet below;

TABLE 4-5: The Total Energy Loss by HRSG and Amount of CO_2 Emission by HRSG Spreadsheet

TIME	EVAPORATOR	ECONOMIZER	HRSG	CO2 EMISSION FACTOR	AMOUNT OF CO2 EMISSION
	ENERGY LOSS, Qlos	ENERGY LOSS, Qlos	ENERGY LOSS, Qlos		
8:00	2622.29	737.76448	3360.06	0.474	1592.67
9:00	2345.58	657.17123	3002.75	0.474	1423.30
10:00	2379.34	646.197797	3025.54	0.474	1434.11
11:00	2362.46	674.067331	3036.53	0.474	1439.31
12:00	2362.46	635.9879798	2998.45	0.474	1421.27
13:00	2356.77	649.7100117	3006.48	0.474	1425.07
14:00	2362.46	647.308921	3009.77	0.474	1426.63
15:00	2345.58	678.9736527	3024.55	0.474	1433.64
16:00	2368.16	660.0216977	3028.18	0.474	1435.36
17:00	2362.32	694.8863893	3057.20	0.474	1449.11
18:00	2379.07	673.1302704	3052.20	0.474	1446.74
19:00	2339.88	670.8622406	3010.75	0.474	1427.09
20:00	2349.99	671.1521743	3021.14	0.474	1432.02



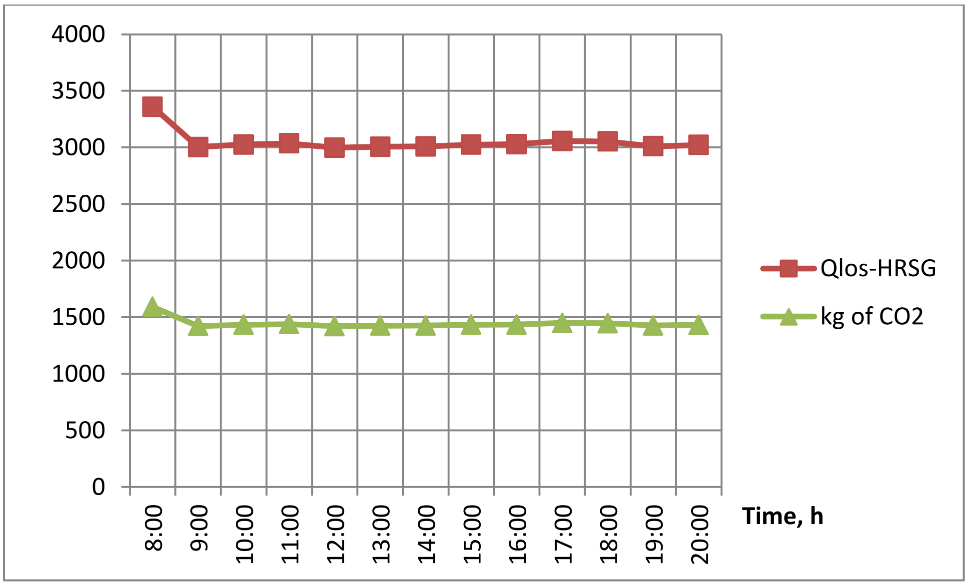


FIGURE 4.5: The Graph of Total Energy Loss and the Amount of CO_2 Emission by HRSG against Time

From the result above, the minimum total energy loss and the amount of CO_2 emission by HRSG are 2998.45 kWh and 1421.27 kg while the maximum total energy loss and the amount of CO_2 emission by HRSG are 3360.06 kWh and

1592.67 kg. From these values, it is detected that the lowest total energy loss and the amount of CO_2 emission occur at 12 pm and the peak value of CO_2 emission is at 8 am. Then, the total energy loss and the amount of CO_2 emission by HRSG is checked with the warm water flow at the economizer.

TABLE 4-6: The Total Energy Loss, the Amount of CO_2 Emission by HRSG & the Warm Water Flow at the Economizer

TIME	ECONOMIZER	HRSG	
	WARM WATER FLOW, ṁww	ENERGY LOSS, Qlos	AMOUNT OF CO2 EMISSION
8:00	1.20	3360.057	1592.67
9:00	1.33	3002.751	1423.30
10:00	1.39	3025.541	1434.11
11:00	1.33	3036.529	1439.31
12:00	1.44	2998.449	1421.27
13:00	1.39	3006.476	1425.07
14:00	1.41	3009.77	1426.63
15:00	1.33	3024.553	1433.64
16:00	1.33	3028.178	1435.36
17:00	1.27	3057.202	1449.11
18:00	1.33	3052.204	1446.74
19:00	1.34	3010.746	1427.09
20:00	1.34	3021.137	1432.02

MINIMUM
MAXIMUM

At 8 am, the warm water flow at the economizer is the lowest and the warm water flow at the economizer is the highest at 12 pm. This concludes that the total energy loss and the amount of CO_2 emission by HRSG depends on the warm water flow at the economizer.

The warm water absorbs heat from the flue gas to the incoming economizer. As the warm water flow increases, the amount of exhaust heat used to generate steam supplied to steam header increases. Thus, the remaining exhaust heat and the amount of CO_2 emission emitted to the environment will decrease.

The 66.6% exhaust heat supplied to HRSG is used to generate steam supplied to steam header. However, the percentage of exhaust heat used by HRSG to generate steam supplied to steam header is not constant throughout the time. Thus, the remaining exhaust heat unused by HRSG will be the energy loss by HRSG and 47.4% of the total energy loss by HRSG will be emitted to the environment as carbon dioxide.

4.3 CO_2 ANALYSIS BY EXHAUST HEAT FROM GT (100%)

4.3.1 The Energy Supplied By Exhaust Heat from GT (Q_{ex}) & Amount of CO_2 Emission by Exhaust Heat from GT

TABLE 4-7: The Energy Supplied By Exhaust Heat from GT (Q_{ex}) & Amount of CO_2 Emission by Exhaust Heat Spreadsheet

TIME	THE ENERGY SUPPLIED BY HOT GASES, Qex	CO2 EMISSION FACTOR	AMOUNT OF CO2 EMISSION, kg
8:00	9775.1	0.474	4633.37
9:00	9418.2	0.474	4464.23
10:00	9241.0	0.474	4380.24
11:00	9113.3	0.474	4319.72
12:00	9316.8	0.474	4416.19
13:00	9189.9	0.474	4356.01
14:00	9367.5	0.474	4440.19
15:00	9392.8	0.474	4452.20
16:00	9418.2	0.474	4464.23
17:00	9215.4	0.474	4368.12
18:00	9138.8	0.474	4331.81
19:00	9775.1	0.474	4633.37
20:00	10057.8	0.474	4767.38

MINIMUM
MAXIMUM

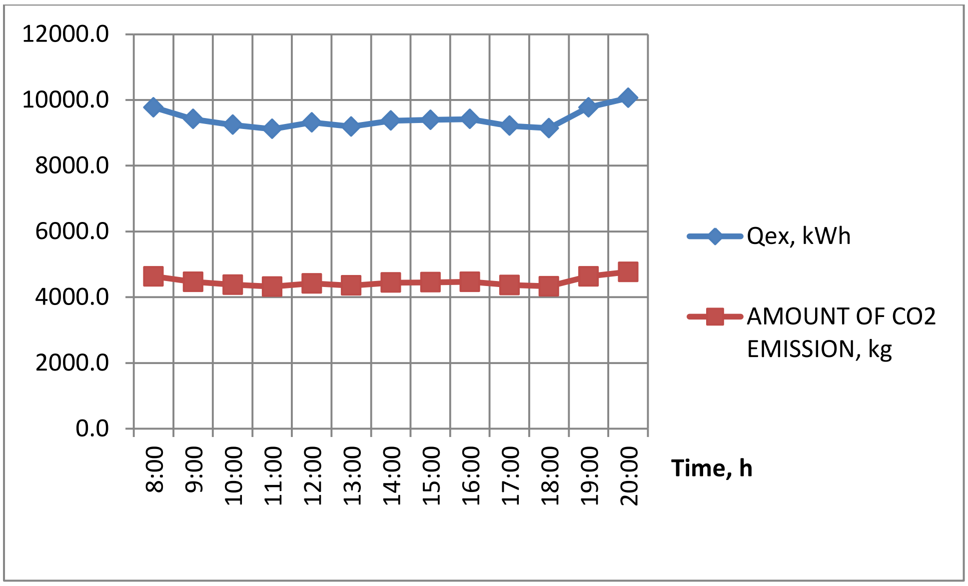


FIGURE 4.6: The Graph of the Energy Supplied by Exhaust Heat and the Amount of CO_2 Emission by Exhaust Heat from GT against Time

From the result above, the minimum energy supplied by exhaust heat and the amount of CO_2 emission are 9113.3 kWh and 4319.72 kg while the maximum energy supplied by exhaust heat and the amount of CO_2 emission are 10057.8 kWh and 4767.38 kg. From these values, it is detected that the lowest energy supplied by exhaust heat and the amount of CO_2 emission occur at 11 am and the peak value of energy supplied by exhaust heat and the amount of CO_2 emission is at 8 pm. Then, the energy supplied by exhaust heat and the amount of CO_2 emission is compared with the temperature of flue gas entering HRSG.

TABLE 4-8: The Energy Supplied by Exhaust Heat, the Amount of CO_2 Emission by Exhaust Heat from GT & the Temperature of Flue Gas Entering HRSG Spreadsheet

TIME	EXHAUST GAS TEMPERATURE	THE ENERGY SUPPLIED BY HOT GASES, Qex	AMOUNT OF CO2 EMISSION, kg

8:00	448	9775.1	4633.37
9:00	434	9418.2	4464.23
10:00	427	9241.0	4380.24
11:00	422	9113.3	4319.72
12:00	430	9316.8	4416.19
13:00	425	9189.9	4356.01
14:00	432	9367.5	4440.19
15:00	433	9392.8	4452.20
16:00	434	9418.2	4464.23
17:00	426	9215.4	4368.12
18:00	423	9138.8	4331.81
19:00	448	9775.1	4633.37
20:00	459	10057.8	4767.38

MINIMUM
MAXIMUM

From the result above, the minimum the energy supplied by exhaust heat and the amount of CO_2 emission by exhaust heat from GT are 9113.3 kWh and 4319.72 kg while the maximum the energy supplied by exhaust heat and the amount of CO_2 emission by exhaust heat from GT are 10057.8 kWh and 4767.38 kg. From these values, it is detected that the lowest the energy supplied by exhaust heat and the amount of CO_2 emission occur at 11am and the peak value of the energy supplied by exhaust heat and CO_2 emission is at 8 pm.

At 11 am, the temperature of flue gas entering HRSG is the lowest and the temperature of flue gas entering HRSG is the highest at 8 pm. This concludes that energy supplied by exhaust heat and the amount of CO_2 emission from GT depends on the temperature of flue gas entering HRSG. As the temperature of flue gas entering HRSG increases, the energy supplied by exhaust heat and the amount of CO_2 emission from GT increases. As a conclusion, the temperature of flue gas entering HRSG is inversely proportional to energy supplied by exhaust heat and the amount of CO_2 emission from GT.

4.4 COMPARISON OF CO_2 ANALYSIS BY HRSG (66.6%) & BY EXHAUST HEAT FROM GT (100%)

The contribution the amount of CO_2 emission by HRSG is compared in terms of percentage with the amount of CO_2 emission by exhaust heat from GT. The percentage of the amount of CO_2 emission by HRSG (%) is referred from Equation (2.18) and shown in the spreadsheet below;

TABLE 4-9: The Percentage Contribution of the Amount of CO2 Emission by HRSG & the Amount of CO2 Emission by Exhaust Heat from GT Spreadsheet

TIME	% HRSG AMOUNT OF CO2 EMISSION, kg	% GT AMOUNT OF CO2 EMISSION, kg
8:00	34.37	65.63
9:00	31.88	68.12
10:00	32.74	67.26
11:00	33.32	66.68
12:00	32.18	67.82
13:00	32.72	67.28
14:00	32.13	67.87
15:00	32.20	67.80
16:00	32.15	67.85
17:00	33.17	66.83
18:00	33.40	66.60
19:00	30.80	69.20
20:00	30.04	69.96

MINIMUM
MAXIMUM

TABLE 4-10: The Minimum, Maximum and Average Amount of CO_2 Emission by HRSG (66.6%) and the Exhaust Heat from GT Spreadsheet

	MIN	MAX	AVERAGE
%HRSG	30.04	34.37	32.21
% GT	65.63	69.96	67.79

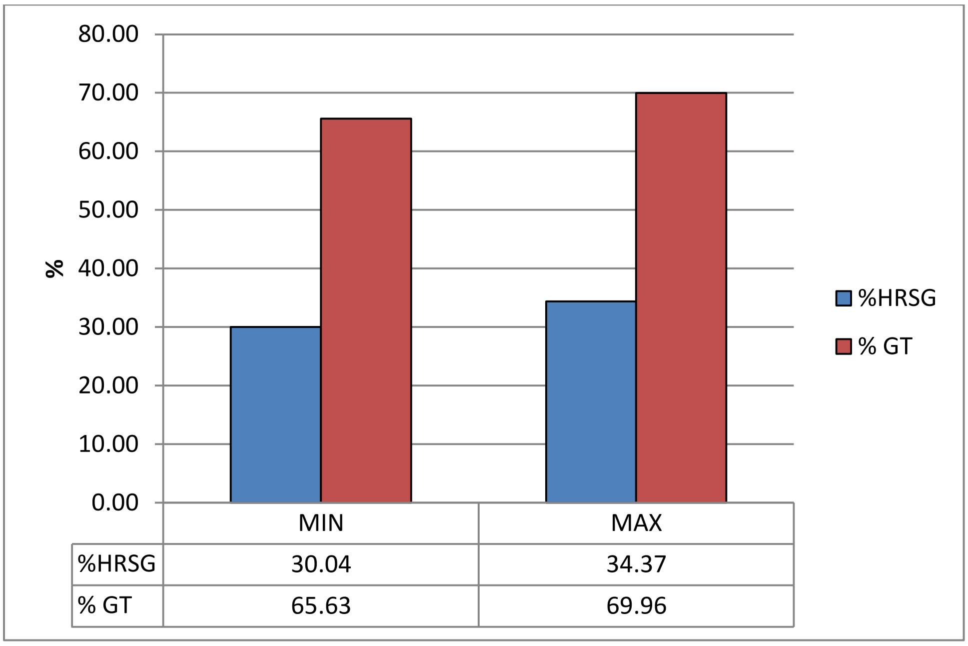


FIGURE 4.7: The Column of the Minimum & Maximum Amount of CO_2 Emission by HRSG & by the Exhaust Heat from GT (%)

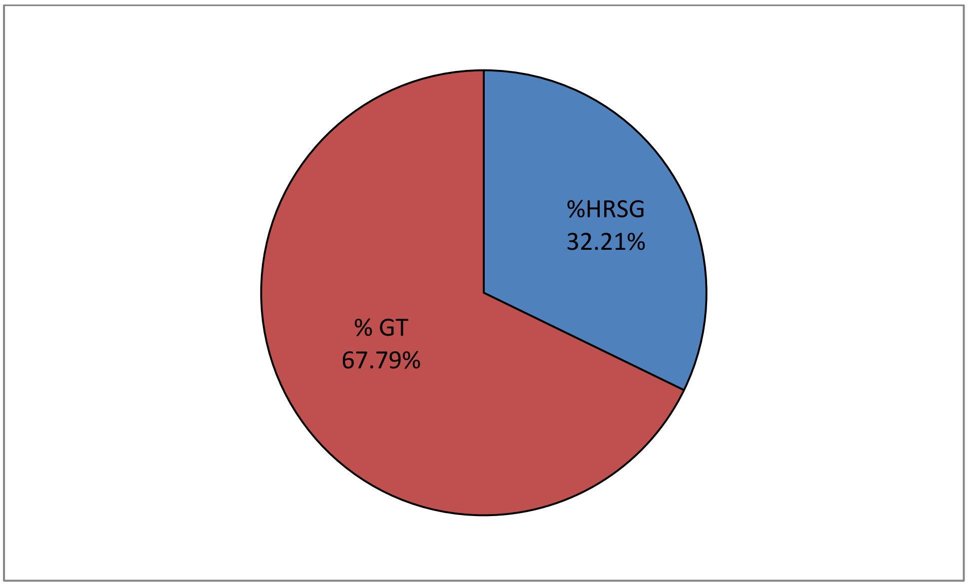


FIGURE 4.8: The Average Percentage of the Amount of CO_2 Emission by HRSG (66.6%) and the Exhaust Heat from GT (100%)

From the result above, it is noticed that the maximum amount of CO_2 emission by HRSG is the minimum amount of CO_2 emission by the exhaust heat from GT at 8am and vice versa at 8pm. The minimum and maximum amount of CO_2

emission by HRSG is recorded as 30.04% and 34.37% respectively while the minimum and maximum amount of CO_2 emission by the exhaust heat from GT is recorded as 65.63% and 69.96% respectively. Thereby, the amount of CO_2 emission by HRSG is inversely proportional with the amount of CO_2 emission by the exhaust heat from GT in a time. From Figure 4.8, HRSG contributes about 32.21% of CO_2 emission at UTP GDC in comparison to the amount of CO_2 emission by the exhaust gas heat from GT which is 67.79% and it is noted that the average percentage difference between the amount of CO_2 emission by HRSG and the amount of CO_2 emission by the exhaust heat from GT is approximately 32.21%.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

Overall, the objective of the project to analyze the CO_2 emission at UTP GDC when 100% of exhaust gas heat from GT is emitted to the environment and when only 66.6% of exhaust heat captured by HRSG is emitted to the environment is completed. The CO_2 analysis should be based on the thermodynamic principle of the First Law of Thermodynamics, mass and energy models. THREE (3) assumptions are used for CO_2 analysis; i. The flow rate of flue gas is kept constant as 19.22 kg/s, ii. The inlet and outlet temperature of evaporator is set as 95^{o}C and 180^{o}C respectively and iii. The temperature of hot gases at economizer is set to 182^{o}C.

Based on the result, the energy supplied by hot gases to HRSG is constant. The constant energy supplies by hot gases to HRSG are due to the energy equality from the flue gas as it enters the HRSG. The steam is generated by HRSG at the evaporator and the amount of steam generated by HRSG depends on the steam flow at evaporator. As the steam flow increases, the amount of exhaust heat used to generate steam supplied to steam header increases. This concludes that the energy of steam generated by HRSG depends on the steam flow at the evaporator.

For CO_2 analysis by HRSG, the percentage of exhaust gas heat used by HRSG to generate steam is not constant throughout the time. Thus, the remaining exhaust heat unused by HRSG will be the total energy loss by HRSG and 47.4% of the total energy loss by HRSG will be emitted to the environment as carbon dioxide. Moreover, as the warm water flow increases, the amount of exhaust heat used by HRSG to generate steam increases before the steam is being supplied to steam header. Thus, the remaining exhaust heat and the amount of CO_2 emission emitted to the environment will decrease. This concludes that the total energy loss and the amount of CO_2 emission by HRSG are inversely proportional to the warm water flow at the economizer.

Moreover, the CO_2 analysis by exhaust heat from GT (100%) concludes that energy supplied by exhaust heat and the amount of CO_2 emission from GT depends on the temperature of flue gas entering HRSG. As the temperature of flue gas entering HRSG increases, the energy supplied by exhaust heat and the amount of CO_2 emission from GT increases. As a conclusion, the energy supplied by exhaust heat and the amount of CO_2 emission from GT are directly proportional to the temperature of flue gas entering HRSG.

Finally, the amount of CO_2 emission by HRSG (66.6%) is compared in terms of percentage with the amount of CO_2 emission by exhaust heat from GT (100%). By comparing these values, it is noted that the amount of CO_2 emission by HRSG is inversely proportional with the amount of CO_2 emission by the exhaust heat from GT because at 8am, the maximum amount of CO_2 emission by HRSG is the minimum amount of CO_2 emission by the exhaust heat from GT. Moreover, it is noted that the amount of CO_2 emission by HRSG is less than when 100% of exhaust heat is emitted to the environment by approximately 35.59%.

5.2 RECOMMENDATION

There are several recommendations to be made regarding this project. Recommendations are not meant to be used to change this project wholly, but to allow improvements in certain aspects and to put some factors into considerations for the evaluation of CO_2 emission of HRSG.

One of the recommendations for future plan is to develop an exergy analysis for the HRSG system. The presentation of thermodynamics and energy model initiated in the previous work should becontinued with emphasis on the exergy concept. Exergy should be defined and represent in terms of four components: physical, kinetic, potential and chemical energy. Additionally, the underlying concept of environment should be discussed in exergy analysis.

Another recommendation for future plan is to study the impact of the amount of CO_2 emission with the global warming potential (GWP). The global warming potential (GWP) is relative measure of how much heat of a greenhouse gas traps in the atmosphere. It should compares the heat trapped by a certain mass of the gas in question to the amount of heat trapped by a similar mass of carbon dioxide. A GWP should be calculated over a specific time interval, commonly 20, 100 or 500 years. GWP is expressed as a factor of carbon dioxide (whose GWP is standardized to 1). For example, the 20 year GWP of methane is 72, which means that if the same mass of methane and carbon dioxide were introduced into the atmosphere, that methane will trap 72 times more heat than the carbon dioxide over the next 20 years.[33]

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APPENDICES

APPENDIX 3-1: HRSG Daily Checklist on 25th July 2013

QI-MSBUTP-OPR-06/PO

Makhostia

MAKHOSTIA SDN. BHD.

HRSG DAILY CHECKLIST

DATE	PANEL DAY SHIFT	PANEL NIGHT SHIFT	SHIFT SUPERINTENDENT
25-07-2013	NOOR ASRAF	Norpaih	SYAHRIDZUAN

B 0303 A / B	STEAM LINE PRESSURE		BOILER STEAM PRESSURE		DRUM WATER LEVEL		STEAM FLOWRATE		FEED WATER FLOWRATE		GT FLUE GAS TEMPERATURE		HOT WELL TEMPERATURE		HOT WELL TANK LEVEL
TIME	kPa		bar		%		ton/hr		ton/hr		°C		°C		mm
	PI 0303A1	PI 0303B1	UMC0101A	UMC0101B	UMC0102A	UMC0102B	FQI 0103A	FQI 0103B	FQI 0104A	FQI 0104B	UMC 0301A	UMC 0301B	T 0301A	T0301B	
0800	828	828	8.69	8.70	64.5	64.9	5.50	4.04	*4.85	4.32	462	448	90.6	90.1	1770
0900	825	824	8.70	8.70	65.6	64.8	6.01	4.53	*4.67	4.77	439	434	86.6	83.6	1899
1000	825	824	8.70	8.70	64.2	64.4	5.98	4.47	*4.86	5.02	430	427	87.6	86.3	1876
1100	825	824	8.70	8.70	64.7	65.0	5.97	4.56	*4.91	4.79	427	422	88.2	87.6	1865
1200	826	825	8.70	8.70	65.2	64.7	6.61	4.56	*4.15	5.17	424	430	88.9	87.2	1850
1300	825	824	8.69	8.70	64.2	64.9	6.02	4.51	*4.46	5.62	425	425	89.1	86.9	1810
1400	825	824	8.70	8.70	65.4	65.0	6.06	4.50	*4.61	5.06	422	432	89.5	87.2	1766
1500	825	824	8.70	8.70	65.3	65.0	6.02	4.53	*4.46	4.78	423	433	89.6	87.7	1788
1600	825	824	8.70	8.70	65.4	64.8	6.05	4.49	*4.49	4.78	422	434	86.4	84.3	1904
1700	824	823	8.68	8.69	64.8	65.2	5.98	4.50	*4.64	4.56	428	426	87.6	86.4	1899
1800	825	824	8.70	8.69	65.1	64.7	6.07	4.47	*4.21	4.78	432	423	88.3	86.6	1891
1900	825	825	8.71	8.70	65.3	64.9	6.01	4.54	*4.22	4.81	445	448	88.7	86.8	1881
2000	824	824	8.70	8.69	64.7	64.9	6.02	4.52	4.34	4.81	457	459	89.0	86.8	1862
2100	825	825	8.71	8.70	64.9	65.0	6.01	4.50	4.28	4.76	454	460	89.4	92.1	1886
2200	–	808		8.55		64.6		4.94		4.89		464	89.6	92.6	1982
2300		–													
0000															
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0200															
0300															
0400															
0500															
0600															
0700															

APPENDIX 4-1

TABLE A-2

Pressure Conversions:
1 bar = 0.1 MPa
= 10^2 kPa

Properties of Saturated Water (Liquid–Vapor): Temperature Table

		Specific Volume m^3/kg		Internal Energy kJ/kg		Enthalpy kJ/kg			Entropy kJ/kg · K		
Temp. °C	Press. bar	Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Sat. Liquid u_f	Sat. Vapor u_g	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Sat. Liquid s_f	Sat. Vapor s_g	Temp. °C
.01	0.00611	1.0002	206.136	0.00	2375.3	0.01	2501.3	2501.4	0.0000	9.1562	.01
4	0.00813	1.0001	157.232	16.77	2380.9	16.78	2491.9	2508.7	0.0610	9.0514	4
5	0.00872	1.0001	147.120	20.97	2382.3	20.98	2489.6	2510.6	0.0761	9.0257	5
6	0.00935	1.0001	137.734	25.19	2383.6	25.20	2487.2	2512.4	0.0912	9.0003	6
8	0.01072	1.0002	120.917	33.59	2386.4	33.60	2482.5	2516.1	0.1212	8.9501	8
10	0.01228	1.0004	106.379	42.00	2389.2	42.01	2477.7	2519.8	0.1510	8.9008	10
11	0.01312	1.0004	99.857	46.20	2390.5	46.20	2475.4	2521.6	0.1658	8.8765	11
12	0.01402	1.0005	93.784	50.41	2391.9	50.41	2473.0	2523.4	0.1806	8.8524	12
13	0.01497	1.0007	88.124	54.60	2393.3	54.60	2470.7	2525.3	0.1953	8.8285	13
14	0.01598	1.0008	82.848	58.79	2394.7	58.80	2468.3	2527.1	0.2099	8.8048	14
15	0.01705	1.0009	77.926	62.99	2396.1	62.99	2465.9	2528.9	0.2245	8.7814	15
16	0.01818	1.0011	73.333	67.18	2397.4	67.19	2463.6	2530.8	0.2390	8.7582	16
17	0.01938	1.0012	69.044	71.38	2398.8	71.38	2461.2	2532.6	0.2535	8.7351	17
18	0.02064	1.0014	65.038	75.57	2400.2	75.58	2458.8	2534.4	0.2679	8.7123	18
19	0.02198	1.0016	61.293	79.76	2401.6	79.77	2456.5	2536.2	0.2823	8.6897	19
20	0.02339	1.0018	57.791	83.95	2402.9	83.96	2454.1	2538.1	0.2966	8.6672	20
21	0.02487	1.0020	54.514	88.14	2404.3	88.14	2451.8	2539.9	0.3109	8.6450	21
22	0.02645	1.0022	51.447	92.32	2405.7	92.33	2449.4	2541.7	0.3251	8.6229	22
23	0.02810	1.0024	48.574	96.51	2407.0	96.52	2447.0	2543.5	0.3393	8.6011	23
24	0.02985	1.0027	45.883	100.70	2408.4	100.70	2444.7	2545.4	0.3534	8.5794	24
25	0.03169	1.0029	43.360	104.88	2409.8	104.89	2442.3	2547.2	0.3674	8.5580	25
26	0.03363	1.0032	40.994	109.06	2411.1	109.07	2439.9	2549.0	0.3814	8.5367	26
27	0.03567	1.0035	38.774	113.25	2412.5	113.25	2437.6	2550.8	0.3954	8.5156	27
28	0.03782	1.0037	36.690	117.42	2413.9	117.43	2435.2	2552.6	0.4093	8.4946	28
29	0.04008	1.0040	34.733	121.60	2415.2	121.61	2432.8	2554.5	0.4231	8.4739	29
30	0.04246	1.0043	32.894	125.78	2416.6	125.79	2430.5	2556.3	0.4369	8.4533	30
31	0.04496	1.0046	31.165	129.96	2418.0	129.97	2428.1	2558.1	0.4507	8.4329	31
32	0.04759	1.0050	29.540	134.14	2419.3	134.15	2425.7	2559.9	0.4644	8.4127	32
33	0.05034	1.0053	28.011	138.32	2420.7	138.33	2423.4	2561.7	0.4781	8.3927	33
34	0.05324	1.0056	26.571	142.50	2422.0	142.50	2421.0	2563.5	0.4917	8.3728	34
35	0.05628	1.0060	25.216	146.67	2423.4	146.68	2418.6	2565.3	0.5053	8.3531	35
36	0.05947	1.0063	23.940	150.85	2424.7	150.86	2416.2	2567.1	0.5188	8.3336	36
38	0.06632	1.0071	21.602	159.20	2427.4	159.21	2411.5	2570.7	0.5458	8.2950	38
40	0.07384	1.0078	19.523	167.56	2430.1	167.57	2406.7	2574.3	0.5725	8.2570	40
45	0.09593	1.0099	15.258	188.44	2436.8	188.45	2394.8	2583.2	0.6387	8.1648	45

APPENDIX 4-2

TABLE A-3

Pressure Conversions:
1 bar = 0.1 MPa
= 10^2 kPa

Properties of Saturated Water (Liquid–Vapor): Pressure Table

		Specific Volume m^3/kg		Internal Energy kJ/kg		Enthalpy kJ/kg			Entropy kJ/kg · K		
Press. bar	Temp. °C	Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Sat. Liquid u_f	Sat. Vapor u_g	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Sat. Liquid s_f	Sat. Vapor s_g	Press. bar
0.04	28.96	1.0040	34.800	121.45	2415.2	121.46	2432.9	2554.4	0.4226	8.4746	0.04
0.06	36.16	1.0064	23.739	151.53	2425.0	151.53	2415.9	2567.4	0.5210	8.3304	0.06
0.08	41.51	1.0084	18.103	173.87	2432.2	173.88	2403.1	2577.0	0.5926	8.2287	0.08
0.10	45.81	1.0102	14.674	191.82	2437.9	191.83	2392.8	2584.7	0.6493	8.1502	0.10
0.20	60.06	1.0172	7.649	251.38	2456.7	251.40	2358.3	2609.7	0.8320	7.9085	0.20
0.30	69.10	1.0223	5.229	289.20	2468.4	289.23	2336.1	2625.3	0.9439	7.7686	0.30
0.40	75.87	1.0265	3.993	317.53	2477.0	317.58	2319.2	2636.8	1.0259	7.6700	0.40
0.50	81.33	1.0300	3.240	340.44	2483.9	340.49	2305.4	2645.9	1.0910	7.5939	0.50
0.60	85.94	1.0331	2.732	359.79	2489.6	359.86	2293.6	2653.5	1.1453	7.5320	0.60
0.70	89.95	1.0360	2.365	376.63	2494.5	376.70	2283.3	2660.0	1.1919	7.4797	0.70
0.80	93.50	1.0380	2.087	391.58	2498.8	391.66	2274.1	2665.8	1.2329	7.4346	0.80
0.90	96.71	1.0410	1.869	405.06	2502.6	405.15	2265.7	2670.9	1.2695	7.3949	0.90
1.00	99.63	1.0432	1.694	417.36	2506.1	417.46	2258.0	2675.5	1.3026	7.3594	1.00
1.50	111.4	1.0528	1.159	466.94	2519.7	467.11	2226.5	2693.6	1.4336	7.2233	1.50
2.00	120.2	1.0605	0.8857	504.49	2529.5	504.70	2201.9	2706.7	1.5301	7.1271	2.00
2.50	127.4	1.0672	0.7187	535.10	2537.2	535.37	2181.5	2716.9	1.6072	7.0527	2.50
3.00	133.6	1.0732	0.6058	561.15	2543.6	561.47	2163.8	2725.3	1.6718	6.9919	3.00
3.50	138.9	1.0786	0.5243	583.95	2546.9	584.33	2148.1	2732.4	1.7275	6.9405	3.50
4.00	143.6	1.0836	0.4625	604.31	2553.6	604.74	2133.8	2738.6	1.7766	6.8959	4.00
4.50	147.9	1.0882	0.4140	622.25	2557.6	623.25	2120.7	2743.9	1.8207	6.8565	4.50
5.00	151.9	1.0926	0.3749	639.68	2561.2	640.23	2108.5	2748.7	1.8607	6.8212	5.00
6.00	158.9	1.1006	0.3157	669.90	2567.4	670.56	2086.3	2756.8	1.9312	6.7600	6.00
7.00	165.0	1.1080	0.2729	696.44	2572.5	697.22	2066.3	2763.5	1.9922	6.7080	7.00
8.00	170.4	1.1148	0.2404	720.22	2576.8	721.11	2048.0	2769.1	2.0462	6.6628	8.00
9.00	175.4	1.1212	0.2150	741.83	2580.5	742.83	2031.1	2773.9	2.0946	6.6226	9.00
10.0	179.9	1.1273	0.1944	761.68	2583.6	762.81	2015.3	2778.1	2.1387	6.5863	10.0
15.0	198.3	1.1539	0.1318	843.16	2594.5	844.84	1947.3	2792.2	2.3150	6.4448	15.0
20.0	212.4	1.1767	0.09963	906.44	2600.3	908.79	1890.7	2799.5	2.4474	6.3409	20.0
25.0	224.0	1.1973	0.07998	959.11	2603.1	962.11	1841.0	2803.1	2.5547	6.2575	25.0
30.0	233.9	1.2165	0.06668	1004.8	2604.1	1008.4	1795.7	2804.2	2.6457	6.1869	30.0
35.0	242.6	1.2347	0.05707	1045.4	2603.7	1049.8	1753.7	2803.4	2.7253	6.1253	35.0
40.0	250.4	1.2522	0.04978	1082.3	2602.3	1087.3	1714.1	2801.4	2.7964	6.0701	40.0
45.0	257.5	1.2692	0.04406	1116.2	2600.1	1121.9	1676.4	2798.3	2.8610	6.0199	45.0
50.0	264.0	1.2859	0.03944	1147.8	2597.1	1154.2	1640.1	2794.3	2.9202	5.9734	50.0
60.0	275.6	1.3187	0.03244	1205.4	2589.7	1213.4	1571.0	2784.3	3.0267	5.8892	60.0
70.0	285.9	1.3513	0.02737	1257.6	2580.5	1267.0	1505.1	2772.1	3.1211	5.8133	70.0
80.0	295.1	1.3842	0.02352	1305.6	2569.8	1316.6	1441.3	2758.0	3.2068	5.7432	80.0
90.0	303.4	1.4178	0.02048	1350.5	2557.8	1363.3	1378.9	2742.1	3.2858	5.6772	90.0
100.	311.1	1.4524	0.01803	1393.0	2544.4	1407.6	1317.1	2724.7	3.3596	5.6141	100.
110.	318.2	1.4886	0.01599	1433.7	2529.8	1450.1	1255.5	2705.6	3.4295	5.5527	110.