ANALYSIS OF PINCH AND APPROACH POINT OF HEAT RECOVERY STEAM GENERATOR (HRSG) OF COGENERATION PLANT

by

Mohamad Fadzley bin Hamssin

Dissertation submitted in partial fulfilment of

the requirements for the

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CERTIFICATION OF APPROVAL

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Approved by,

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(AP Ir. Dr. Mohd Amin Bin Abd Majid)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

September 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 except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MOHAMAD FADZLEY BIN HAMSSIN

ABSTRACT

This report presents the analysis of pinch and approach point of Heat Recovery Steam Generator (HRSG) of a cogeneration plant. The analysis based on the heat recovery steam generator (HRSG) in Universiti Teknologi Petronas (UTP) Gas District Cooling (GDC) Plant. Pinch point, approach point, steam pressure and HRSG inlet gas temperature are taken as manipulative variables. Pinch point is the temperature difference between evaporator outlet gas temperature and saturation temperature while approach point is the temperature difference between saturation temperature and economizer outlet water temperature. Pinch and approach point should be taken into account in designing HRSG as both of these parameters are used to determine the heat transfer surface area of the HRSG. Designing the HRSG by using pinch and approach point can prevent the temperature cross between gas stream and water/steam stream. In single pressure stage HRSG that consists of evaporator and economizer, the selection of the steam pressure is based on the output steam temperature demand. High steam pressure will produce high steam temperature. The HRSG inlet flue gas temperature will different if different type of gas turbine is used. Different gas turbine has different exhaust gas temperature and mass flow rate of flue gas. Four analysis were performed based on these parameters to evaluate the performance of HRSG. These analysis were conducted using spreadsheet. According to the pinch point, approach point and steam pressure analysis results, decreased of these parameters value individually will increased the steam production rate and thus increased the efficiency of HRSG. For HRSG inlet gas temperature analysis, the steam production rate and efficiency were increased when this parameter value increased.

ACKNOWLEDGEMENTS

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LIST OF ABBREVIATIONS

UTP	Universiti Teknologi PETRONAS
GDC	Gas District Cooling
CCPP	Combined Cycle Power Plant
GTG	Gas Turbine Generator
SAC	Steam Absorption Chiller
EC	Electric Air Cooled Chillers
TES	Thermal Energy Storage

LIST OF NOMENCLATURES

Δt_P	Pinch Point Temperature Difference, ℃
Δt_A	Approach Point Temperature Difference, ℃
$\dot{m}_g$	Mass flowrate of Flue Gas, kg/s
t_1	Temperature of Flue Gas enter the HRSG, ℃
t_2	Temperature of Flue Gas out of Evaporator, ℃
t_3	Stack Temperature, ℃
t_a	Steam Temperature, ℃
t_b	Temperature of Water/Steam enter the evaporator,℃
t_c	Temperature of Water/Steam out of economizer,℃
t_d	Feed water temperature,℃
$\dot{m}_s$	Mass flowrate of water/steam, kg/s
Q_{EVA}	Evaporator duty, kJ/s
Q_{ECO}	Economizer duty, kJ/s
C_{p_g}	Gas specific heat
η_{HRSG}	HRSG Efficiency
$t_{ambient}$	Ambient Temperature

CHAPTER 1

INTRODUCTION

1.1 Project Background

Heat Recovery Steam Generator (HRSG) is the most important component in the Combined Cycle Power Plant (CCPP) and Cogeneration Plant. It is utilized to capture thermal energy (flue gas) from the gas turbine exhaust to generate steam by heating demineralised water. In Combined Cycle Plant (CCP), the superheated steam is used to drive the steam turbine for the power generation. Cogeneration plant used the steam produced for others industrial purpose such as Gas District Cooling (GDC), chemical processing, water desalination etc.

In Heat Recovery Steam Generator there are three main components which are economizer, evaporator and superheater. These three components consist of bundle of tubes that act as heat exchanger. Economizer pre-heats the feedwater until temperature almost close to the saturation temperature. The economizer changes the feedwater state form liquid to saturated liquid. The saturated liquid that enters the evaporator will be turned to saturated vapour/saturated steam. The evaporator consists of drum, riser and downcomer. The evaporation process occurs within the riser. The mixture of saturated water and saturated vapour will be separated in the drum by means of density difference. The saturated vapour in the drum is sent to the superheater for the further heating to produce superheated vapour. The superheated vapour is used to run the steam turbine or used in others processes.

In designing the heat recovery steam generator (HRSG), pinch and approach point temperature difference are the most important parameters that should be taken into account. Pinch and approach point temperature difference are analyse during the design phase to determine the heat transfer surface area of the tube inside the heat recovery steam generator (HRSG). These two parameters also set to prevent the temperature cross between the hot stream and cold stream. Besides, the pinch and approach point also responsible in determining the performance of HRSG. The performance of HRSG also can be varies if different steam pressure used in the system. The saturation pressure of the steam depends on the steam pressure. Higher steam pressure will give higher saturation temperature. Different saturation temperature cause different value evaporator outlet gas temperature and economizer outlet water temperature as saturation temperature related to the pinch and approach point.

HRSG inlet flue gas temperature also can affect the performance of HRSG. For example, the use of different type of gas turbine or supplementary firing can change this parameter value. Different gas turbine produce different exhaust gas temperature depending on the type of manufacturer, capacity, size, pressure ratio, ambient temperature and the other factors. For supplementary firing case, the additional fuel is fired with flue gas before it entering the HRSG to increase the temperature of the flue gas entering the HRSG.

1.2 Problem Statement

The performance of the Heat Recovery Steam Generator depends on many factors such as the ambient temperature of the HRSG, load of the gas turbine, steam pressure in the HRSG, pinch and approach point temperature difference, HRSG inlet gas temperature etc. Pinch and approach point temperature difference greatly affect the steam production rate as both are used in determining the heat transfer surface area needed. Selection of pinch and approach point temperature difference depending on the steam demand. Higher pinch and approach point temperature difference will cause low heat recovery from flue gas. Too small pinch and approach point temperature difference will increase the heat recovery steam generator (HRSG) size.

1.3 Objective

To evaluate the effect of pinch and approach point, steam pressure and HRSG inlet gas temperature on the performance of heat recovery steam generator (HRSG). The purpose of these analysis is to find the opportunity to improve the performance of the HRSG.

1.4 Scope of Study

i. The Universiti Teknologi Petronas (UTP) Gas District Cooling (GDC) Heat Recovery Steam Generator (HRSG) used as the case study.

ii. The analysis of heat recovery steam generator (HRSG) performance based on difference manipulative parameter; pinch point temperature difference, approach point temperature difference, steam pressure and HRSG inlet gas temperature

iii. Spreadsheet was used to analyse the effect of the above parameters on the heat recovery steam generator (HRSG) performance.

1.5 Relevancy of Project

Enhancing the performance of HRSG resulting the extra steam generation from the same amount of fuel (natural gas) used to operate the gas turbine. Hence, it can optimize the use of fuel (natural gas). The fuel consumption also will be optimized if the efficiency of HRSG increases.

1.6 Feasibility of Project

This project is feasible as the simulation software that will be used in this project is available in the University. The data for the analysis obtained from the Universiti Teknologi Petronas (UTP) Gas District Cooling (GDC) Plant. So the project can be done within the time frame given.

CHAPTER 2

LITERATURE REVIEW

2.1 Heat Recovery Steam Generator Performance Analysis

Heat Recovery Steam Generator needs the gas turbine to operate. It captures the heat energy from the gas turbine exhaust (flue gas) to generate steam for the power generation (Combined Cycle Power Plant) or it used for the other purpose (cogeneration plant). Heat recovery steam generator consists of three main heat exchanger components which are economizer, evaporator and superheater [1]. Economizer pre-heats the feedwater until temperature almost close to the saturation temperature. The economizer changes the feedwater state form water to saturated liquid. The saturated liquid that enters the evaporator will be turned to saturated vapour/saturated steam. The evaporator consists of drum, riser and downcomer. The evaporation process occurs within the riser. The mixture of saturated water and saturated vapour will be separated in the drum by means of density difference. The saturated vapour in the drum is sent to the superheater for the further heating to produce superheated vapour. The superheated vapour is used to run the steam turbine or used in others processes.

Combined cycle power plant is the combination of the Brayton Cycle and Rankine cycle [2]. The steam that was produced is used to drive the steam turbine for the additional power generation hence increase the overall plant efficiency. According to V. Ganapathy, 1996 [3], the gas turbine has high efficiency ranging from 25% to 35% and it can be reached 55% to 60% in the combined cycle mode. The application of HRSG for the cogeneration plant can be found mostly in chemical industries. He also state that the system efficiency of the cogeneration mode is in between 75% to 85%.

The HRSG can be classified to their steam pressure. There are three types of pressure system which are single-pressure, double-pressure and triple-pressure. In Industrial Boiler and Heat Recovery Steam Generator book, V. Ganapathy, 2003 [4], he states that the single pressure unit are inefficient due to the high exit gas temperature from HRSG. High exit gas temperature is caused by high steam pressure. Multiple pressure unit of HRSG lowering the exit gas temperature by maximizing heat recovery until the steam pressure become low. A. Rahim et al. [5], study about the effect of single pressure, dual pressure and triple pressure HRSG design on the net power generation and overall efficiency of the cycle. The variables are steam pressure, pinch point temperature and approach temperature. As a result the net power output the efficiency increases in dual and triple pressure units.

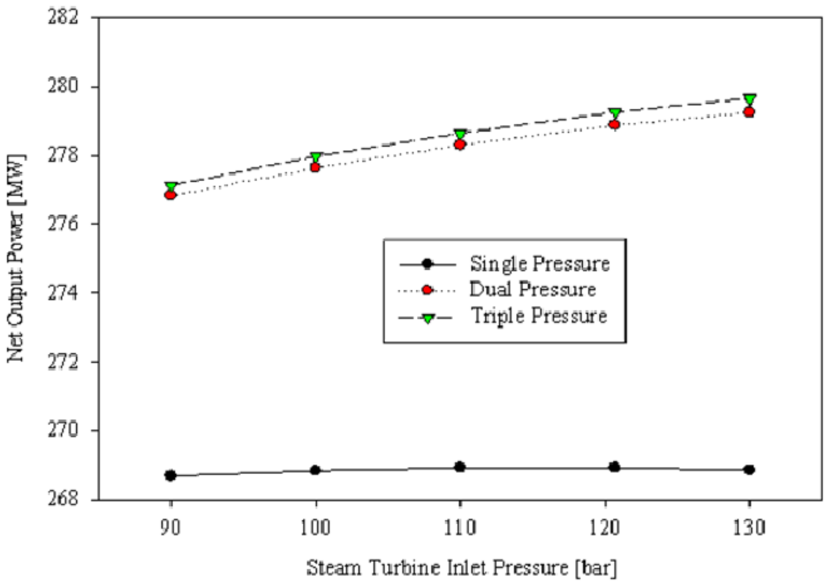

Figure 2.1: Net Output Power vs. Steam Turbine Inlet Temperature

A. Rahim, M., Amirabedin, E., Yilmazoglu M. Z. & Durmaz, A. (2010, July). Analysis of Heat Recovery Steam Generator in Combined Cycle Power Plants. Paper presented at the 2nd International Conference on Nuclear and Renewable Energy Resources, Ankara, Turkey.

Figure 2.1 shows the effect of the pressure in single, dual and triple pressure HRSG on the net output power produced. The net output power will increases as the steam turbine inlet pressure increase. The steam turbine inlet pressure gives more effect to the net output power in dual and triple pressure stage of HRSG compared to the single pressure stage of HRSG system.

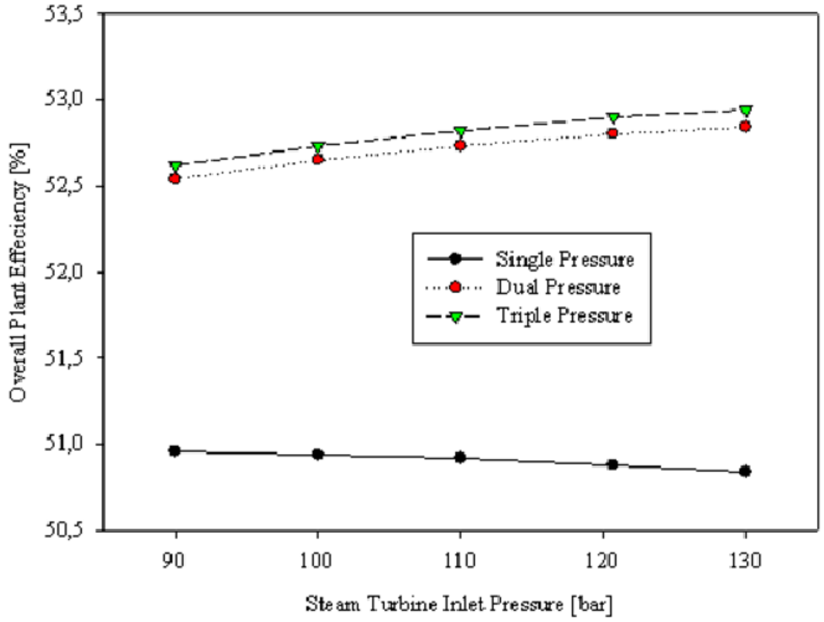

Figure 2.2: Overall Efficiency vs. Steam Turbine Inlet Temperature

A. Rahim, M., Amirabedin, E., Yilmazoglu M. Z. & Durmaz, A. (2010, July). Analysis of Heat Recovery Steam Generator in Combined Cycle Power Plants. Paper presented at the 2nd International Conference on Nuclear and Renewable Energy Resources, Ankara, Turkey.

From Figure 2.2, the overall plant efficiency for the dual and triple pressure system is increasing due to their net output power produced. For the single pressure system, the overall plant efficiency is reducing when the steam inlet pressure. According to V. Ganapathy, 2003 [4], "The higher the steam pressure, the higher the exit gas temperature. Hence when high pressure steam is generated, it is not possible to cool the exhaust gases to an economically justifiable level with single-pressure HRSG" (p. 41).

In designing the HRSG, the gas/steam temperature profile is the most important factor that should be focused. V. Ganapathy, 2003 [4], state that the off-design performance of an HRSG can be simulated without designing the tube size, surface area, etc. It can be done by analyzing the gas/steam temperature profile.

Gas/steam temperature profile of HRSG is a graph that shows the temperature of the exhaust gas and water/steam at the inlet and outlet of each heat exchanger component of HRSG. The gas/steam temperature profile can be design by using the formula that will be discussed below.

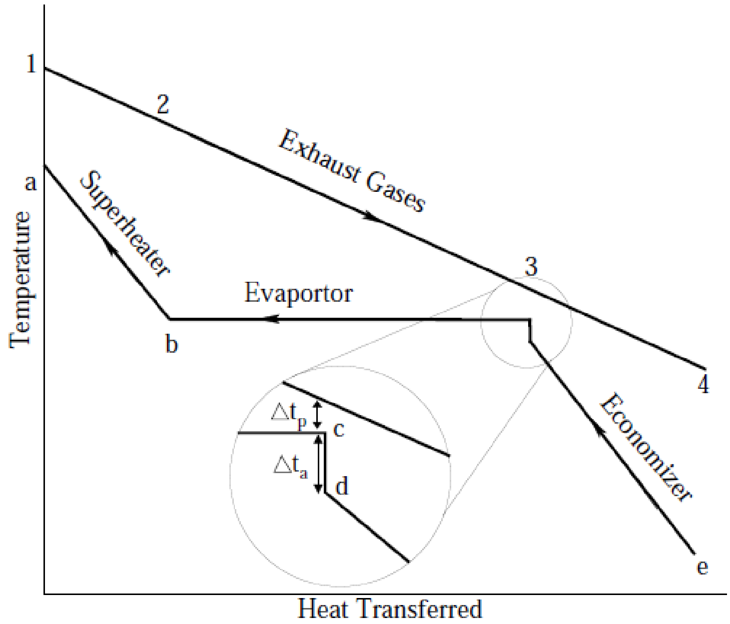

Figure 2.3: Gas/Steam Temperature Profile of HRSG

Aref, P (2012). Development of a Framework for Thermoeconomic Optimization of Simple and Combined Gas-Turbine Cycles. Unpublished doctoral dissertation, CRANFIELD UNIVERSITY, Bedfordshire MK43 0AL, United Kingdom

Figure 2.3 shows the gas/steam temperature profile for the single-pressure stage HRSG. There are two design parameter of HRSG in the gas/steam temperature profile: pinch point temperature difference,ΔT_p, and approach point temperature difference,ΔT_a. The pinch point temperature difference is the difference between the exhaust gas temperature leaving the evaporator,T_3, and the temperature of saturated temperature,$T_{s(p)}$ [5]. Approach point temperature difference,ΔT_a, is the difference between the temperature of saturated steam,$T_{s(p)}$, and the temperature of water leaving the economizer,T_d [5]. Franco and Russo, 2002 [6], used the pinch and approach point temperature difference in their study to optimize the performance and efficiency of the HRSG. A. Rahim, 2010 [7], state that increase the pinch point temperature difference will cause small heat transfer and low capacity of HRSG. Singh. O and Sharma. M, 2012 [8], state that the higher pinch point temperature difference results in the increased gas temperature entering the superheater and evaporator. Thus, the steam generation will reduce and the efficiency of HRSG decreases. Kaviri et al. 2012 [12], the efficiency of HRSG will decreases when pinch point temperature difference increases. This is because less energy of exhaust gas being absorb by the water in HRSG. Moreover, the exergy loss in the HRSG is reduced if the temperature of the superheater [13]. The pinch point temperature difference also affects the heat transfer surface area. Smaller pinch point temperature difference will required larger heat transfer surface area hence increasing the cost of production.

Increase the approach point temperature difference also gives the same result as pinch point temperature case and it is greatly affect the efficiency of single-pressure HRSG. Starr, F (2003) [10], states that if the value of approach point temperature difference is equal to zero, the water at the exit of economizer will tend to boil. This phenomenon is called steaming economizer. Zero value of approach point temperature difference means the gas temperature at the economizer inlet is equal to the temperature of water leaving the economizer. Steaming economizer will cause water hammer, vibration or deposition of salt in economizer tubes which can reduce the HRSG performance [3].

There are several opinions about the temperature range for the pinch and approach point temperature difference. The typical pinch and approach point temperature difference that used in industry is 5℃ to 12℃ and 8℃ to 15℃ respectively (Aref. P, 2012).

The formula below is used to design the HRSG temperature profile.

$$\mathrm{T_c} = \mathrm{T_d} = \mathrm{T_{s(p)}} \tag{2.1}$$

where $T_{s(p)}$ is the temperature of saturated steam at a given feedwater pump pressure. By assuming the value of pinch point temperature difference, ΔT_p, the exhaust gas temperature leaving the evaporator, T_3, can be determined as:

$$\mathrm{T_3} = \mathrm{T_c} + \Delta\mathrm{T_p} \tag{2.2}$$

The temperature of water leaving the economizer, T_d, also can be determined from given approach point temperature difference, ΔT_a.

$$T_d = T_c + \Delta T_a \tag{2.3}$$

The heat exchange from exhaust gas temperature to the superheater and evaporator can be calculated by using the formula below;

$$\dot{Q}_{1-3} = C_p \times \dot{m}_g \times (T_1 - T_3) = \dot{m}_s \times (h_a - h_d) \tag{2.4}$$

Where; C_p is the gas specific heat at constant pressure, $\dot{m}_g$ is the mass flow rate of gas, $\dot{m}_s$ is the mass flow rate of water, h_a is the enthalpy of superheated steam and h_d is the enthalpy of saturated water.

From equation (2.4), the mass flow rate of water can be determined;

$$\dot{m}_s = \frac{\dot{Q}_{1-3}}{h_a - h_d} \tag{2.5}$$

The energy balance in the economizer is given by;

$$\dot{Q}_{3-4} = \dot{Q}_{e-d} \tag{2.6}$$

$$C_p \times \dot{m}_g \times (T_3 - T_4) = \dot{m}_s \times (h_d - h_e) \tag{2.7}$$

$$T_4 = T_3 - \frac{\dot{m}_s \times (h_d - h_e)}{C_p - \dot{m}_g} \tag{2.8}$$

Where h_e is the enthalpy of the feedwater.

By using the equation (2.8), we can determine the exit gas temperature, T_4. V. Ganapathy, 1996 [3], state that, in designing the temperature profile of HRSG, the exit gas temperature, T_4 cannot be assumed arbitrarily. Temperature cross or steaming in the economizer might be occurring if the exit gas temperature is arbitrarily chosen. In designing the temperature profile of HRSG, two conditions must be met for steam generation to occur; $T_3 > T_s$ and $T_4 > T_e$.

From the temperature profile designed, the efficiency of HRSG can be calculated by using equation below;

$$\eta_{HRSG} = \frac{T_1 - T_4}{T_1 - T_{air}} \quad (2.9)$$

2.2 Analysis Heat Recovery Steam Generator Parameter

As a conclusion, pressures of steam in HRSG and temperature profile greatly affect the performance of the HRSG. The overall plant efficiency will increase when the steam pressure increases except single pressure system where its efficiency decreases. In analysing gas/steam temperature profile of HRSG, by assuming the value of pinch and approach point temperature, the design and off-design performance of HRSG can be simulated. HRSG performance is related to the pinch and approach point temperature difference. The smaller the value of the pinch point temperature difference, the higher the rate of heat transfer hence generating more steam. The effect of approach point temperature difference is same with the effect of pinch point. However, if the value of approach point temperature difference is very small, the water inside the economizer will start to boil.

2.3 Universiti Teknologi Petronas (UTP) Gas District Cooling Plant

The Universiti Teknologi Petronas (UTP) Gas District Cooling (GDC) plant was designed as cogeneration and gas district cooling (GDC) plant. It has the capacity to generate electricity power of 8.4 MW from two gas turbines and produce chilled water by using combination of two unit of absorption chillers and four unit of electric chillers. The absorption chiller has capacity of 1250 RT while the electric chiller has the capacity of 325 RT. The UTP Gas District Cooling Plant was designed to operate for 24 hours. During day, two unit of gas turbine will be operated to generate electricity and produce steam for steam absorption chiller (SAC) while only one gas turbine is used at night. The steam was produced by Heat Recovery Steam Generator (HRSG) and it only operates during the peak period from 6 a.m to 6 p.m (I. Ibrahim et al. 2012)[15].

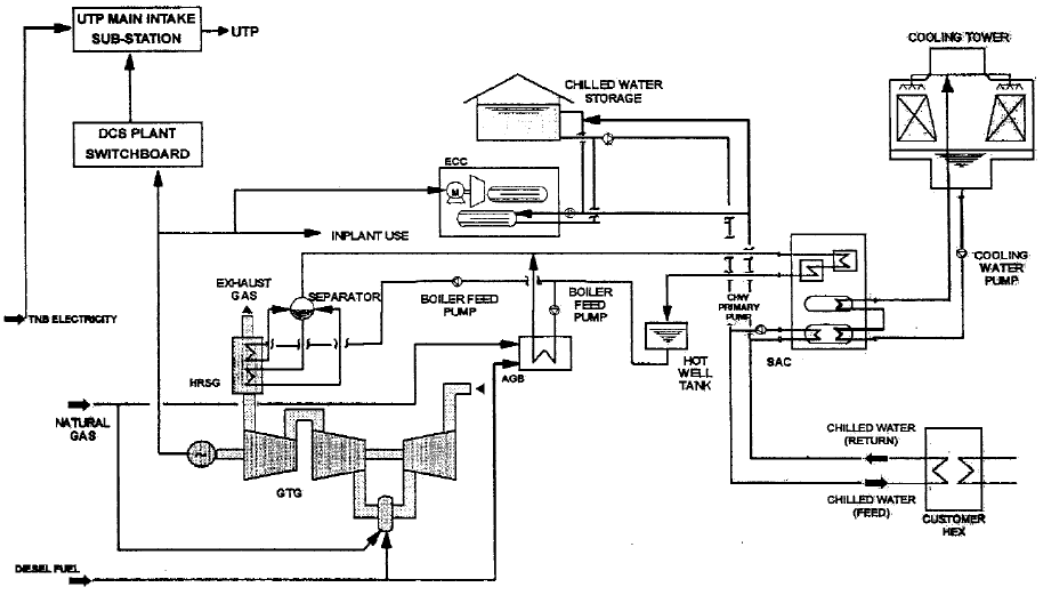

Figure 2.4: Schematic Diagram of UTP Gas District Cooling Plant

Gilani, M.A.A. Majid, R. Chalilullah and S. Hassan. (2006, September). A Case Study on Electricity and Chilled Water Production of a Gas District Cooling Plant, 20-27

As shown in figure 2.4, the main components of Universiti Teknologi Petronas (UTP) Gas District Cooling (GDC) Plant are listed in table 2.1.

Table 2.2: Main Components of Universiti Teknologi Petronas (UTP) Gas District Cooling (GDC) Plant

Component	Quantity	Capacity of Each Unit
Gas Turbine Generator (GTG)	2 units	4.2 MW
Heat Recovery Steam Generator (HRSG)	2 units	12 Ton/hour
Steam Absorption Chiller (SAC)	2 units	1250 RT
Electric Air Cooled Chillers (EC)	4 units	325 RT
Thermal Energy Storage (TES)	1 unit	10 000 RTh
Auxiliary Boiler	1 unit	6 Ton/hour

2.3.1 Universiti Teknologi Petronas (UTP) Gas District Cooling (GDC) Heat Recovery Steam Generator (HRSG)

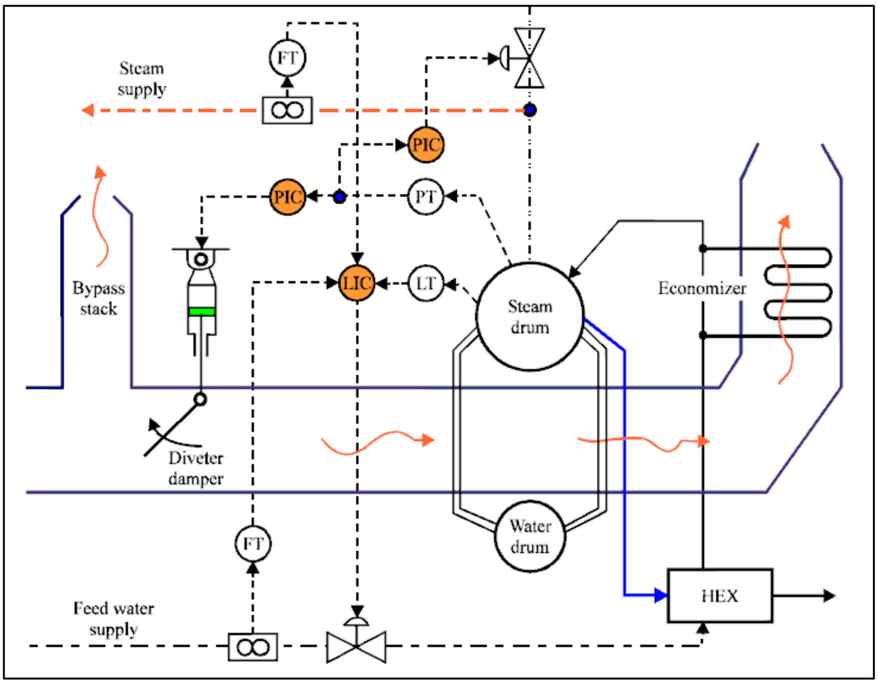

Figure 2.5 Schematic Diagram of UTP GDC Heat Recovery Steam Generator

M.A.A. Majid, A.L. Tamiru and A. Zainuddin. (2013). Historical Data Based Models for Chilled Water Production from Waste Heat of Turbine. Journal of Applied Sciences, 12(2), 301-307.

From the Figure 2.5, the UTP GDC Heat Recovery Steam Generator consists of two main components which are economizer and evaporator. The evaporator consists of steam drum, water drum and blow-down heat exchanger. The water circulate between these two drums by mean of natural circulation (M.A.A. Majid, 2013) [20]. The steam was produced in the evaporator will be supplied to steam absorption chiller (SAC). The UTP GDC Heat Recovery Steam Generator use single pressure system. The flow rate of the flue gas from the exhaust gas turbine controlled by diverter damper. The position of the diverter damper depends on the steam demand.

CHAPTER 3

METHODOLOGY

3.1 Project Methodology

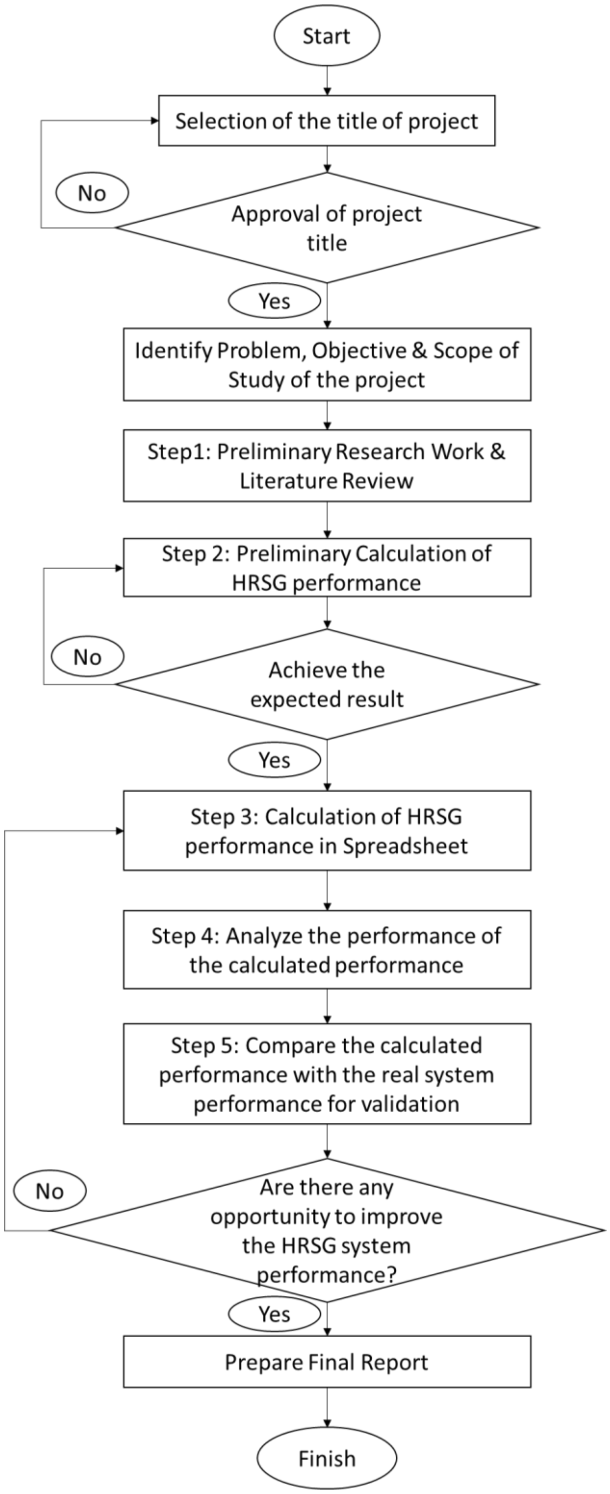

Figure 3.1: Project Methodology

Figure 3.1 illustrates the project activities that need to be carry out for this project. The details of each step are as follows:

Step 1: Preliminary Research

The research started with the identification of the problem statement, objective of study and scope of study. The background study of Heat Recovery Steam Generator (HRSG) is carried out in order to know about its components and how it operates. The other research paper, articles and journal that related to the HRSG performance is reviewed. The purpose of the literature review is to study about research methodology and to know the expected result that should be obtained at the end of the project.

Step 2: Preliminary Simulation

The preliminary calculation will be conducted by using the system test parameter value taken from the other research paper. The equations used for this calculation based on the literature review.

Step 3: Calculation of the HRSG Performance

The calculation of the HRSG performance will be conducted by using the system parameter value from the Gas District Cooling (GDC) HRSG. This calculation will be carried out by using Spreadsheet. The X-Steam version 2.6, IAPWS IF97 Excel Steam Tables by Magnus Holmgren is used in this calculation for Spreadsheet. Five different analysis is carried out to analyze the HRSG performance which are pinch point analysis, approach point analysis, steam pressure analysis and HRSG flue gas inlet temperature analysis.

Step 4: Analyzing the HRSG performance

From the calculation of HRSG performance by using five different manipulative variable, the HRSG performance is analyze in term of efficiency, rate of heat transfer and steam generation. The analysis is carried out based on the pattern of the graph.

Step 5: Comparing the HRSG performance

The performance of HRSG from the simulation will be compared to the actual performance of the HRSG from the case study for validation. The capacity of the UTP GDC HRSG is 12.6 Ton/hour.

3.2 HRSG Performance Calculation Procedure

There are four analysis to evaluate the performance of HRSG which are Pinch Point Temperature Difference Analysis and Approach Point Temperature Difference Analysis, steam pressure analysis and HRSG inlet gas temperature analysis.

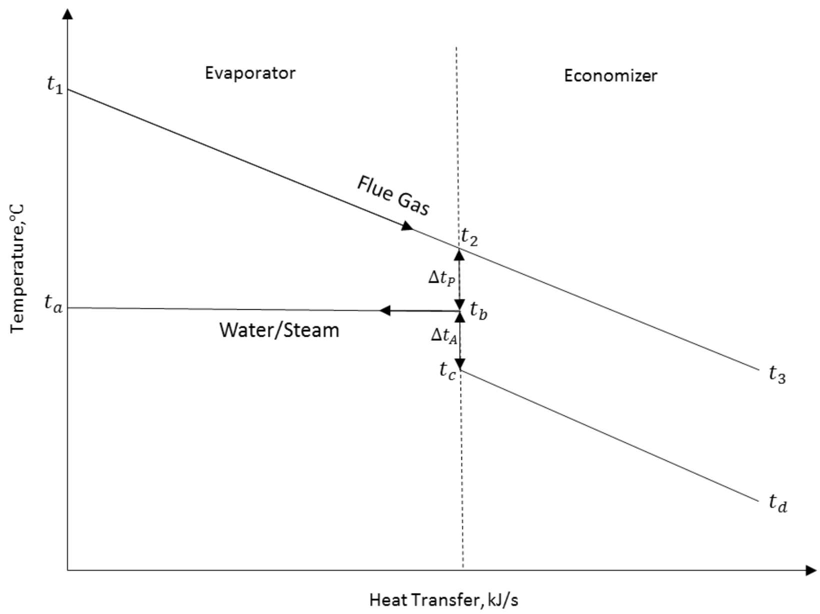

Figure 3.2: Temperature profile for HRSG that consists of evaporator and economizer [22]

Table 3.1: Symbols of Parameter in temperature profile

Δt_P	Pinch Point Temperature Difference, ℃
Δt_A	Approach Point Temperature Difference, ℃
$\dot{m}_g$	Mass flowrate of Flue Gas, kg/s
t_1	Temperature of Flue Gas enter the HRSG, ℃
t_2	Temperature of Flue Gas out of Evaporator, ℃
t_3	Stack Temperature, ℃
t_a	Steam Temperature, ℃
t_b	Temperature of Water/Steam enter the evaporator,℃
t_c	Temperature of Water/Steam out of economizer,℃
t_d	Feed water temperature,℃
$\dot{m}_s$	Mass flowrate of water/steam, kg/s
Q_{1-2}	Evaporator duty, kJ/s
Q_{2-3}	Economizer duty, kJ/s

List of Equations (Aref. P. 2012)

$$t_a = t_b = t_{sat\,@\,P_s} \quad (3.1)$$

Assume, Δt_p and Δt_a

$$t_2 = t_{sat\,@\,P_s} + \Delta t_p \quad (3.2)$$

$$t_c = t_{sat\,@\,P_s} - \Delta t_a \quad (3.3)$$

Table 3.2: Gas specific heat for flue gas temperatures at various temperatures [21]

Temperature (℃)	Gas Specific Heat, C_{P_g} (kJ/kg K)
93.3	1.058892
204.4	1.081921
315.6	1.104245
426.7	1.132165
537.8	1.158962

Evaporator Duty from flue gas stream

$$\dot{Q}_{EVA} = \dot{m}_g \times C_{p_g} \times (t_1 - t_2) \quad (3.4)$$

Evaporator Duty from water/steam stream

$$\dot{Q}_{EVA} = \dot{m}_s \times (h_a - h_c) \quad (3.5)$$

Energy balance equation between flue gas stream and water/steam stream in Evaporator

$$\dot{Q}_{EVA} = \dot{m}_g \times C_{p_g} \times (t_1 - t_2) = \dot{m}_s \times (h_a - h_c) \quad (3.6)$$

Mass flow rate of water/steam

$$\dot{m}_s = \frac{\dot{m}_g \times C_{p_g} \times (t_1 - t_2)}{(h_a - h_c)} \quad (3.7)$$

Economizer Duty from water/steam stream

$$\dot{Q}_{ECO} = \dot{m}_s \times (h_c - h_d) \tag{3.8}$$

Economizer Duty from flue gas stream

$$\dot{Q}_{ECO} = \dot{m}_g \times C_{p_g} \times (t_2 - t_3) \tag{3.9}$$

Energy balance equation between flue gas stream and water/steam stream in Economizer

$$\dot{Q}_{ECO} = \dot{m}_g \times C_{p_g} \times (t_2 - t_3) = \dot{m}_s \times (h_c - h_d) \tag{3.10}$$

Stack Temperature

$$t_3 = t_2 - \frac{\dot{m}_s \times (h_c - h_d)}{\dot{m}_g \times C_{p_g}} \tag{3.11}$$

HRSG Efficiency

$$\eta_{HRSG} = \frac{t_1 - t_3}{t_1 - t_{ambient}} \tag{3.12}$$

Pinch Point Analysis Procedure

*****All the calculations are based on the above equation.

1. Get the value of the system test parameter from UTP Gas District Cooling HRSG.
2. Find the Saturation temperature at steam pressure.
3. Set the pinch point temperature difference as manipulative variable and approach point temperature difference as constant variable.
4. Calculate the evaporator outlet flue gas temperature, t_2 and economizer outlet water temperature, t_c.
5. Get the gas specific heat for evaporator and economizer based on the gas inlet temperature from Table 3.3 by using interpolation.
6. Calculate the evaporator duty from the flue gas stream.
7. Apply the energy balance equation between flue gas stream and water/steam stream for evaporator duty and calculate the mass flow rate of the water/steam.
8. Calculate the economizer duty from the water/steam stream.
9. Apply the energy balance equation between flue gas stream and water/steam stream for economizer duty and calculate the economizer outlet flue gas temperature (stack temperature).
10. Calculate the efficiency of the HRSG.
11. Analyse the calculated value.
12. Compare the calculated value with the real system (UTP GDC HRSG).

Approach Point Analysis Procedure

The calculation steps is same with pinch point temperature difference analysis. For the step number two, set the approach point temperature difference as manipulative variable and pinch point temperature difference as constant variable.

Steam Pressure Analysis Procedure

The calculation steps is same with pinch point temperature difference analysis. For the step number two, both the pinch and approach point temperature difference is set as constant. The calculation is performed by using different value of steam pressure.

HRSG Flue Gas Inlet Temperature Analysis Procedure

The calculation steps is same with steam pressure analysis. The calculation is performed by using different value HRSG flue gas inlet temperature.

3.2 Gantt Chart

Final Year Project 1

Table 3.3: Final Year Project 1 Gantt Chart

Details	Months & Weeks													
	May		June				July				August			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Selection of Project Topic	●													
Research Work & Literature Review														
Preliminary Simulation of Pinch Point Analysis														
Preliminary Simulation of Approach Point Analysis														
Preliminary Simulation of Steam Pressure Analysis														
Preliminary Simulation of HRSG inlet flue gas temperature Analysis														
Analysis of Preliminary Simulation														
Preparing Interim Report														
Submission of Interim Report														●

Estimated Time

● Milestone

Final Year Project 2

Table 3.4: Final Year Project 2 Gantt Chart

Details	**Months & Weeks**														
	September		**October**				**November**			**December**				**January**	
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Simulation of Pinch Point Analysis	■	■													
Simulation of Approach Point Analysis			■	■											
Simulation of Steam Pressure Analysis					■	■									
Simulation of HRSG inlet flue gas temperature Analysis							■	■							
Analysis of the simulation	■	■	■	■	■	■	■	■	■	■	■				
Preparing Final Report and Technical Report										■	■	■			
Submission of Dissertation & Technical Paper (Softcopy)													●		
Oral Presentation														●	
Submission of Dissertation (Hard Bound)															●

■ Estimated Time

● Milestone

3.3 Key Milestones

Table 3.5: Final Year Project 1 Key Milestones

Event	Period
Research Work & Literature Review	20th May 2013 – 24th May 2013
Preliminary Simulation of Pinch Point Analysis	27th May 2013 – 8th June 2013
Preliminary Simulation of Approach Point Analysis	10th June 2013 – 22nd June 2013
Preliminary Simulation of Steam Pressure Analysis	24st June 2013 –6th July 2013
Preliminary Simulation of HRSG inlet flue gas temperature Analysis	8th July 2013 –20th July 2013
Analysis of Preliminary Simulation	20th May 2013 – 20th July 2013

Table 3.6: Final Year Project 2 Key Milestones

Event	Period
Simulation of Pinch Point Analysis	23rd September 2013 – 3th November 2013
Simulation of Approach Point Analysis	4th November 2013 – 16th November 2013
Simulation of Steam Pressure Analysis	18th November 2013 – 30th December 2013
Simulation of HRSG inlet flue gas temperature Analysis	2nd December 2013 – 13th December 2013
Analysis of the simulation	23rd September 2013 – 13th December 2013

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Analysis of Heat Recovery Steam Generator (HRSG) Performance

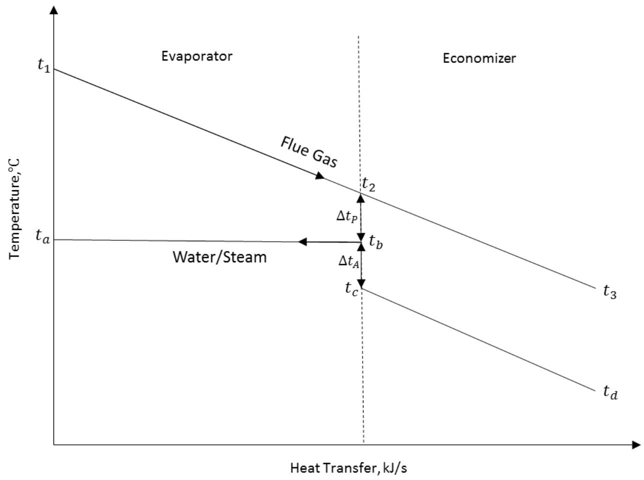

Figure 4.1: Temperature Profile of Single Pressure HRSG [22]

Figure 4.1 shows the theoretical temperature profile of single pressure heat recovery steam generator (HRSG) that consists of evaporator and economizer. It represent the UTP GDC HRSG for the calculation. The symbols in the Figure 4.1 are listed in Table 4.1.

Table 4.1: Symbols of Parameter Used in Calculation

Δt_P	Pinch Point Temperature Difference, ℃
Δt_A	Approach Point Temperature Difference, ℃
$\dot{m}_g$	Mass flowrate of Flue Gas, kg/s
t_1	Temperature of Flue Gas enter the HRSG, ℃
t_2	Temperature of Flue Gas out of Evaporator, ℃
t_3	Stack Temperature, ℃
t_a	Steam Temperature, ℃
t_b	Temperature of Water/Steam enter the evaporator,℃
t_c	Temperature of Water/Steam out of economizer,℃
t_d	Feed water temperature,℃
$\dot{m}_s$	Mass flowrate of water/steam, kg/s
Q_{1-2}	Evaporator duty, kJ/s
Q_{2-3}	Economizer duty, kJ/s

Table 4.2: UTP GDC System Parameter Value [22]

Flue Gas	
Mass Flowrate of Flue Gas, $\dot{m}$	20 kg/s
Temperature of Flue Gas, t_1	500 ^{o}C
Water/Steam	
Temperature of Feedwater, t_e	90 ^{o}C
Pressure of Steam, P	9 bar
Saturation Temperature, $t_{sat\ @\ 9\ bar}$	175.36 ^{o}C
Steam Temperature, t_a	175.36 ^{o}C

Table 4.2 shows the basic data from the flue gas stream and water/steam stream of Universiti Teknologi Petronas (UTP) Gas District Cooling (GDC) HRSG. This data shall be used in the calculation of the HRSG performance.

4.1.1 Pinch Point Analysis

The calculation of HRSG performance for pinch point analysis is based on the data in Table 4.2. The pinch point temperature difference is set as manipulative variable with the value 2℃ to 20℃ while the approach point temperature difference is set as constant value of 10℃. The Table 4.3 below shows the data of the constant parameter in this analysis.

Figure 4.3: The data of constant parameters for pinch point analysis [22]

Constant Parameter	
Mass Flow rate of flue gas, $\dot{m}_g$ (kg/s)	20
Inlet Flue Gas Temperature, t_1 (℃)	500
Steam Pressure, P_s (bar)	9
Saturation Temperature, $t_{sat@P}$ (℃)	175.36
Approach Point, Δt_A (℃)	10
Feed water Temperature, t_d (℃)	90
Ambient Temperature, $t_{ambient}$ (℃)	34

Figure 4.4: The temperature of the water/steam and its enthalpy for pinch point analysis

Temperature of Water/Steam	
Steam Temperature, t_a (℃)	175.36
Evaporator Inlet Water Temperature, t_b (℃)	175.36
Economizer Outlet Water Temperature, t_c (℃)	165.36
Enthalpy of Water/Steam	
Enthalpy of Saturated Vapour of Steam at t_a ,ha (kJ/kg)	2773.03762
Enthalpy of Saturated Liquid of Steam at t_b ,hb (kJ/kg)	742.724615
Enthalpy of Saturated Liquid at t_c, hc (kJ/kg)	698.910886
Enthalpy of Saturated Liquid at t_d, hd (kJ/kg)	376.968444

Table 4.4 shows the enthalpy of the water and steam calculated using the X-Steam version 2.6, IAPWS IF97 Excel Steam Tables. The functions used listed in Appendix-A

Table 4.5: Results of the pinch point analysis

Pinch Point (Celsius)	Evaporator Outlet Gas Temperature, t2 (Celsius)	Evaporator Duty (kJ/s)	Mass flow rate of water/steam (kg/s)	Mass flow rate of water/steam (ton/hour)	Economizer Duty (kJ/s)	Stack Temperature, t4 (Celsius)	HRSG Duty (kJ/s)	Efficiency
2	177.36	7412.9764	3.5740	12.8665	1150.6297	123.89	8641.3336	0.8071
4	179.36	7367.0247	3.5519	12.7867	1143.4971	126.25	8587.2566	0.8020
6	181.36	7321.0730	3.5297	12.7070	1136.3646	128.60	8533.1863	0.7970
8	183.36	7275.1213	3.5076	12.6272	1129.2320	130.95	8479.1229	0.7919
10	185.36	7229.1696	3.4854	12.5475	1122.0995	133.31	8425.0663	0.7869
12	187.36	7183.2180	3.4632	12.4677	1114.9669	135.66	8371.0164	0.7818
14	189.36	7137.2663	3.4411	12.3879	1107.8344	138.01	8316.9733	0.7768
16	191.36	7091.3146	3.4189	12.3082	1100.7018	140.36	8262.9370	0.7718
18	193.36	7045.3629	3.3968	12.2284	1093.5693	142.72	8208.9074	0.7667
20	195.36	6999.4112	3.3746	12.1487	1086.4368	145.07	8154.8845	0.7617

Tables 4.5 shows the results of the pinch point analysis based on the parameter in table 4.3 and table 4.4. The effect of pinch point temperature difference on efficiency, HRSG duty, steam production rate and stack temperature are plotted in the Figure 4.2, Figure, 4.3 and Figure 4.4 respectively.

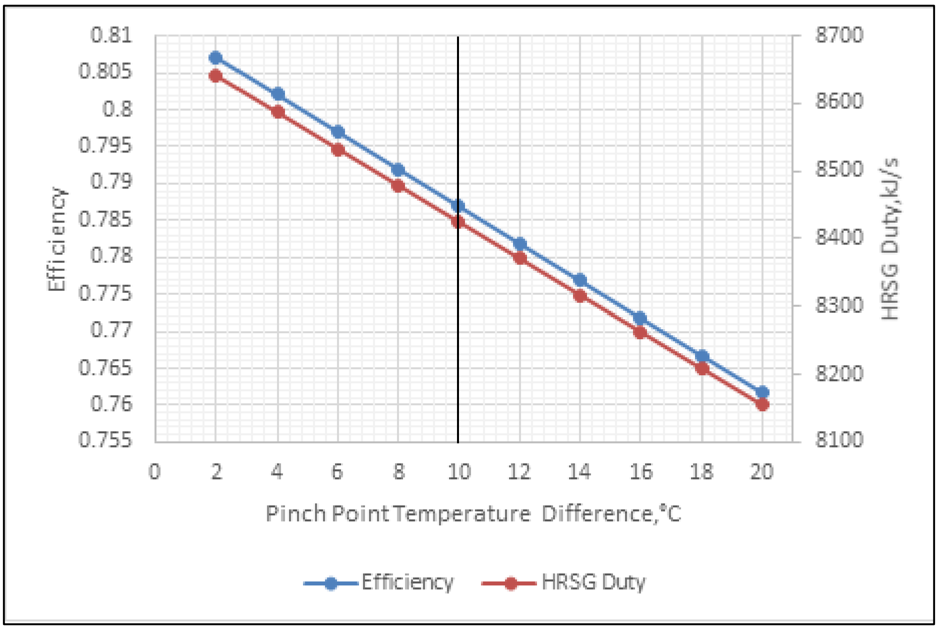

Figure 4.2: HRSG Efficiency & HRSG Duty vs Pinch Point Temperature Difference

The Figure 4.2 shows the relationship of the HRSG efficiency, HRSG duty and pinch point temperature difference. Based on the graph, decreased the pinch point temperature difference increased the HRSG duty. The pinch point temperature difference determined the evaporator outlet gas temperature,t_2. Decreasing the pinch point temperature difference decreased the evaporator outlet gas temperature,t_2. So the difference between evaporator inlet gas temperature,t_1 and evaporator outlet gas temperature,t_2 $(t_1 - t_2)$ also increased. Hence the evaporator duty increases as it is proportional to difference between evaporator inlet gas temperature,t_1 and evaporator outlet gas temperature,t_2 $(t_1 - t_2)$. Thus, the HRSG duty also increased due to increasing evaporator duty.

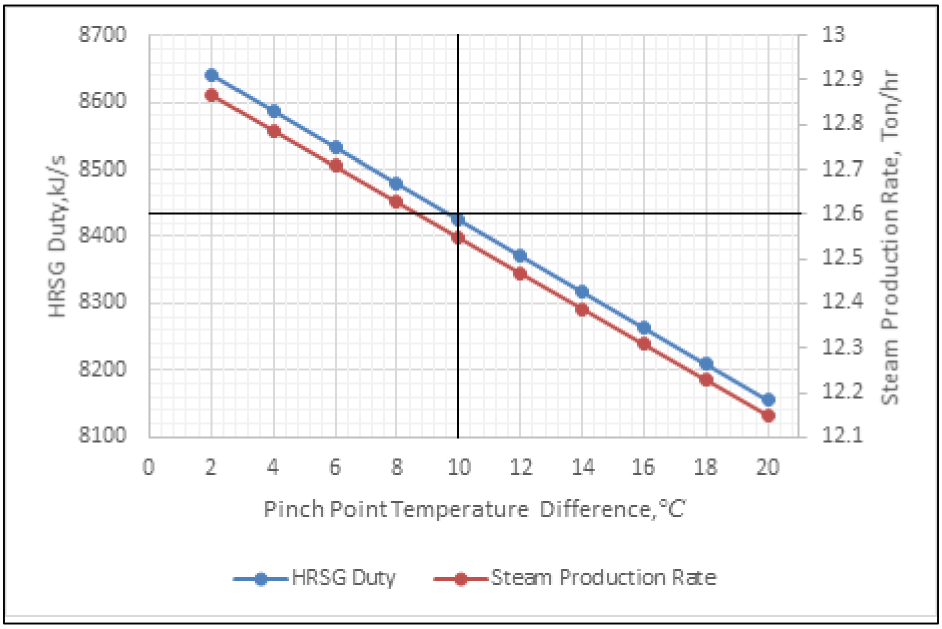

Figure 4.3: HRSG Duty & Steam production rate vs Pinch Point Temperature Difference

Figure 4.3 represents the effect of pinch point temperature difference on HRSG duty and steam production rate (mass flow rate of steam/water). Decreased the pinch point temperature difference will increased the evaporator duty and eventually increased HRSG duty. The steam production rate depends on the evaporator duty as both of it proportional to each other. The higher the evaporator duty increased the steam production rate.

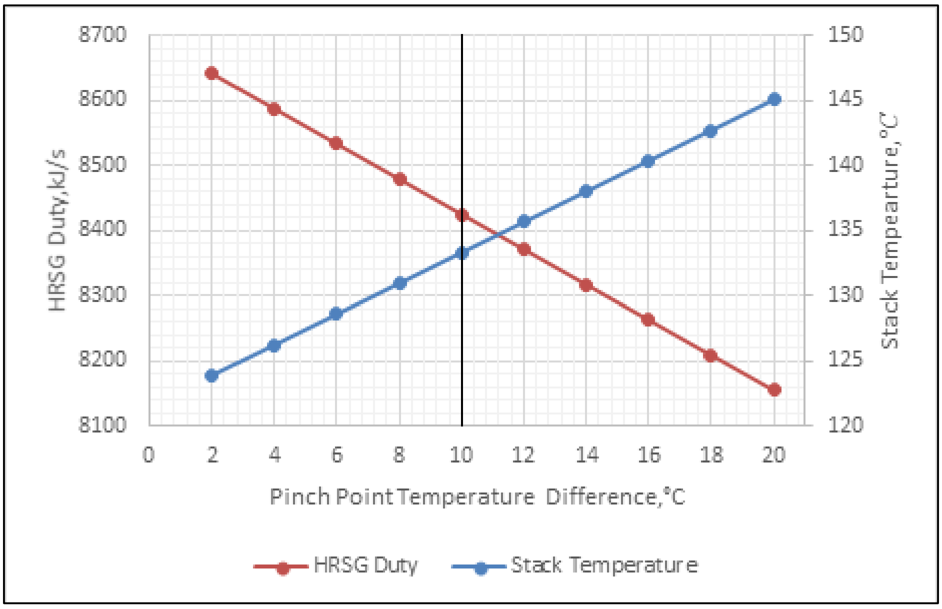

Figure 4.4 HRSG Duty & Stack Temperature vs Pinch Point Temperature Difference

From the graph in Figure 4.4, reducing the pinch point temperature difference will decreased the stack temperature. Decreasing the pinch point temperature difference increased the HRSG duty as the result of increased economizer duty. High HRSG duty means high steam production rate. So, it can recover more waste heat from the flue gas. Thus, more heat will be transferred to the water inside the economizer. As a result, the stack temperature will decreased.

As shown in the Figure 4.4, the 2°C of pinch point temperature difference produced 123.89°C of stack temperature with the HRSG effectiveness of 80.71%. When the pinch point temperature difference increases to 20°C, the stack temperature increased to 145.07°C with the HRSG effectiveness of 76.17%.

The black straight line on the Figure 4.2, Figure 4.3 and Figure 4.3 indicate the current pinch point of the UTP GDC HRSG. In order to increase the performance of the HRSG, the value of pinch point that should be used is below 10°C. So, the HRSG need additional heat transfer surface area.

4.1.2 Approach Point Analysis

The calculation of HRSG performance for pinch point analysis is based on the data in Table 4.2. The analysis was carried out using different approach point temperature difference with the value 2℃ to 20℃ and the constant value of 10℃ for pinch point temperature difference is set as. The data of the constant parameters are tabulated in Table 4.6 as shown below.

Table 4.6: The data of constant parameters for approach point analysis [22]

Constant Parameter	
Mass Flow rate of flue gas, $\dot{m}_g$	20 kg/s
Inlet Flue Gas Temperature, t_1	500℃
Steam Pressure, P_s	9 bar
Saturation Temperature, $t_{sat@P}$	175.3578℃
Pinch Point, Δt_P	10℃
Feed water Temperature, t_d	90℃
Ambient Temperature, $t_{ambient}$	34℃

Table 4.7: The temperature of the water/steam and its enthalpy for approach point analysis

Temperature of Water/Steam	
Steam Temperature, t_a (℃)	175.36
Evaporator Inlet Water Temperature, t_b (℃)	175.36
Enthalpy of Water/Steam	
Enthalpy of Saturated Vapour of Steam at t_a ,ha (kJ/kg)	2773.03762
Enthalpy of Saturated Liquid of Steam at t_b ,hb (kJ/kg)	742.724615
Enthalpy of Saturated Liquid at t_d, hd (kJ/kg)	376.968444

Table 4.7 shows the temperature of the water/steam and its enthalpy calculated based on their temperature using the X-Steam version 2.6, IAPWS IF97 Excel Steam Tables. The functions used listed in Appendix-A.

Table 4.8: Results of the approach point analysis

Approach Point (Celsius)	Evaporator Outlet Gas Temperature, t2 (Celsius)	Evaporator Duty (kJ/s)	Economizer Outlet Water Temperature, tc (Celsius)	Enthalpy of Saturated Liquid @ Tc, hc (kJ/kg)	Mass flow rate of water/steam (kg/s)	Mass flow rate of water/steam (ton/hour)	Economizer Duty (kJ/s)	Stack Temperature, t4 (Celsius)	HRSG Duty (kJ/s)	Efficiency
2	185.36	7229.1696	173.36	733.9334	3.5453	12.7630	1265.5363	126.65	8577.9365	0.8012
4	185.36	7229.1696	171.36	725.1568	3.5301	12.7083	1229.1305	128.34	8539.1364	0.7975
6	185.36	7229.1696	169.36	716.3944	3.5150	12.6541	1193.0936	130.01	8500.7295	0.7940
8	185.36	7229.1696	167.36	707.6459	3.5001	12.6005	1157.4189	131.67	8462.7085	0.7904
10	185.36	7229.1696	165.36	698.9109	3.4854	12.5475	1122.0995	133.31	8425.0663	0.7869
12	185.36	7229.1696	163.36	690.1891	3.4708	12.4949	1087.1290	134.93	8387.7959	0.7834
14	185.36	7229.1696	161.36	681.4801	3.4564	12.4429	1052.5011	136.54	8350.8906	0.7800
16	185.36	7229.1696	159.36	672.7837	3.4420	12.3914	1018.2096	138.13	8314.3439	0.7766
18	185.36	7229.1696	157.36	664.0995	3.4279	12.3403	984.2486	139.70	8278.1493	0.7732
20	185.36	7229.1696	155.36	655.4273	3.4138	12.2898	950.6121	141.26	8242.3007	0.7698

Table 4.6 shows the calculated results of the approach point analysis. Based on the data in Table 4.6, three graphs represent the relationship between efficiency, HRSG duty, steam production rate and stack temperature to approach point temperature difference was plotted in Figure 4.5, Figure 4.6 and Figure 4.7.

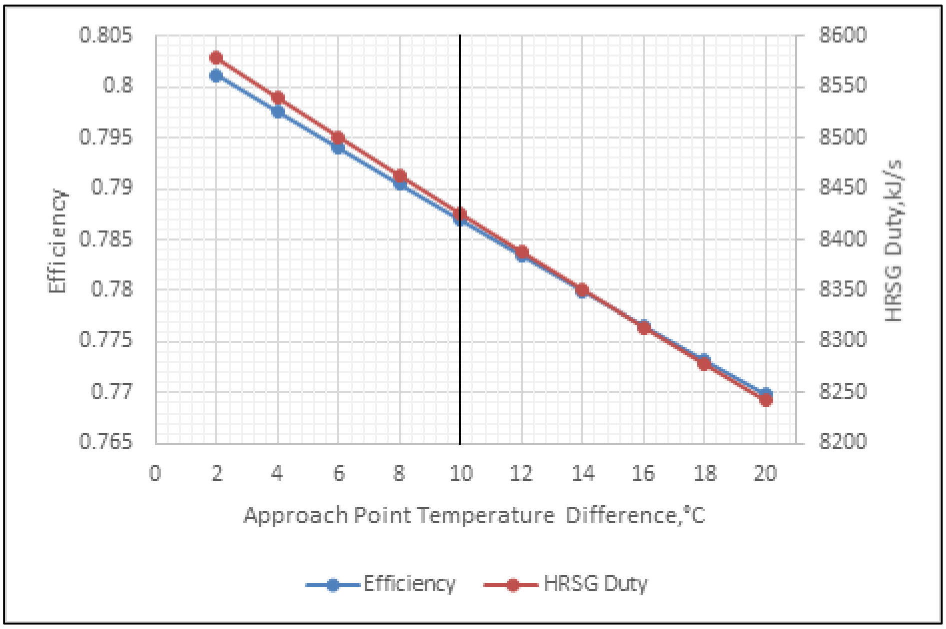

Figure 4.5: HRSG Efficiency & HRSG Duty vs Approach Point Temperature Difference

Figure 4.5 shows represent the effect of approach point temperature difference on HRSG efficiency and HRSG duty. Based on the graph, decreased the approach point temperature difference increased the economizer duty. The approach point temperature difference determined the economizer outlet water temperature,t_c. Increasing the approach point temperature difference decreased the economizer outlet water temperature,t_c and also decreased its saturated liquid enthalpy. So the economizer duty will decreased. As a result, the HRSG duty will also decreased.

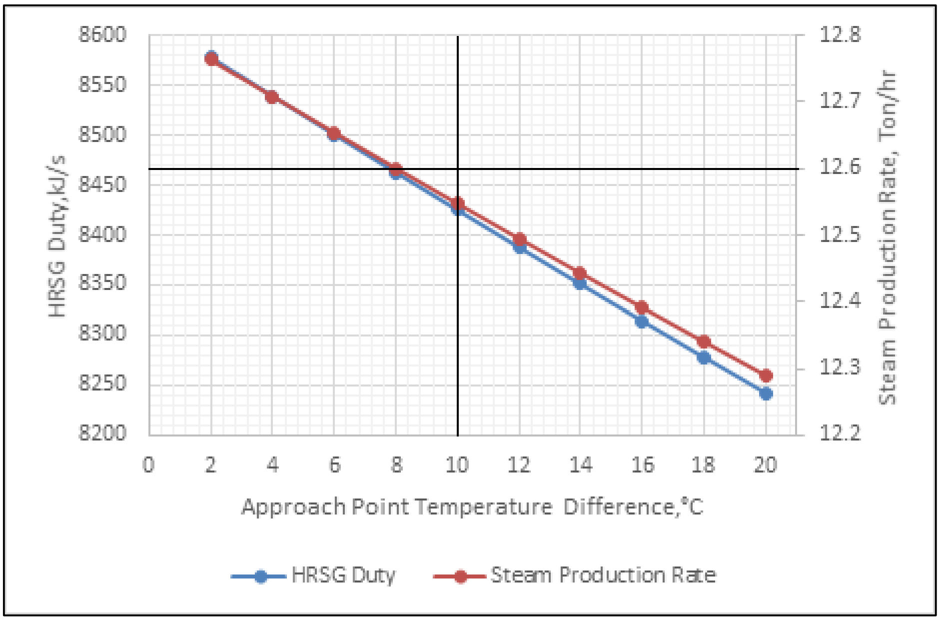

Figure 4.6: HRSG Duty & Steam Production Rate vs Approach Point Temperature Difference

Based on Figure 4.6, the HRSG duty and steam production rate decreased when the approach point temperature difference decreased. This is because the mass flow rate of water/steam depend on the evaporator duty. Decreased the approach point temperature increased the economizer outlet water temperature,t_c and eventually increased its enthalpy, h_c. Increasing the economizer outlet water enthalpy decreased the difference value between steam enthalpy and economizer outlet water enthalpy $(h_a - h_c)$. Hence, it decreases the evaporator duty as well as steam production rate. Thus, mass flow rate of water/steam flow through the HRSG also decreased.

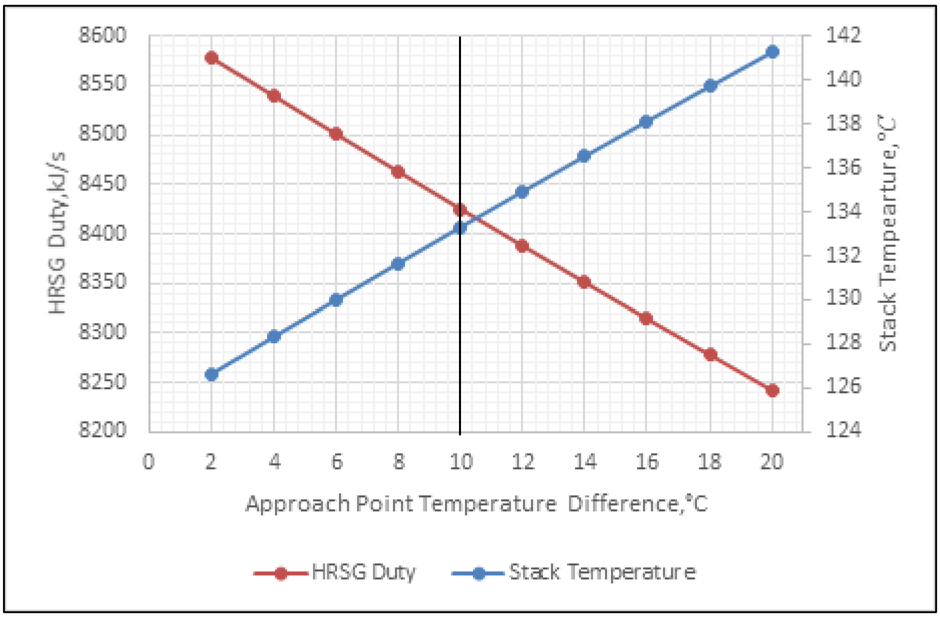

Figure 4.7: HRSG Duty & Stack Temperature vs Approach Point Temperature Difference

Figure 4.7 shows the relationship between HRSG duty and stack temperature when the value of the approach point temperature difference are changes. As discuss before, decreasing the approach point temperature difference increased the economizer duty. When the economizer duty increased, the heat recovery from flue gas also increased. Thus, more heat transfer to the water and it reduced the stack temperature.

By referring to the temperature profile in Figure 4.1, the area between flue gas stream line and water/steam stream line represent the HRSG heat loss. Using low value approach point temperature difference will slightly reduce this area (heat loss) and increase the heat recovery. So the stack temperature will also reduce which make the HRSG efficiency increases.

However, the effect of changes in approach point temperature difference on HRSG performance is less compared to the pinch point temperature difference. This is because the main purpose setting the approach point temperature difference in the HRSG is to prevent the water in the economizer from steaming. If the temperature of water leaving the economizer is equal to the temperature of water entering the evaporator, the water inside the economizer tends to steaming. Steaming in the economizer will lead to some problem such as water hammer, vibration, thermal shock etc. To avoid steaming problem, a certain temperature range between economizer outlet and evaporator inlet in the water steam stream (approach point temperature difference) is set based on practical experience.

The black straight line on the Figure 4.5, Figure 4.6 and Figure 4.7 shows the current approach point of the UTP GDC HRSG. In order to increase the performance of the HRSG, the value of approach point that should be used is below 10℃. So, the HRSG need additional heat transfer surface area to carry out the duty.

4.1.3 Steam Pressure Analysis

Calculation based on the UTP GDC System Parameter data in Table 4.2. The pinch and approach point temperature difference is set to be constant of 10 °C. In this analysis, the performance of HRSG is evaluated based on the different steam pressure from 5 bar to 50 bar. The value of the constant parameters are tabulated in Table 4.9 as shown below.

Table 4.9: The data of constant parameters for steam pressure analysis [22]

Constant Parameter	
Mass Flow rate of flue gas, $\dot{m}_g$	20 kg/s
Inlet Flue Gas Temperature, t_1	500°C
Pinch Point, Δt_P	10°C
Approach Point, Δt_A	10°C
Feed water Temperature, t_d	90°C
Ambient Temperature, $t_{ambient}$	34°C

Table 4.10: The temperature of the water/steam and its enthalpy for steam pressure analysis

Saturation Temperature, Tsat (Celsius)	Steam Temperature, ta (Celcius)	Enthalpy of Saturated Vapor of Steam at ta (kJ/kg)	Evaporator Inlet Water Temperature, tb (Celsius)	Enthalpy of Saturated Liquid of Steam at tb (kJ/kg)	Economizer Outlet Water Temperature, tc (Celsius)	Enthalpy of Saturated Liquid at tc, hc (kJ/kg)
151.84	151.84	2748.1076	151.84	640.1853	141.84	597.0867
179.89	179.89	2777.1195	179.89	762.6828	169.89	718.7055
198.30	198.30	2791.0105	198.30	844.7169	188.30	799.9704
212.38	212.38	2798.3841	212.38	908.6219	202.38	863.1550
223.96	223.96	2802.0427	223.96	961.9832	213.96	915.8212
233.86	233.86	2803.2647	233.86	1008.3714	223.86	961.5274
242.56	242.56	2802.7435	242.56	1049.7753	232.56	1002.2549
250.36	250.36	2800.8973	250.36	1087.4260	240.36	1039.2294
257.44	257.44	2797.9970	257.44	1122.1430	247.44	1073.2662
263.94	263.94	2794.2271	263.94	1154.5020	253.94	1104.9378

Table 4.10 shows the temperature of the water/steam and its enthalpy calculated based on their temperature using the X-Steam version 2.6, IAPWS IF97 Excel Steam Tables. The functions used listed in Appendix-A.

Table 4.11: Results of the steam pressure analysis

Pressure (bar)	Evaporator Outlet Gas Temperature, t2 (Celsius)	Evaporator Duty (kJ/s)	Mass flow rate of water/steam (kg/s)	Mass flow rate of water/steam (ton/hour)	Economizer Duty (kJ/s)	Stack Temperature, t4 (Celsius)	HRSG Duty (kJ/s)	Efficiency
5	161.84	7769.5978	3.6121	13.0034	795.0784	124.77	8621.1528	0.8052
10	189.89	7125.1394	3.4615	12.4613	1182.9127	135.07	8384.6567	0.7831
15	208.30	6702.1630	3.3662	12.1182	1423.8931	142.56	8212.4603	0.7670
20	222.38	6378.4497	3.2960	11.8655	1602.4542	148.62	8073.1764	0.7540
25	233.96	6112.5743	3.2406	11.6663	1746.2304	153.77	7954.9341	0.7430
30	243.86	5885.0684	3.1954	11.5034	1867.8936	158.26	7851.7594	0.7333
35	252.56	5685.1036	3.1575	11.3671	1974.3630	162.25	7760.1660	0.7248
40	260.36	5505.9883	3.1254	11.2516	2069.8571	165.83	7677.9252	0.7171
45	267.44	5343.2768	3.0980	11.1529	2157.1550	169.06	7603.5228	0.7102
50	273.94	5193.8534	3.0746	11.0685	2238.1993	172.01	7535.8868	0.7038

Based on the results tabulated in Table 4.11, three graphs are plotted to see the effect of different steam pressure on the HRSG efficiency, HRSG duty, stack temperature and steam production as shown in Figure 4.7, Figure 4.8 and Figure 4.9 respectively.

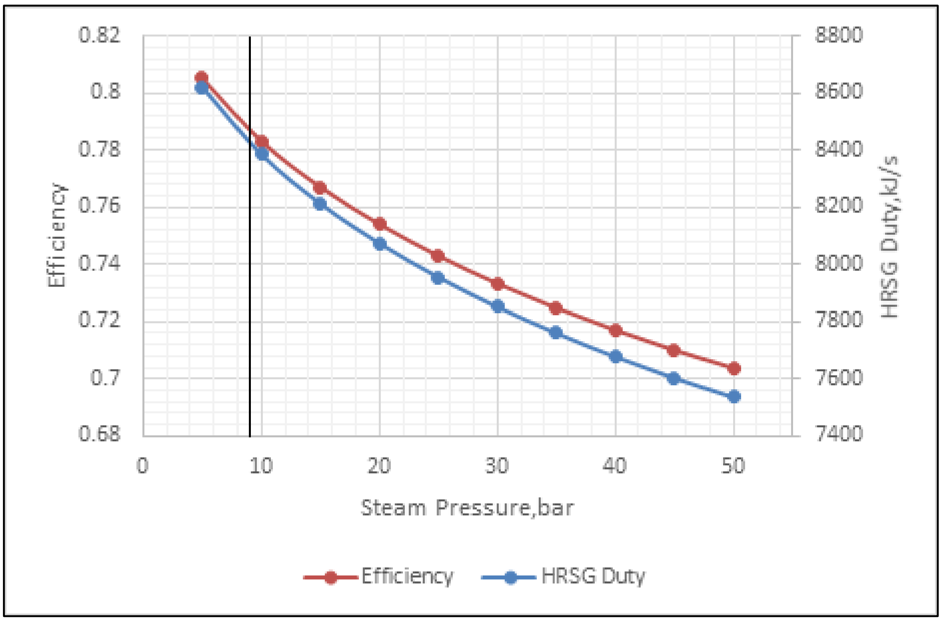

Figure 4.8: HRSG Efficiency & HRSG Duty vs Steam Pressure

Figure 4.8 represent the relationship between HRSG efficiency, HRSG duty and steam pressure. The HRSG duty will decreases from 8621 kJ/s to 7535 kJ/s when the operating steam pressure increases from 5 bar to 50 bar. This is because the saturation temperature of the steam will increase as the steam pressure increases. So the evaporator outlet gas temperature, t_2 also will increase with the constant value of pinch point temperature difference. The evaporator duty is proportional to the difference value between evaporator inlet gas temperature, t_1 and evaporator outlet gas temperature,t_2, $(t_1 - t_2)$. The high evaporator outlet gas temperature will cause low heat recovery in evaporator which resulting the low evaporator duty. Hence, it will reduced the HRSG duty.

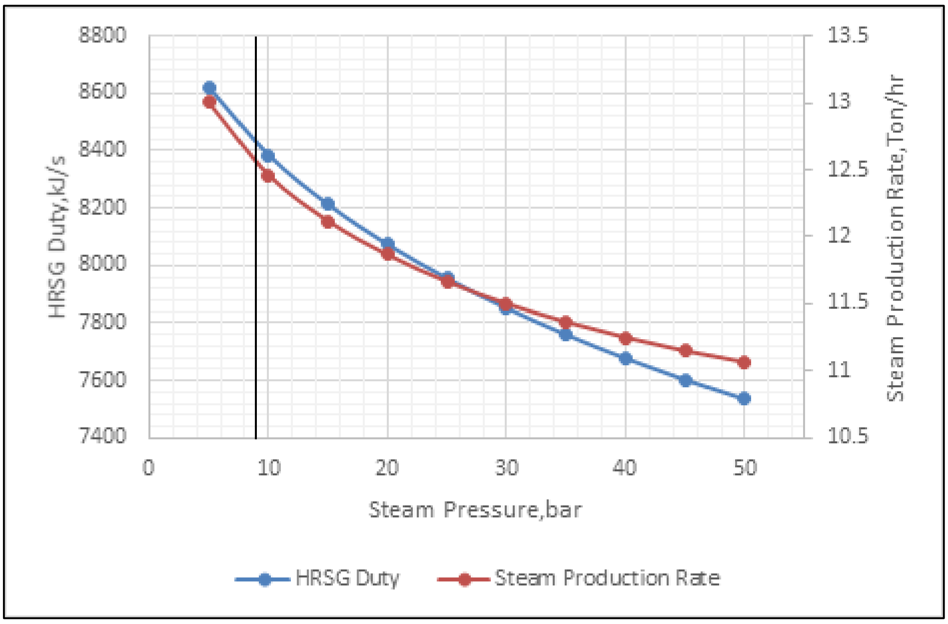

Figure 4.9: HRSG Duty & Steam Production Rate vs Steam Pressure

Figure 4.9 shows the relationship of HRSG duty and steam production rate when steam pressure varies. Increasing the steam pressure of the system decreased the evaporator duty. So, the HRSG duty also increased. When the HRSG duty is low, the steam production rate also low. The low steam production rate will decreased the water flow through the economizer.

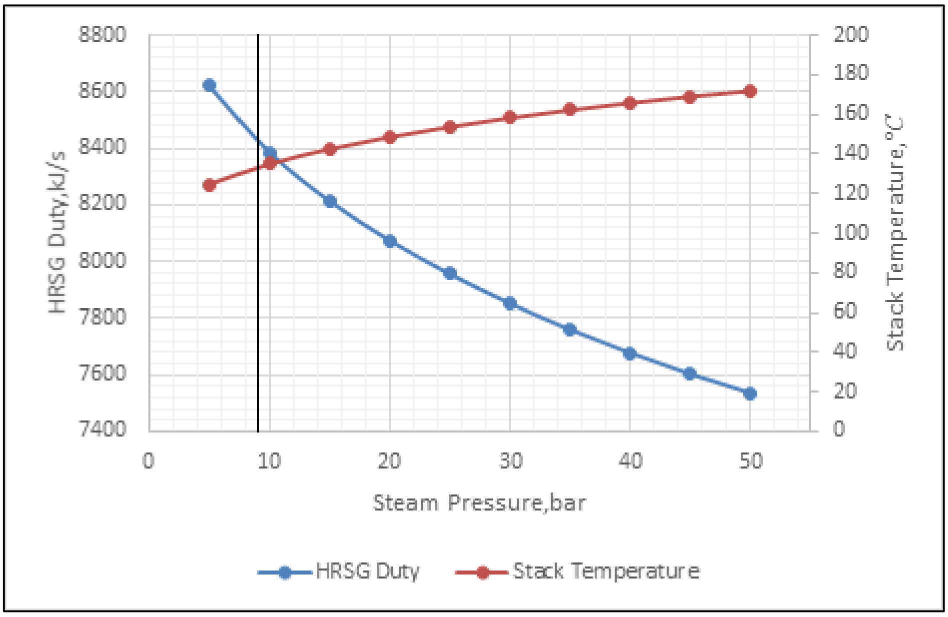

Figure 4.10: HRSG Duty & Stack Temperature vs Steam Pressure

Figure 4.10, shows the effect of steam pressure on HRSG duty and stack temperature. As discussed before, increasing the steam pressure decreased the HRSG duty. When HRSG duty decreasing, the steam production also decreasing. Thus less heat recover from the flue gas will increase the stack temperature.

The black straight line on the Figure 4.8, Figure 4.9 and Figure 4.10 the current operating steam pressure of the UTP GDC HRSG which is 9 bar. In order to increase the performance of the HRSG, the operating steam pressure of the system should be reduced. However, the selection of the operating steam pressure also need to consider the output steam temperature demands.

4.1.4 HRSG Inlet Flue Gas Temperature Analysis

This analysis is carried out to evaluate the effect of different HRSG inlet gas temperature. The different HRSG inlet gas temperature can represent the use of different type of gas turbine or supplementary firing cases. Different gas turbine produce different exhaust gas temperature depending on the type of manufacturer, capacity, size, pressure ratio, ambient temperature and the other factors. For supplementary firing case, the additional fuel is fired with flue gas before it entering the HRSG. Supplementary firing used to increase the temperature of the flue gas entering the HRSG. The purpose of this analysis is to illustrate both the cases for performance evaluation.

The calculation based on the UTP GDC System Parameter data in Table 4.2. In this analysis, the performance of HRSG is evaluated based on the different gas inlet temperature from 500 ℃ bar to 1000 ℃ with the increasing value of 50℃. The value of constant parameters are shown in the Table 4.12 below.

Table 4.12: The data of constant parameters for HRSG inlet flue gas temperature analysis [22]

Constant Parameter	
Mass Flow rate of flue gas, $\dot{m}_g$	20 kg/s
Steam Pressure, P_s	9 bar
Saturation Temperature, $t_{sat@P}$	175.36℃
Pinch Point, Δt_P	10℃
Approach Point, Δt_A	10℃
Feed water Temperature, t_d	90℃
Ambient Temperature, $t_{ambient}$	34℃

Table 4.13 below shows the temperature of the water/steam and its enthalpy calculated based on their temperature using the X-Steam version 2.6, IAPWS IF97 Excel Steam Tables. The functions used listed in Appendix-A.

Table 4.13: The temperature of the water/steam and its enthalpy for HRSG inlet flue gas temperature analysis

Temperature of Water/Steam	
Steam Temperature, t_a (℃)	175.36
Evaporator Inlet Water Temperature, t_b (℃)	175.36
Economizer Outlet Water Temperature, t_c (℃)	165.36
Enthalpy of Water/Steam	
Enthalpy of Saturated Vapour of Steam at t_a ,ha (kJ/kg)	2773.03762
Enthalpy of Saturated Liquid of Steam at t_b ,hb (kJ/kg)	742.724615
Enthalpy of Saturated Liquid at t_c, hc (kJ/kg)	698.910886
Enthalpy of Saturated Liquid at t_d, hd (kJ/kg)	376.968444

Table 4.14: Results of HRSG inlet flue gas temperature analysis

HRSG Inlet Flue Gas Temperature, ta (Celsius)	Evaporator Outlet Gas Temperature, t2 (Celsius)	Evaporator Duty (kJ/s)	Mass flow rate of water/steam (kg/s)	Mass flow rate of water/steam (ton/hour)	Economizer Duty (kJ/s)	Stack Temperature, t4 (Celsius)	HRSG Duty (kJ/s)	Efficiency
500	185.36	7229.1696	3.4854	12.5475	1122.0995	133.31	8425.0663	0.7869
550	185.36	8460.1175	4.0789	14.6840	1313.1651	124.44	9873.3696	0.8247
600	185.36	9713.5958	4.6832	16.8596	1507.7279	115.42	11351.9973	0.8561
650	185.36	10989.6047	5.2984	19.0743	1705.7878	106.23	12861.0591	0.8827
700	185.36	12288.1440	5.9245	21.3282	1907.3449	96.88	14400.6646	0.9056
750	185.36	13609.2138	6.5614	23.6211	2112.3991	87.37	15970.9235	0.9255
800	185.36	14952.8141	7.2092	25.9532	2320.9505	77.70	17571.9453	0.9430
850	185.36	16318.9449	7.8679	28.3243	2532.9990	67.86	19203.8398	0.9585
900	185.36	17707.6061	8.5374	30.7346	2748.5447	57.86	20866.7166	0.9724
950	185.36	19118.7979	9.2178	33.1839	2967.5874	47.70	22560.6853	0.9850
1000	185.36	20552.5201	9.9090	35.6724	3190.1274	37.38	24285.8556	0.9965

The results of the calculation of HRSG inlet flue gas temperature analysis are tabulated in the Table 4.14. From this data, the graph that represents the effect of different HRSG inlet flue gas temperature on the efficiency, HRSG duty, steam production rate and stack temperature are plotted in Figure 4.11, Figure 4.12 and Figure 4.13.

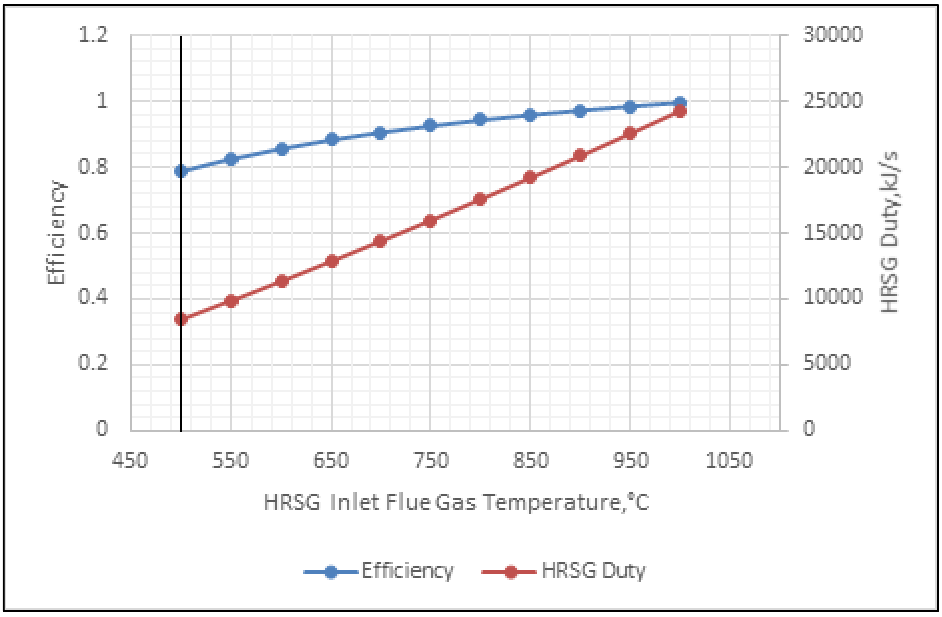

Figure 4.11: HRSG Efficiency & HRSG Duty vs HRSG inlet flue gas temperature

Figure 4.11 shows the relationship between HRSG efficiency, HRSG duty and HRSG inlet flue gas temperature. Based on the result, increasing the HRSG inlet flue gas temperature will increase the HRSG duty. This is because the evaporator duty is proportional to the difference between HRSG inlet flue gas temperature and the evaporator outlet gas temperature, $(t_1 - t_2)$. In this analysis the steam pressure and pinch point temperature difference are kept constant. So the evaporator outlet gas temperature, t_2 also constant. When the HRSG inlet flue gas temperature, t_1, the evaporator duty also increased. Hence, it will increase the HRSG duty.

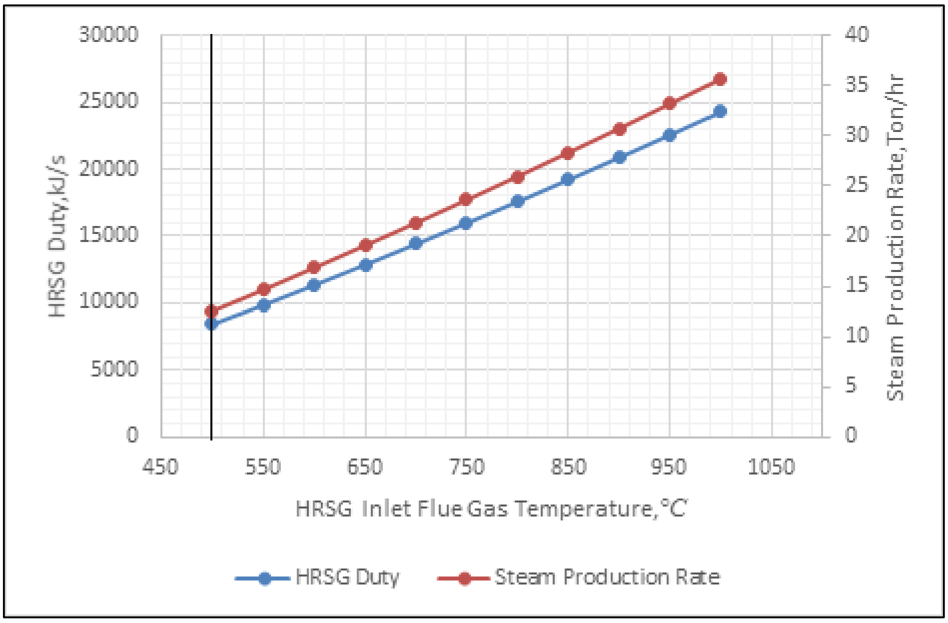

Figure 4.12: HRSG Duty & Steam production vs HRSG flue gas inlet temperature

Figure 4.12 shows the effect of HRSG flue gas inlet temperature on the HRSG duty and steam production rate. As discuss before, the steam production rate is proportional to the evaporator duty. When the HRSG flue gas inlet temperature increased, the evaporator duty also increased. So the water/steam mass flow rate needed to produce steam also increased.

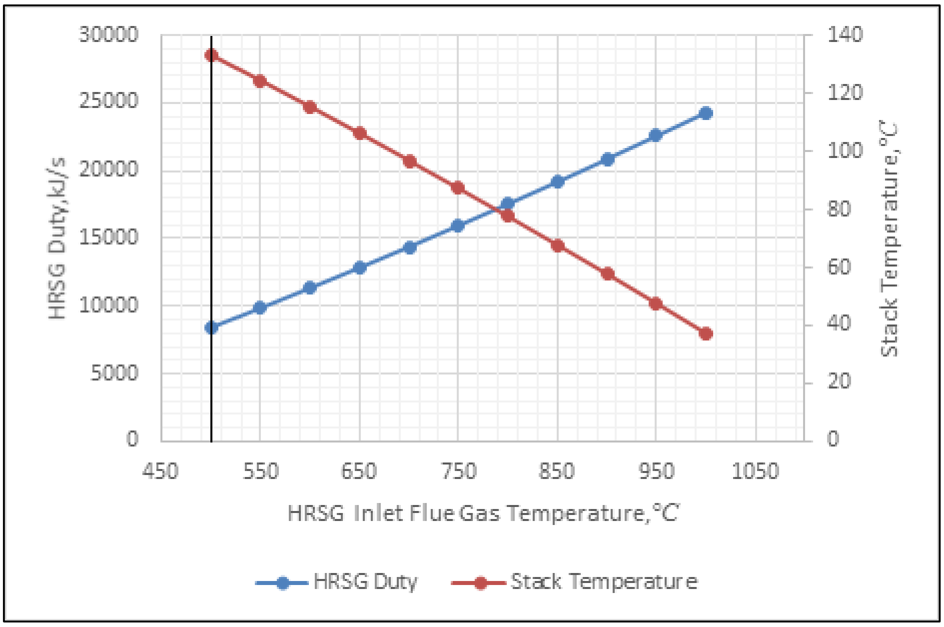

Figure 4.13: HRSG Duty & Stack Temperature vs HRSG flue gas inlet temperature

Figure 4.13, shows the effect of HRSG flue gas inlet temperature on HRSG duty and stack temperature. As discuss before, increasing the HRSG flue gas inlet temperature increased the HRSG duty. When HRSG duty increased, the steam production rate also increased. Thus more heat recovery from the flue gas to produce steam and cause the stack temperature to reduce.

The black straight line on the Figure 4.11, Figure 4.12 and Figure 4.13 indicate the current UTP GDC HRSG inlet flue gas temperature which is 500℃. The higher the HRSG inlet flue gas temperature, the higher the performance of HRSG. The HRSG inlet flue gas temperature can be increased by using supplementary firing or using different type of gas turbine. Changing the gas turbine is impossible to implement because of the expensive cost. The supplementary firing looks possible to be implement but it need some alteration on the HRSG inlet.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

The study shows the effects of pinch point, approach point, steam pressure, HRSG inlet gas temperature and mass flow rate of flue gas on the performance heat recovery steam generator (HRSG) in Universiti Teknologi Petronas (UTP) Gas District Cooling (GDC) Plant. These five parameters were analysed using spreadsheet. From these analysis, the following findings are listed below;

i. Reducing pinch point temperature difference decreased the stack temperature. Low stack temperature means high heat recovery. Thus, increased the HRSG duty, increased the steam production rate and increased the effectiveness of the HRSG. The summary of the pinch point analysis results tabulated in Table 5.1.

Table 5.1: Summary of the Pinch Point Analysis Results

Pinch Point (Celcius)	Steam Production Rate (ton/hour)	Stack Temperature, T4 (Celcius)	HRSG Duty (kJ/s)	Efficiency
2	12.8665	123.8948	8641.3336	0.80709
4	12.7867	126.2485	8587.2566	0.80204
6	12.7070	128.6018	8533.1863	0.79699
8	12.6272	130.9549	8479.1229	0.79194
10	12.5475	133.3077	8425.0663	0.78689
12	12.4677	135.6601	8371.0164	0.78185
14	12.3879	138.0123	8316.9733	0.7768
16	12.3082	140.3642	8262.937	0.77175
18	12.2284	142.7157	8208.9074	0.7667
20	12.1487	145.0670	8154.8845	0.76166

ii. Reducing approach point temperature difference decreased the stack temperature. However the decreased is lower than the effect of pinch point. Low stack temperature means high heat recovery. Hence, slightly increased the HRSG duty, steam production rate and efficiency of HRSG. The summary of the approach point analysis results tabulated in Table 5.2.

Table 5.2: Summary of the Approach Point Analysis Results

Approach Point (Celcius)	Steam Production Rate (ton/hour)	Stack Temperature, T4 (Celcius)	HRSG Duty (kJ/s)	Efficiency
2	12.7630	126.6541	8577.9365	0.80117
4	12.7083	128.3429	8539.1364	0.79755
6	12.6541	130.0145	8500.7295	0.79396
8	12.6005	131.6693	8462.7085	0.79041
10	12.5475	133.3077	8425.0663	0.78689
12	12.4949	134.9298	8387.7959	0.78341
14	12.4429	136.5361	8350.8906	0.77997
16	12.3914	138.1267	8314.3439	0.77655
18	12.3403	139.7021	8278.1493	0.77317
20	12.2898	141.2623	8242.3007	0.76982

iii. Reducing steam pressure of the system decreased the saturation temperature of steam in evaporator. With the fixed pinch point temperature difference value, the evaporator outlet gas temperature, t_2 (refer Figure 4.1) also decreased. So the HRSG duty and steam production rate increased. Thus reducing steam pressure will increase the HRSG efficiency. The summary of the steam pressure analysis results tabulated in Table 5.3.

Table 5.3: Summary of the Steam Pressure Analysis Results

Steam Pressure (bar)	Steam Production Rate (ton/hour)	Stack Temperature, T4 (Celcius)	HRSG Duty (kJ/s)	Efficiency
5	13.0034	124.7732	8621.1528	0.80521
10	12.4613	135.0664	8384.6567	0.78312
15	12.1182	142.5611	8212.4603	0.76704
20	11.8655	148.6233	8073.1764	0.75403
25	11.6663	153.7697	7954.9341	0.74298
30	11.5034	158.2602	7851.7594	0.73335
35	11.3671	162.2468	7760.166	0.72479
40	11.2516	165.8262	7677.9252	0.71711
45	11.1529	169.0645	7603.5228	0.71016
50	11.0685	172.0083	7535.8868	0.70384

iv. Increasing HRSG inlet flue gas temperature increased the HRSG duty and steam production rate. So the efficiency of HRSG will increase if the HRSG inlet flue gas temperature increases. The summary of the HRSG inlet flue gas temperature analysis results tabulated in Table 5.4.

Table 5.4: Summary of the HRSG Inlet Flue Gas Temperature Analysis Results

HRSG inlet flue gas temperature (Celcius)	Steam Production Rate (ton/hour)	Stack Temperature, T4 (Celcius)	HRSG Duty (kJ/s)	Efficiency
500	12.5475	133.3077	8425.0663	0.78689
550	14.6840	124.4448	9873.3696	0.82472
600	16.8596	115.4197	11351.997	0.85615
650	19.0743	106.2324	12861.059	0.88274
700	21.3282	96.8829	14400.665	0.90558
750	23.6211	87.3712	15970.923	0.92546
800	25.9532	77.6972	17571.945	0.94295
850	28.3243	67.8611	19203.84	0.9585
900	30.7346	57.8627	20866.717	0.97244
950	33.1839	47.7021	22560.685	0.98504
1000	35.6724	37.3792	24285.8556	0.9965

Based on the above findings, it can be concluded pinch point temperature difference greatly affect the performance of heat recovery steam generator (HRSG) in term of steam production rate, heat recovery steam generator (HRSG) duty and efficiency. The approach point temperature difference only slightly affect the performance of heat recovery steam generator (HRSG) as it main purpose is to prevent steaming in economizer. In steam pressure analysis, it shows that the low steam pressure can provide better performance of heat recovery steam generator (HRSG). For heat recovery steam generator (HRSG) inlet gas temperature and mass flow rate of flue gas, the bigger these parameter value will provide better performance of heat recovery steam generator (HRSG).

More accurate results can be obtained if the heat loss, blowdown and flue gas pressure drop in the HRSG system are considered for the analysis. Moreover the exergy analysis in HRSG system is also recommended to analyze the maximum useful work in the steam production process for the future project. Other than that the analysis on multipressure stage HRSG and its configuration are recommended.

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APPENDICES

Appendix A

X Steam Tables v2.6 http://www.x-eng.com

Steam tables by Magnus Holmgren according to IAPWS IF-97

The excel scripts are stored inside this workbook. (No extra files are needed. Start from a copy of this workbook. This page can be removed)

For error-reporting, feedback, other units etc. contact:magnus@x-eng.com

The steam tables are free and provided as is. We take no responsibilities for any errors in the code or damage thereby.

OBS: This workbook uses macros. Set security options in Tools:Macro:Security… to enable macros.

Temperature	
Tsat_p	Saturation temperature
T_ph	Temperature as a function of pressure and enthalpy
T_ps	Temperature as a function of pressure and entropy
T_hs	Temperature as a function of enthalpy and entropy
Pressure	
psat_T	Saturation pressure
p_hs	Pressure as a function of h and s.
p_hrho	Pressure as a function of h and rho (density). Very inaccurate for solid water region since it's almost incompressible!
Enthalpy	
hV_p	Saturated vapour enthalpy
hL_p	Saturated liquid enthalpy
hV_T	Saturated vapour enthalpy
hL_T	Saturated liquid enthalpy
h_pT	Enthalpy as a function of pressure and temperature.
h_ps	Enthalpy as a function of pressure and entropy.

h_px	Enthalpy as a function of pressure and vapour fraction
h_Tx	Enthalpy as a function of temperature and vapour fraction
h_prho	Enthalpy as a function of pressure and density. Observe for low temperatures (liquid) this equation has 2 solutions. (Not valid!!)