Parametric Study on Steam Generation of Heat Recovery Steam Generator at 2 × 4.2MW District Cooling Plant

by

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16743

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Mechanical)

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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
May 2015

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.

ONG CHUAN FAITH

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ABSTRACT

This research was conducted to study the various parameters that have significant impact on the steam generation of a heat recovery steam generator (HRSG) in the gas district cooling (GDC) plant in UTP. Through this study, the amount of steam generated by the HRSG with respect to different operating conditions was analyzed to identify improvements for the HRSG. The main parameters that have significant impact on the steam generation of a HRSG are the exhaust gas temperature entering the HRSG, the operating pressure of the HRSG, the approach point and pinch point, heat transfer surface area of the HRSG components, and the operating load. Other factors that could have an impact on the amount of steam generated by the HRSG include the exhaust gas analysis, arrangement of the components of the HRSG, the type of circulation in the HRSG, etc. In this research, the parameters that were studied are the exhaust gas temperature, the feedwater temperature, the ambient temperature and the pinch and approach point. The parametric study was carried out using Microsoft Excel spreadsheet and a simulation was done by using Engineering Equation Solver (EES) to obtain the results.

This research concludes that the higher the exhaust gas temperature that enters the HRSG, the more steam is generated by the HRSG. When the exhaust gas temperature was increased from 638 K to 659 K, the amount of steam generated by the HRSG also increased by 11%, which is from 2.00 kg/s to 2.22 kg/s. The result of this study shows that the temperature of the feedwater entering the HRSG through the economizer has no impact the steam generation of the HRSG. However, the ambient temperature does affect the amount of steam generated by the HRSG. As the ambient temperature increases, the amount of steam generated decreases. Throughout the day the highest amount of steam generation occurs during the morning and night where temperature is the lowest. Lastly, this study also found that the higher is the pinch and approach point of a HRSG, lesser steam is generated. When 15 K pinch and approach point were set, the amount of steam generated decreased by 3.74 % compared to when 10 K pinch and approach point were used. The HRSG in UTP GDC plant have a high pinch and approach point of about 55 K. If this high pinch and approach point can be reduced to the recommended range of 10 K to 15 K, the amount of steam generated could have been doubled.

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CHAPTER 1

INTRODUCTION

1.1 Project Background

Demand for power and steam generation has been increasing throughout the world due to the large increase in population and the spurt in industrial growth [1]. Nearly every industry requires the usage of steam, either to generate power or to be used in process plants. Because of this, steam generators and heat recovery boilers became a vital component and many researches has been done to improve the energy utilization and to recover energy efficiently from various waste gas sources.

Heat sources in industrial processes can be at very high temperatures, 540-1375°C and applications have been developed to recover as much energy from these effluents as possible in order to improve the overall energy utilization [1]. Heat recovery steam generators (HRSGs) play an important role in power generation via steam turbine, steam absorption chillers and process equipment.

1.2 Problem Statement

There are various parameters that can affect the amount of steam generated by a HRSG including ambient temperature, pinch and approach point, the exhaust gas temperature entering the HRSG, the feedwater temperature, etc. How can these parameters affect the HRSG and how can more steam be generated by the HRSG is of interest in this study. Also, how the amount of steam generated by a HRSG can be predicted to estimate the performance of the HRSG.

1.3 Objective

The objective of this research is to study the parameters and their effect on the steam generation of the HRSG. By developing a model, the degree of impact of the change in the parameters to the HRSG can be predicted and the amount of steam generated can be increased.

1.4 Scope of Study

- The parameters of heat recovery steam generator which will impact the steam generation of the HRSG.
- Cover 2 units of HRSG operating at 12 ton/hour.
- Both HRSG are water-tube, single-pressure type with evaporator and economizer
- Both the HRSG are driven by exhaust gases from gas turbines.

CHAPTER 2

LITERATURE REVIEW

2.1 Gas Turbine

Gas turbines are widely used to generate power in power plants due to its ability to generate great amount of power relatively to its size and weight and it is becoming popular due to its compactness, low weight and multiple fuel application [3]. The industrial gas turbines used in power plants can be classified into two major types which is a simple open cycle or a closed cycle [4]. These gas turbines typically have a single-shaft configuration and consist of a compressor, a combustion chamber, and a turbine [5] as shown in Figure 2.1. The basic working principle of the gas turbine is by compressing air into high very high pressure to be mixed with fuel and combusted in the combustion chamber to produce high temperature gas which is expanded through a turbine to produce work which drives the same shaft connecting the compressor and turbine [6].

In the simple open cycle gas turbine, the combustion products are exhausted to the atmosphere with relatively high temperatures in the range of 427°C to 627°C [7]. These high thermal energy exhaust gas are wasted into the environment while it may be utilized in various ways to recover the energy [8]. Thus, a gas turbine is often coupled with a steam turbine which recovers the wasted heat using a heat recovery steam generator (HRSG), where heat is transferred from the gas turbine exhaust to water flowing in the tubes to generate steam in a combined cycle [9]. The exhaust gas temperature of the gas turbine plays an important role in the temperature profile of a HRSG as the exhaust gas is directly channelled to the HRSG which is located behind the gas turbine [10].

According to Ganapathy [11], ambient temperature, altitude, and load of the gas turbine will affect the exhaust gas flow and temperature of a gas turbine. Tiwari et al [12] found that the gas turbine cycle efficiency decreases by 0.03 to 0.07% for every °C rise in ambient temperature. This is due to the lower gas density at higher temperature which causes the mass flow of the gas to be decreased [1, 12]. The exhaust gas temperature also decreases as the gas turbine operates at lower load [11]. Generally, gas turbines perform poorly at low loads, which affect not only their performance but also that of the HRSG located behind them, the lower load on the gas turbine, the lower the flue gas temperature entering the HRSG and thus, the lesser amount of steam generated [1].

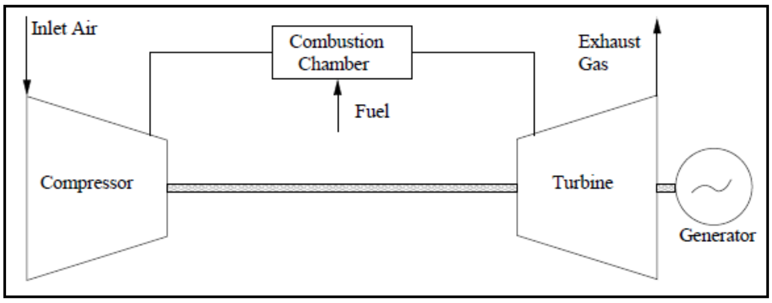


Figure 2.1: The arrangement of a simple Brayton cycle [4]

2.2 Combined Cycle

The combined cycle process couples the topping Brayton cycle with a bottoming Rankine cycle where the exhaust gas from the Brayton cycle enters the HRSG of the Rankine cycle to be cooled and generate steam [2, 18]. The combined cycle take advantage of the fact that the gas cycle operates at a higher temperature than the steam cycle [13-14]. Both the gas turbine and the steam cycle are linked through a HRSG as shown in Figure 2.2 below, where the exhaust heat from the gas turbine is absorbed to produce steam at suitable pressure and temperature [15]. These steam recovered in the HRSG can then be used for process or to generate power using a steam turbine [1].

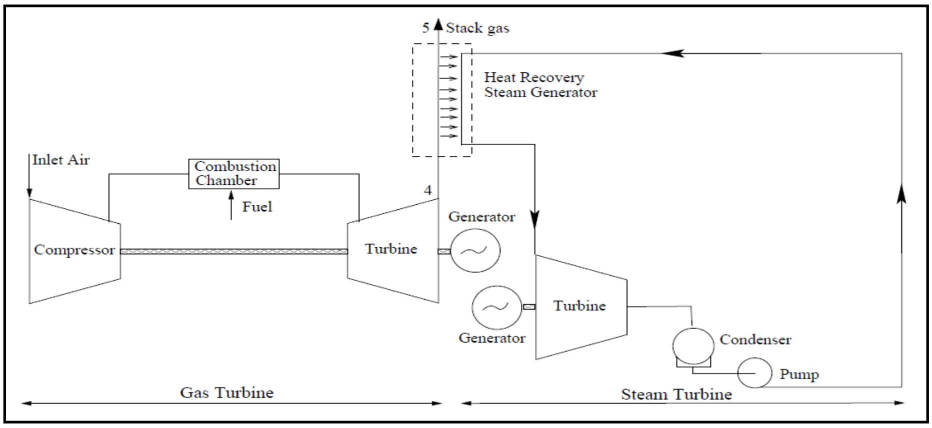


Figure 2.2: The arrangement of a typical combine cycle [4]

2.3 Heat Recovery Steam Generator (HRSG)

Heat recovery steam generator (HRSGs) is the main component of combined cycle power plants used to recover waste heat from high enthalpy flue gas leaving gas turbines to generate steam [16]. The HRSG consists of three heat exchanger sections which are the economizer, the evaporator, and the superheater [11, 17, 20] as shown in Figure 2.3. Feed water is pumped into the economizer where it is the furthest away from the gas turbine to be heated up to a temperature close to its saturation point. The saturated water then enters the evaporator and turns into saturated steam. A drum is used to separate the water from the saturated steam which is then passed into the superheater to be heated into dry superheated steam [4].

HRSG can be classified into a few categories such as pressure-level, type of circulation, fired or unfired, and fire tube or water tube type [1]. The common pressure levels used in HRSG are single-pressure, dual-pressure and triple-pressure HRSGs [4]. The single-pressure HRSG is relatively simple but the stack temperature (gas temperature leaving the HRSG) is relatively high. Multi pressure level configurations such as dual and triple-pressure HRSG are able to extract more heat from the gas turbine exhaust gas and therefore the stack temperature is lower [1, 4].

There are generally 2 types of circulation used in HRSG, which is the natural-circulation (NC) and the forced-circulation (FC) HRSG. For the NC HRSG, the water steam mixture passes through the evaporator tubes the 'natural' density difference between steam and water while the FC HRSG uses a pump to help circulate the water steam mixture [19]. According to Pasha and Jolly [19], the pressure drop in the FC will be higher than that of the NC because the design of FC uses smaller tubes.

Ganapathy [1] explained that an unfired HRSG is ineffective compared to a supplementary fired HRSG. He mentioned that the oxygen content in the flue gas is sufficient to be supplementary fired without the need for additional air [11]. He also added that by supplementary firing the HRSG, the exhaust gas temperature can be increased to a range of 650°C to 850°C and this can be used to produce more steam [11].

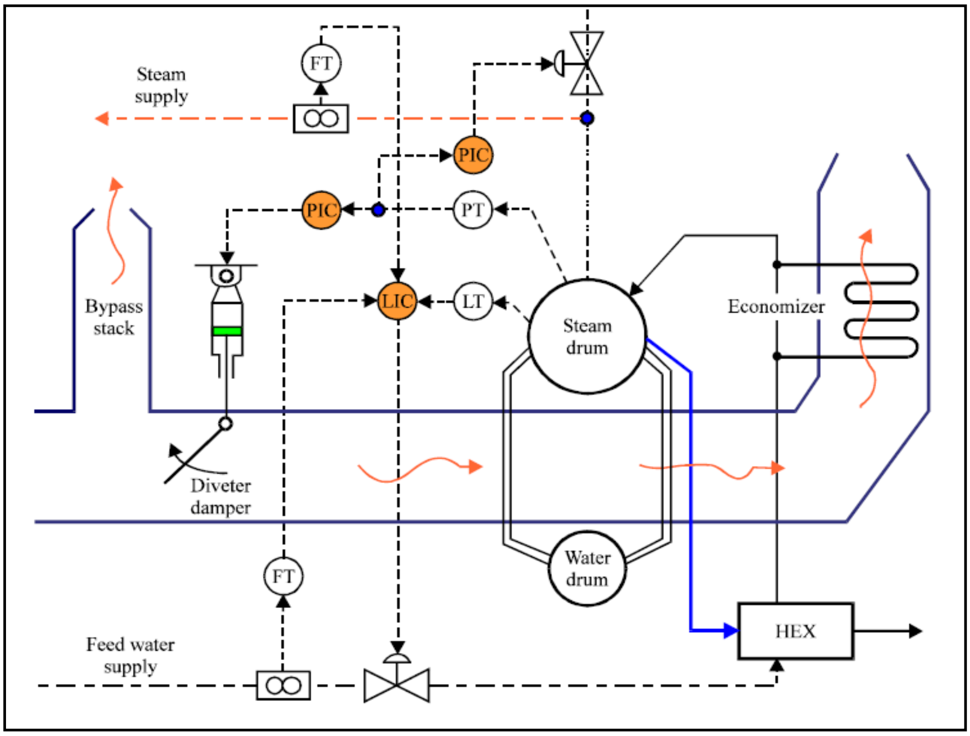


Figure 2.3: Schematic diagram of the HRSG used in UTP GDC [23]

2.4 Temperature Profile of HRSG

The temperature profile of HRSG needs to be understood in order to understand the performance aspects of HRSGs [11]. A few parameters that dictates the temperature profile of the HRSG includes the flue gas flow rate, the exhaust gas temperature, the saturation temperature, the steam pressure, the approach and pinch point, the feedwater temperature [1, 2, 4, 7, 20]. In the temperature profile, a lower exit temperature (stack temperature) is desired because more heat is recovered by the HRSG [4, 11]. Ganapathy [1] concluded that in a single-pressure HRSG, the exit gas temperature is a function of the steam pressure and temperature. He explained that higher steam pressure will produce lower the exit gas temperature due to the higher saturation temperature of the steam which absorbs more heat from the flue gas.

Pinch and approach points are two important parameters that govern the HRSG temperature profiles and a low pinch and approach points should be used to maximize steam production [1, 2, 4, 11, 20]. The pinch point is the difference of the temperature of the exhaust gas at the inlet of the evaporator and the saturated steam temperature and the approach point is the difference of the saturated steam temperature and the temperature of the saturated water at the outlet of the economizer [1] as shown in Figure 2.4. According to Casarosa et al [2], the pinch and approach point range is usually 10°C to 20°C whereas Aref [4] mentioned that the value is usually in the range of 8°C to 15°C. In order to determine the temperature profile for the HRSG given the exhaust gas temperature and the pressure of steam, the pinch and approach point needs to be determined first [1]. However, the pinch and approach points cannot be selected arbitrarily to avoid temperatures cross to occur in the temperature profile [11]. Temperature cross is the situation where the gas temperature leaving the evaporator is lower than the saturation temperature and the exit gas temperature from the economizer is lower than the feedwater temperature.

Ganapathy [1] also identified gas analysis as a parameter that can change the temperature profile of a HRSG. If the exhaust gas contains large amount of hydrogen or water vapour, the specific heat capacity and the thermal conductivity of the gas is larger and hence carries more heat energy into the HRSG. Casarosa [2] did an optimization research for HRSG and he identified the mass flow ratio between the hot and cold stream as an important parameter. The higher the mass flow ratio of hot to cold stream, the lesser heat is recovered and hence the stack temperature will be higher.

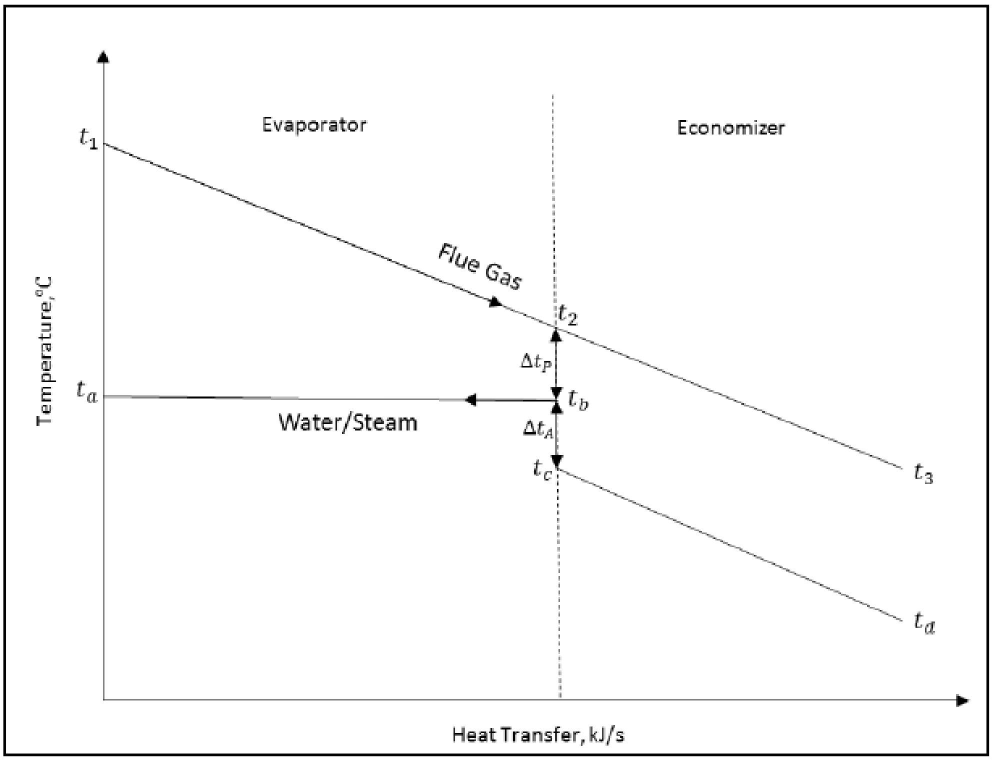


Figure 2.4: Typical temperature profile of HRSG [1]

2.5 Universiti Teknologi Petronas Gas District Cooling

The Gas District Cooling (GDC) in Universiti Teknologi Petronas (UTP) was set up to generate electricity and chilled water for the university. The GDC plant has a capacity to supply 8.4MW of electricity and 6,300RT of chilled water to UTP. The plant operates on a cogeneration cycle whereby the gas turbine is used to produce electricity by burning natural gas and diesel while a HRSG is used to recover the heat from the exhaust gas to produce steam which is used in the steam absorption chillers to produce chilled water. Two units of gas turbines of 4.2MW capacity are used to generate electricity and producing high temperature exhaust gas to produce steam in the HRSG at 12 ton/h each. Figure 2.5 below shows the data that was collected from the control room in UTP GDC plant.

The HRSG used in the GDC plant are water-tube type HRSG from Vickers Hoskin. Both the HRSG only consists of an economizer and an evaporator without a superheater as opposed to conventional HRSGs. It receives flue gas from the gas turbine at an average temperature of 520°C to produce steam of 175°C temperature at about 8.7 bar pressure. The feedwater entering the economizer is preheated to about 75°C and is heated to about 165°C in the economizer before entering the evaporator. The average flue gas temperature leaving the HRSG is about 130°C.

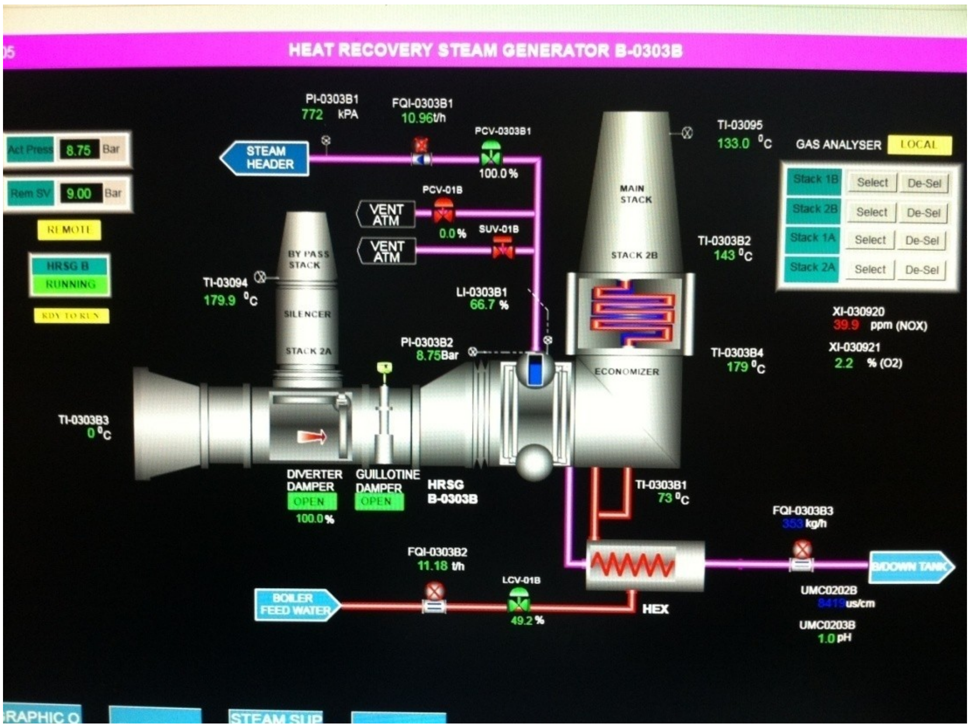
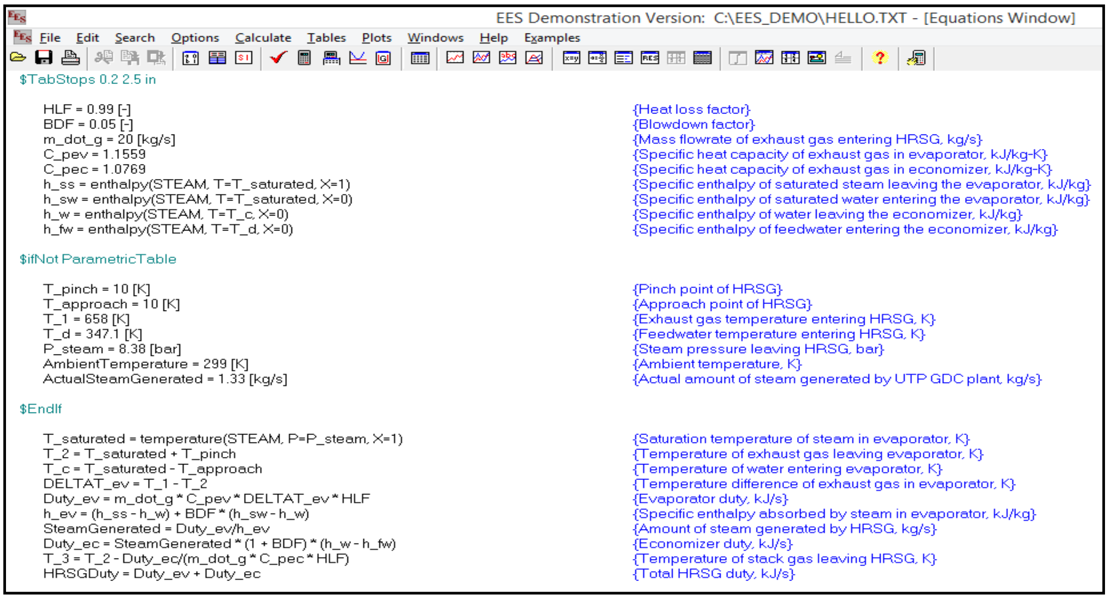


Figure 2.5: Data collected from the control room of GDC plant [21]

2.6 EES Software

The EES software is a program that can solve general equations including non-linear algebraic and differential equations. The program can also be used to solve differential and integral equations, do optimization, provide uncertainty analyses, perform linear and non-linear regression, convert units, check unit consistency, and generate publication-quality plots [24]. A major feature of EES is the high accuracy thermodynamic and transport property database that is provided for hundreds of substances in a manner that allows it to be used with the equation solving capability [24].

Data was acquired from the daily HRSG data logging from GDC plant in UTP that was operated by Makhostia Sdn. Bhd. The data that was used is taken on the 10th of June 2015 (Wednesday). The ambient temperature was taken from a weather forecast online [22]. From these data, the effects of exhaust gas temperature, feedwater temperature, ambient temperature and pinch and approach point can be found by using the spreadsheet. Graphs were plotted to illustrate the results and to see the relationship between the parameters and the HRSG performance and a model is done with EES software to simulate the results. The program written with EES software is shown in Figure 2.6 below.



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    HLF = 0.99 [-]                                          {Heat loss factor}
    BDF = 0.05 [-]                                          {Blowdown factor}
    m_dot_g = 20 [kg/s]                                     {Mass flowrate of exhaust gas entering HRSG, kg/s}
    C_pev = 1.1559                                          {Specific heat capacity of exhaust gas in evaporator, kJ/kg-K}
    C_pec = 1.0769                                          {Specific heat capacity of exhaust gas in economizer, kJ/kg-K}
    h_ss = enthalpy(STEAM, T=T_saturated, X=1)              {Specific enthalpy of saturated steam leaving the evaporator, kJ/kg}
    h_sw = enthalpy(STEAM, T=T_saturated, X=0)              {Specific enthalpy of saturated water entering the evaporator, kJ/kg}
    h_w = enthalpy(STEAM, T=T_c, X=0)                       {Specific enthalpy of water leaving the economizer, kJ/kg}
    h_fw = enthalpy(STEAM, T=T_d, X=0)                      {Specific enthalpy of feedwater entering the economizer, kJ/kg}

$ifNot ParametricTable

    T_pinch = 10 [K]                                        {Pinch point of HRSG}
    T_approach = 10 [K]                                     {Approach point of HRSG}
    T_1 = 658 [K]                                           {Exhaust gas temperature entering HRSG, K}
    T_d = 347.1 [K]                                         {Feedwater temperature entering HRSG, K}
    P_steam = 8.38 [bar]                                    {Steam pressure leaving HRSG, bar}
    AmbientTemperature = 299 [K]                            {Ambient temperature, K}
    ActualSteamGenerated = 1.33 [kg/s]                      {Actual amount of steam generated by UTP GDC plant, kg/s}

$EndIf

    T_saturated = temperature(STEAM, P=P_steam, X=1)        {Saturation temperature of steam in evaporator, K}
    T_2 = T_saturated + T_pinch                             {Temperature of exhaust gas leaving evaporator, K}
    T_c = T_saturated - T_approach                          {Temperature of water entering evaporator, K}
    DELTAT_ev = T_1 - T_2                                   {Temperature difference of exhaust gas in evaporator, K}
    Duty_ev = m_dot_g * C_pev * DELTAT_ev * HLF             {Evaporator duty, kJ/s}
    h_ev = (h_ss - h_w) + BDF * (h_sw - h_w)                {Specific enthalpy absorbed by steam in evaporator, kJ/kg}
    SteamGenerated = Duty_ev/h_ev                           {Amount of steam generated by HRSG, kg/s}
    Duty_ec = SteamGenerated * (1 + BDF) * (h_w - h_fw)     {Economizer duty, kJ/s}
    T_3 = T_2 - Duty_ec/(m_dot_g * C_pec * HLF)             {Temperature of stack gas leaving HRSG, K}
    HRSGDuty = Duty_ev + Duty_ec                            {Total HRSG duty, kJ/s}
```

Figure 2.6: The program written using EES software

CHAPTER 3

METHODOLOGY

3.1 Project Methodology

The HRSG produces steam by using the high temperature exhaust from the gas turbine to boil the feedwater. The temperature profile of the HRSG shows the temperature change of the exhaust gas and the feedwater in each of the components of the HRSG and is useful to determine the efficiency of the HRSG. Figure 3.1 shows the project methodology to plot the temperature profile of a HRSG. EES software will be used for simulation and analyzing the temperature profile. Table 3.2 and 3.3 below shows the Gantt chart that was used to breakdown the task into weeks to be completed. Figure 3.4 and 3.5 shows the key milestones that are achieved in FYP 1 and FYP 2.

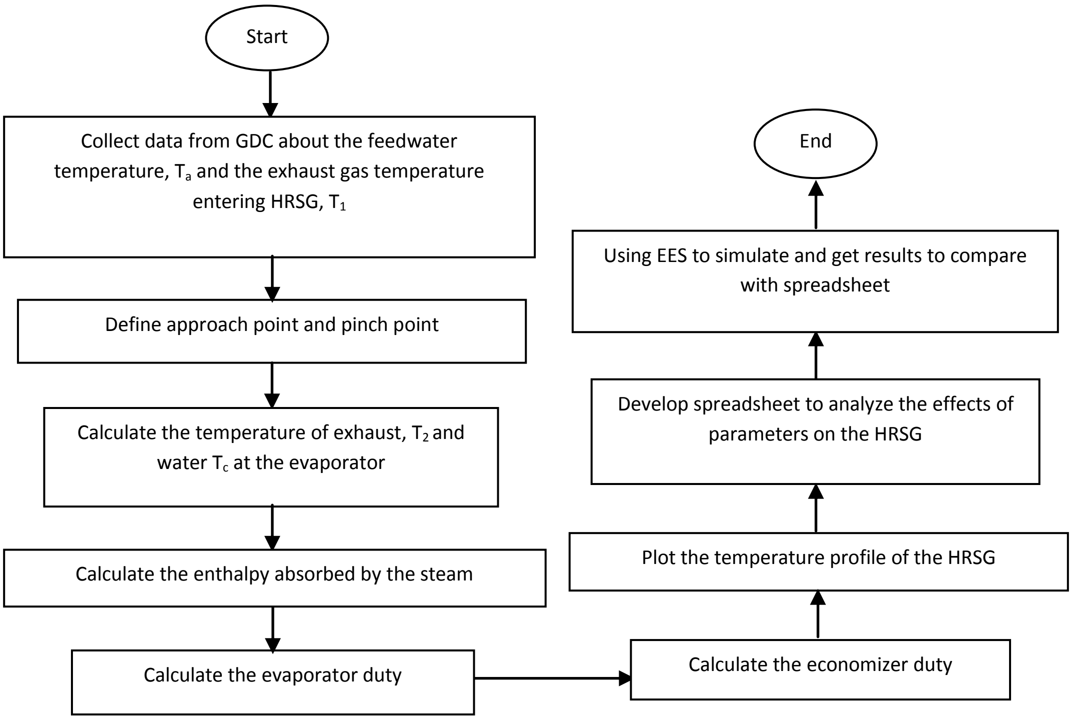

Figure 3.1: Project methodology

Table 3.1: Gantt Chart for FYP 1

Activity	Months & Weeks													
	January			February				March				April		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
FYP title confirmation and first meeting with Dr Amin	■	■												
Literature review on combined power plant, HRSG and various journals on improving the perfomance of the HRSG		■	■	■										
Literature review on the various parameters that will affect HRSG				■	■									
Literature review on how to develop the temperature profile and its significance					■	■								
Submission of extended proposal						■	■							
Visit to GDC plant to retrieve data and information							■	■						
Preliminary calculations								■	■					
Developing of first temperature profile									■	■				
Proposal defence for FYP										■				
Analyzing temperature profile for further improvements										■	■			
Preparing interim report										■	■	■	■	■
Submission of interim report														■

Table 3.2: Gantt Chart for FYP 2

Activity	**Months & Weeks**													
	May			**June**				**July**				**August**		
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Develop spreadsheet model	■	■												
Visit to GDC plant to retrieve data and information		■	■											
Finding results using spreadsheet for exhaust temperature			■	■										
Finding results using spreadsheet for feedwater temperature				■	■									
Finding results using spreadsheet for ambient temperature					■	■								
Finding results using spreadsheet for different pinch and approach point						■	■							
Submission of progress report							■							
Simulation using EES								■	■	■	■	■		
Preparation for final and technical report								■	■	■	■	■	■	■
Pre-Sedex presentation										■				
Viva											■			
Submission of dissertation (softbound) and technical report												■		
Submission of dissertation (hardbound)														■

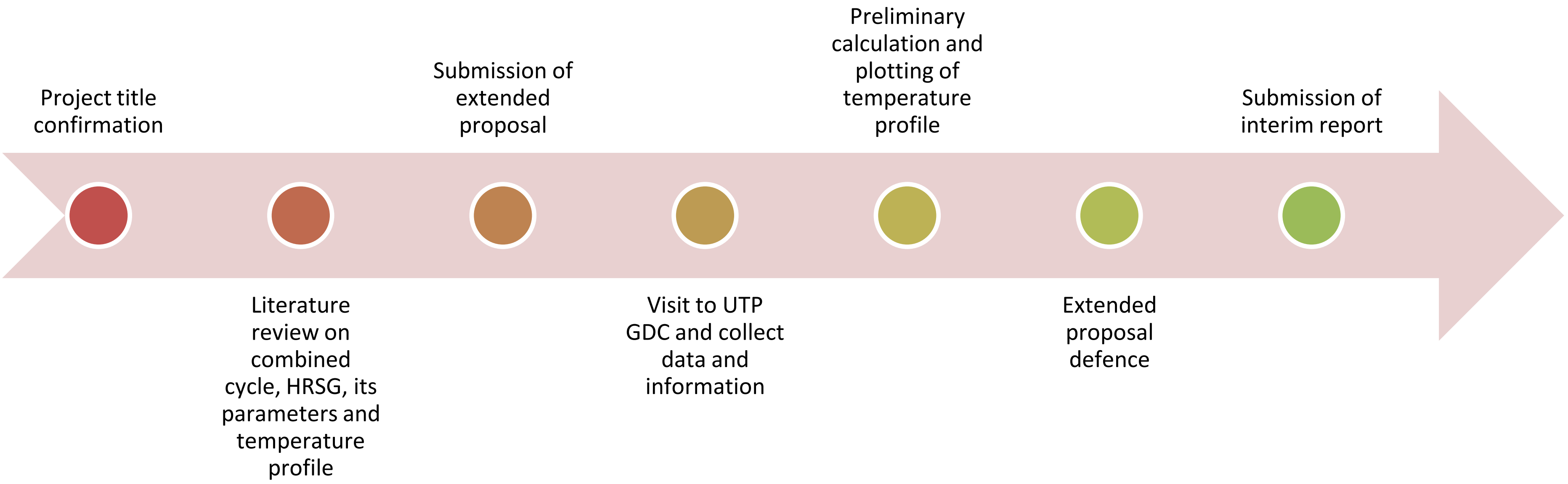

Figure 3.2: Key milestones for FYP 1

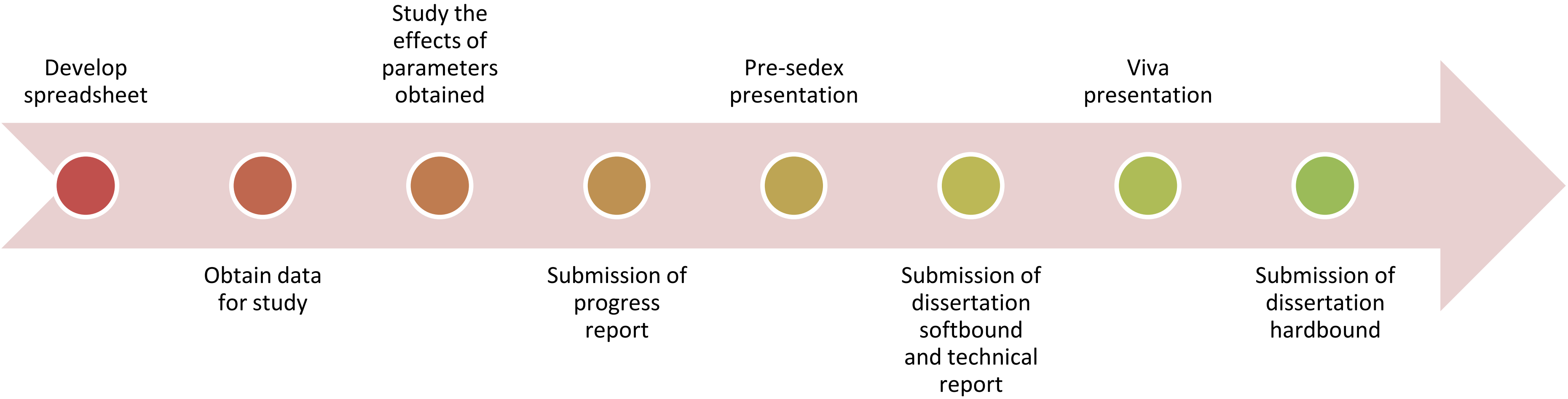

Figure 3.3: Key milestones for FYP 2

3.2 Governing Equations

In order to plot the gas/steam temperature profiles for the HRSG with a given exhaust gas temperature and steam pressure, the pinch and approach point needs to be determined first. From the pinch point and approach point, the evaporator duty can be evaluated [1]. The specific heat capacity of the gas is gotten by interpolation of the properties in various temperatures as shown in Table 3.3.

$$T_2 = T_{sat} + T_p \tag{3.1}$$

$$T_c = T_{sat} - T_a \tag{3.2}$$

$$Evaporator\ duty = \dot{m}_g \times C_{p,ev} \times \Delta T_{ev} \times heat\ loss\ factor \tag{3.3}$$

Where,

T_c = temperature of water entering the evaporator

T_2 = temperature of flue gas leaving the evaporator

T_{sat} = saturation temperature at the evaporator

T_p = pinch point

T_a = approach point

$\dot{m}_g$ = exhaust gas flow rate

$C_{p,ev}$ = average gas specific heat at evaporator

ΔT_{ev} = difference of flue gas temperature in the evaporator

Table 3.3 Specific heats of turbine exhaust gases at various temperatures [1]

Temperature (°C)	Gas Specific Heat (kJ/kg.K)
93.3	1.058892
204.4	1.081921
315.6	1.104245
426.7	1.132165
537.8	1.158962

Next, the enthalpy absorbed by the steam in the evaporator is determined [1].

$$\begin{array}{l}\textit{Enthalpy absorbed by}\\ \textit{steam in evaporator}\end{array} = (h_{ss} - h_w) + \ BDF\ (h_{sw} - h_w) \tag{3.4}$$

Where,

h_{ss} = enthalpy of saturated steam

h_w = enthalpy of water entering the evaporator

h_{sw} = enthalpy of saturated water

BDF = blowdown factor of the boiler

With the evaporator duty and the enthalpy absorbed by the steam in the evaporator known, the amount of steam generated can be calculated [1].

$$Steam\ Generated = \frac{Evaporator\ \ Duty}{Enthalpy\ \ absorbed\ \ by\ steam\ \ in\ the\ evaporator} \tag{3.5}$$

The economizer duty can be calculated by the following equation [1].

$$Economizer\ Duty = \dot{m}_s \times (1 + BDF) \times (h_w - h_{fw}) \tag{3.6}$$

Where,

$\dot{m}_s$ = steam flow rate

h_{fw} = enthalpy of feedwater entering economizer

From the economizer duty, the stack temperature of the flue gas at the inlet of the economizer can be determined [1].

$$T_3 = T_2 - \frac{Economizer\ \ Duty}{\dot{m}_g \times C_{p,ec} \times heat\ loss\ factor} \tag{3.7}$$

Where,

T_3 = the stack temperature of flue gas

$C_{p,ec}$ = average gas specific heat at economizer

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Microsoft Excel Spreadsheet

In order to study the impact of the different parameters on the HRSG, a spreadsheet was developed using Microsoft Excel. The set of equations 3.1 to 3.7 were used to develop the spreadsheet model as shown in Appendix 1 below. After the spreadsheet model was developed, the variation of several parameters was done and graphs were plotted to study the effects on the performance of the HRSG. The parameters that were varied include the pinch and approach point, exhaust gas temperature T_1, the feedwater temperature, and the ambient temperature.

4.2 Temperature Profile of HRSG in UTP GDC

The operating parameters of the HRSG in UTP GDC plant was obtained from the daily checklist done by the panel engineer at the plant. Table 4.1 below shows the average of the operating parameter for 18/02/2015.

Table 4.1: The average of the operating parameters from UTP GDC

Steam Pressure (Bar)	8.695
Exhaust Gas Temperature, T_1 (K)	791.25
Feedwater Temperature, T_d (K)	350.75
Steam Flowrate, $\dot{m}_s$ (kg/s)	2.296
Exhaust Gas Flowrate, $\dot{m}_g$ (kg/s)	20

From the operating parameters obtained from the GDC plant, the following important parameters as shown in Table 4.2 are obtained from the steam table and from recommended values taken from the literature review [1].

Table 4.2: Parameters taken from steam tables and from recommended values

Pinch Point	10
Approach Point	10
Saturation Temperature, T_{sat} (K)	446.90
Enthalpy of saturated steam, h_{ss} (kJ/kg)	2771.7
Enthalpy of saturated water, h_{sw} (kJ/kg)	736.3
Enthalpy of water entering evaporator, h_w (kJ/kg)	692.6
Enthalpy of feedwater entering economizer, h_{fw} (kJ/kg)	325.5
Blowdown Factor, BDF	0.05
Heat Loss Factor, HLF	0.99

The average specific heat of the exhaust gas is calculated by interpolation from Table 3.3 above. From it, the specific heat for the exhaust gas is calculated to be as follow as shown in Table 4.3.

Table 4.3: Average specific heat capacity of exhaust gas by interpolation [1]

Average Exhaust Gas Specific Heat at Evaporator, $C_{p,g\ ev}$ (kJ/kg . K)	1.1559
Average Exhaust Gas Specific Heat at Economizer, $C_{p,g\ ec}$ (kJ/kg . K)	1.0769

The remaining parameters are calculated using the equations mentioned in the methodology. After all parameters were calculated, the temperature profile of the HRSG can be plotted as shown in Figure 4.1 below.

$$T_2 = 446.90 + 10 = 456.90K$$

$$T_c = 446.90 - 10 = 436.90\ K$$

$$Evaporator\ duty = 20 \times 1.1559 \times (791.25 - 456.90) \times 0.99$$

$$= 7652.21\ kJ/s$$

$$\text{Enthalpy absorbed by steam in evaporator} = (2771.7 - 692.6) + 0.05\,(736.3 - 692.6)$$

$$= 2081.29\ kJ/kg$$

$$Steam\ Generated = \frac{7652.21}{2081.29} = 3.68\ kg/s$$

$$Economizer\ Duty = 3.68 \times (1 + 0.05) \times (692.6 - 325.5)$$

$$= 1417.19\ kJ/s$$

$$T_3 = 456.90 - \frac{1417.19}{20 \times 1.0769 \times 0.99} = 390.44K$$

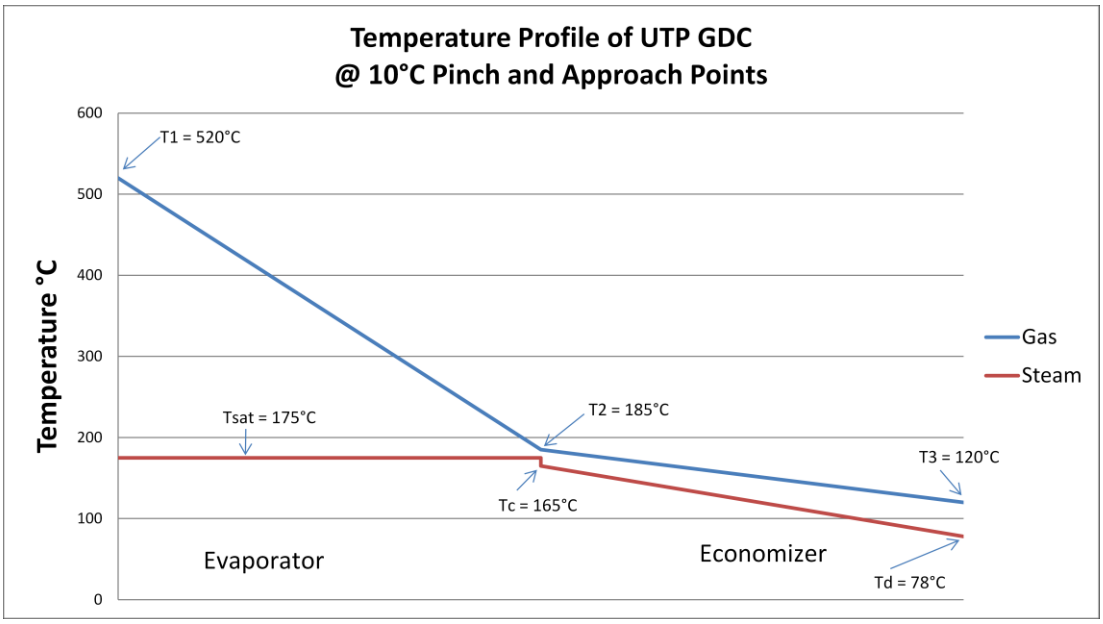

Figure 4.1: The temperature profile for the HRSG in UTP GDC plant

4.3.2 Effects of Exhaust Gas Temperature

The graphs in Figure 4.2 and Figure 4.3 below show the effects of the change in exhaust gas temperature on the amount of steam generated by the HRSG. Figure 16 shows the graph obtained from the spreadsheet while figure 17 shows the graph from EES software. From both of these graphs, it shows that the amount of steam generated increases as the exhaust gas temperature gets higher. As the exhaust gas temperature increase from 638K to 659K, the amount of steam yielded by the HRSG increase by 11%, from 2.00 kg/s to 2.22 kg/s. This finding is consistent with the finding of Ganapathy [1] where he mentioned the reason is because more heat energy is available in the higher temperature exhaust gas which leads to more heat transferred to the water and thus, more steam is generated.

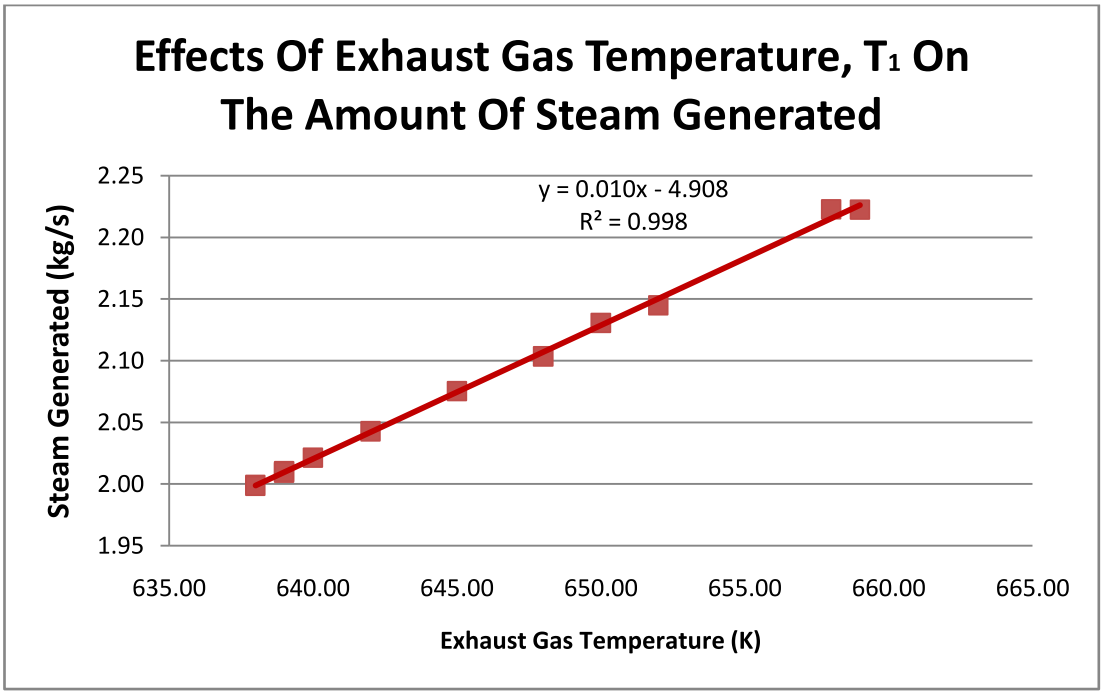

Figure 4.2: The graph of steam generated against exhaust gas temperature obtained from Microsoft Excel spreadsheet

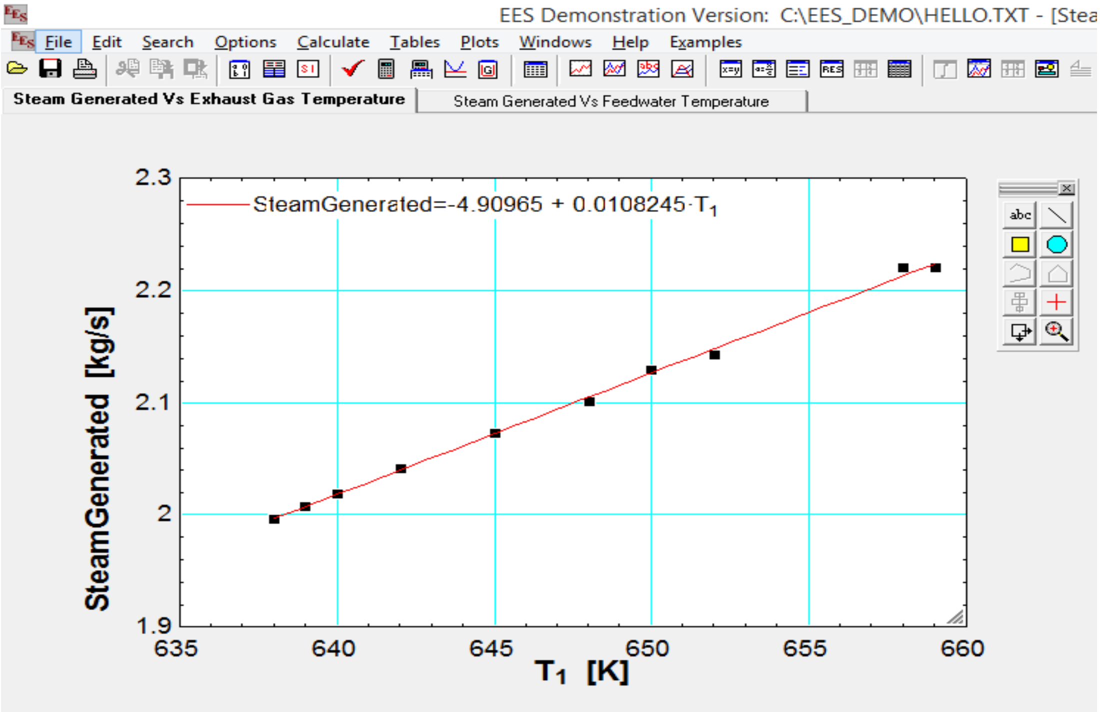

Figure 4.3: The graph of steam generated against exhaust gas temperature obtained from EES software

4.3.3 Effects of feedwater temperature

The graphs below in Figure 4.4 and Figure 4.5 below show the amount of steam generated by the HRSG at various feedwater temperatures. The steam produced by the HRSG is used in steam absorption chillers for producing chill water where the steam will condense into warm water and then recirculate back into the hotwell tank where the feedwater is kept at a temperature of 70°C to 80°C. However, from the results obtained from the experiment, it shows little to no relationship between the feedwater temperature and the amount of steam generated by the HRSG.

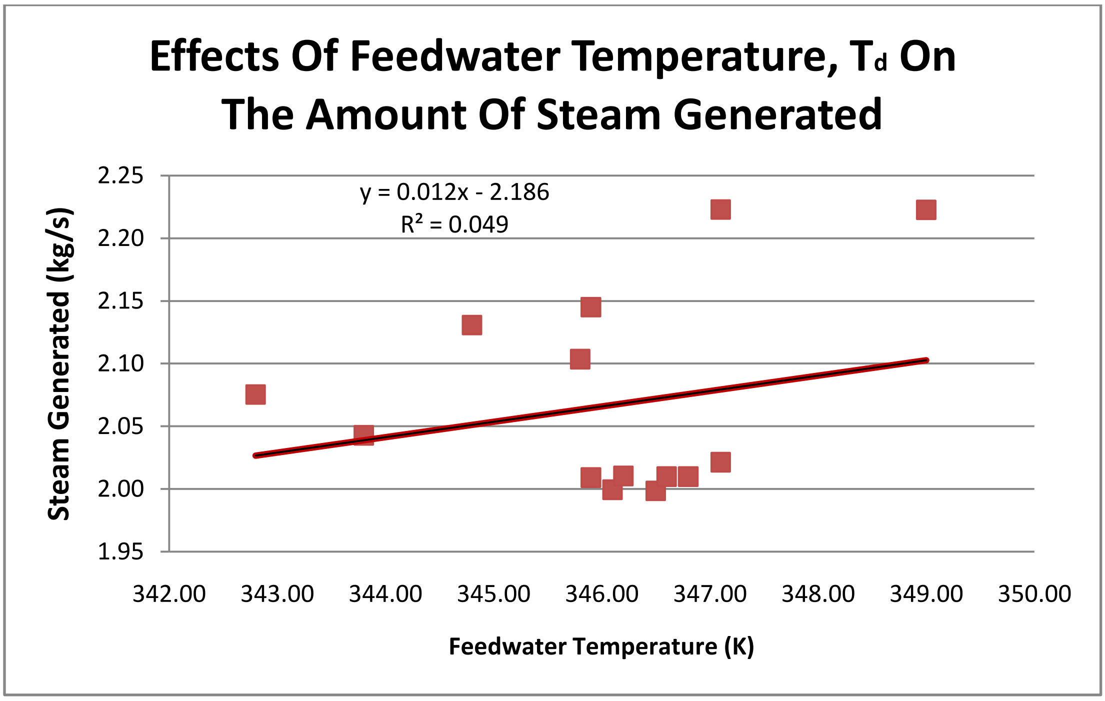

Figure 4.4: The graph of steam generated against the feedwater temperature obtained from Microsoft Excel spreadsheet

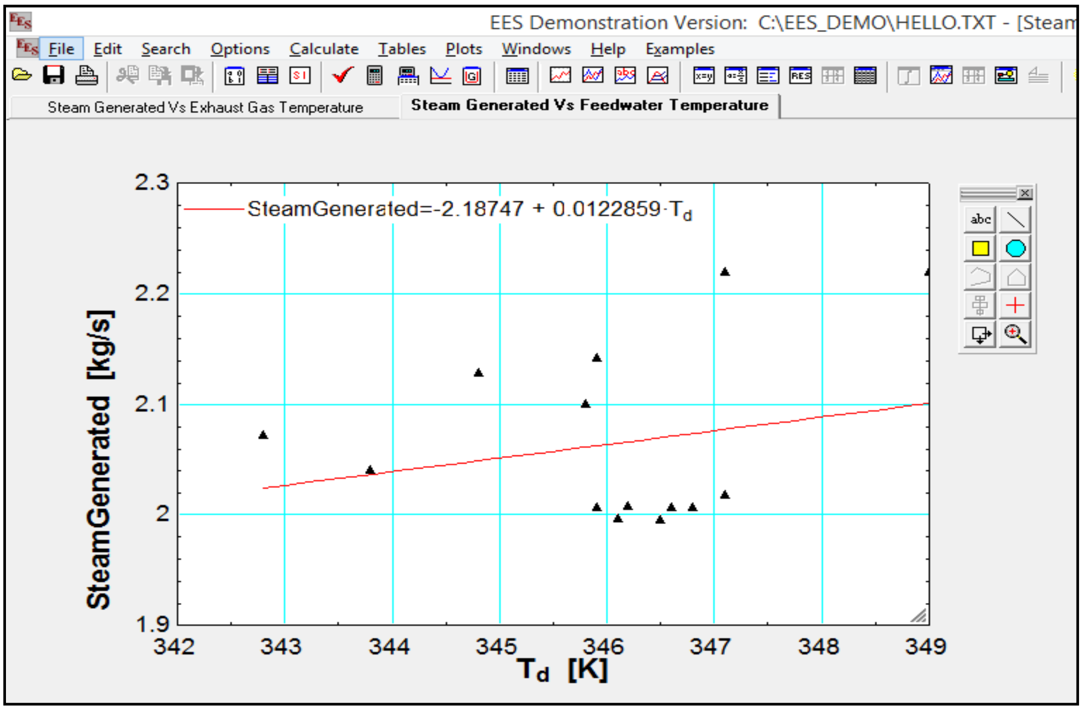

Figure 4.5: The graph of steam generated against the feedwater temperature obtained from EES software

4.3.4 Effects of Ambient Temperature

The graphs in Figure 4.6 and Figure 4.7 below show the relationship between the ambient temperature with the amount of steam generated. From the result, it shows that there is some relationship between the ambient temperature and the HRSG performance. It is observed that as the ambient temperature increases, the amount of steam generated is lesser. However, this relationship is not linear but it has the relationship of $y = 0.007x^2 - 4.664x + 712$. Looking at Appendix 5 below, it is clearly seen that in the morning and night time where the ambient temperature is lowest, the amount of steam generated is highest meanwhile in the afternoon where the ambient temperature is the highest, the amount of steam generated is the lowest. The reason behind this is explained by Ganapathy [11] and Tiwari et. al. [12] who wrote about the relationship between the ambient temperature and the exhaust gas flow and temperature. The explanation for this phenomenon is that at higher ambient temperature, the air density is lower and that affects the performance of the gas turbine which in turns affects the HRSG behind it. The result of this experiment confirms the research of the authors who stated that higher ambient temperature will cause lower gas turbine load which then affects the HRSG performance to be poorer.

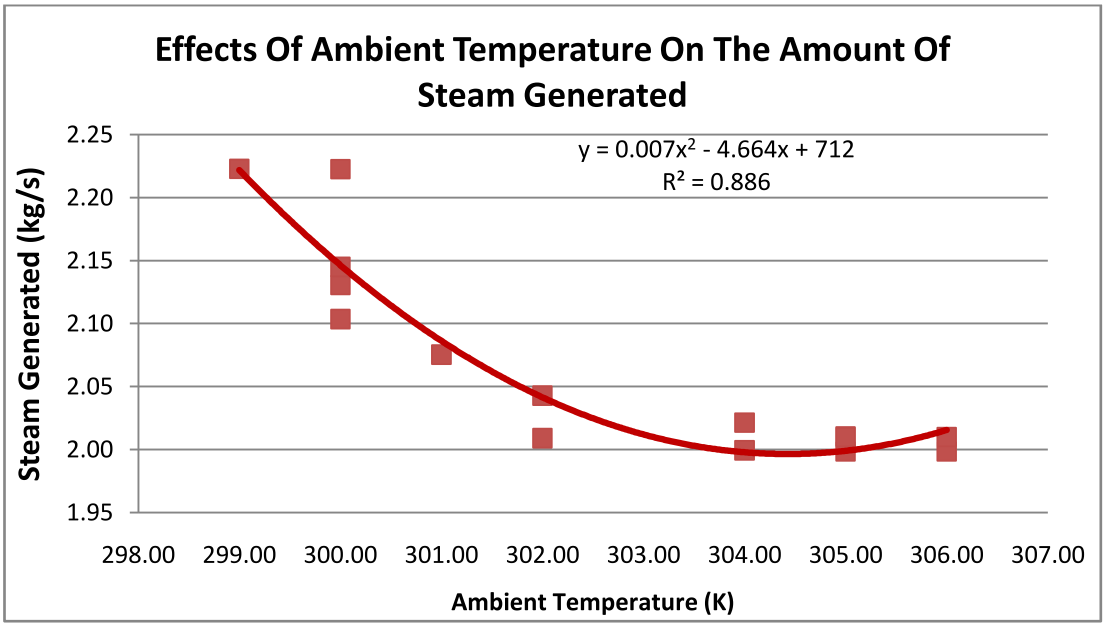

Figure 4.6: The graph of steam generated against ambient temperature obtained from Microsoft Excel spreadsheet

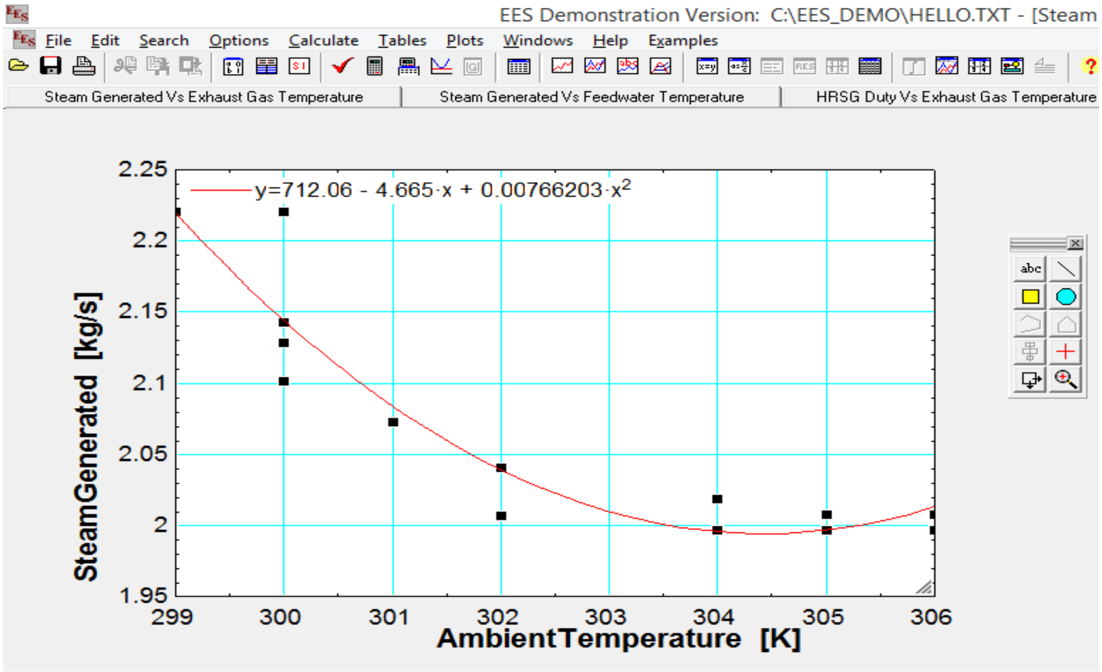

Figure 4.7: The graph of steam generated against ambient temperature obtained from EES software

4.3.5 Effects of exhaust gas temperature with 15°C pinch and approach points

The two graphs in Figure 4.8 and Figure 4.9 below show the change in the amount of steam generated by the HRSG with the exhaust gas temperature for both 10°C and 15°C pinch and approach points. From the results, it is clear that the higher the pinch and approach point, the lesser amount of steam is generated. The amount of steam generated decreased by 3.74% when the pinch and approach point is increased by 5°C from 10°C to 15°C. This shows that the HRSG is performing better at lower pinch and approach point which is supported by Ganapathy and the other authors in the literature review. The reason is because when the pinch and approach point is designed to be lower, more heat is recovered from the exhaust gas to heat up the water into steam. Also in the graph, the actual amount of steam that is being generated at the UTP GDC plant is plotted with the EES software. The EES model was used to estimate the pinch and approach point of the current HRSG used in the UTP GDC plant and it is found to be 55K which is very high. Therefore, the amount of steam generated by the HRSG is very low compared to the simulated amount. If the pinch and approach point is designed to the recommended range of 10K – 15K, the amount of steam generated could have been almost doubled from what is being produced now. HRSG that is designed with high pinch and approach point is not fully utilizing the high amount of heat energy that comes from the gas turbine.

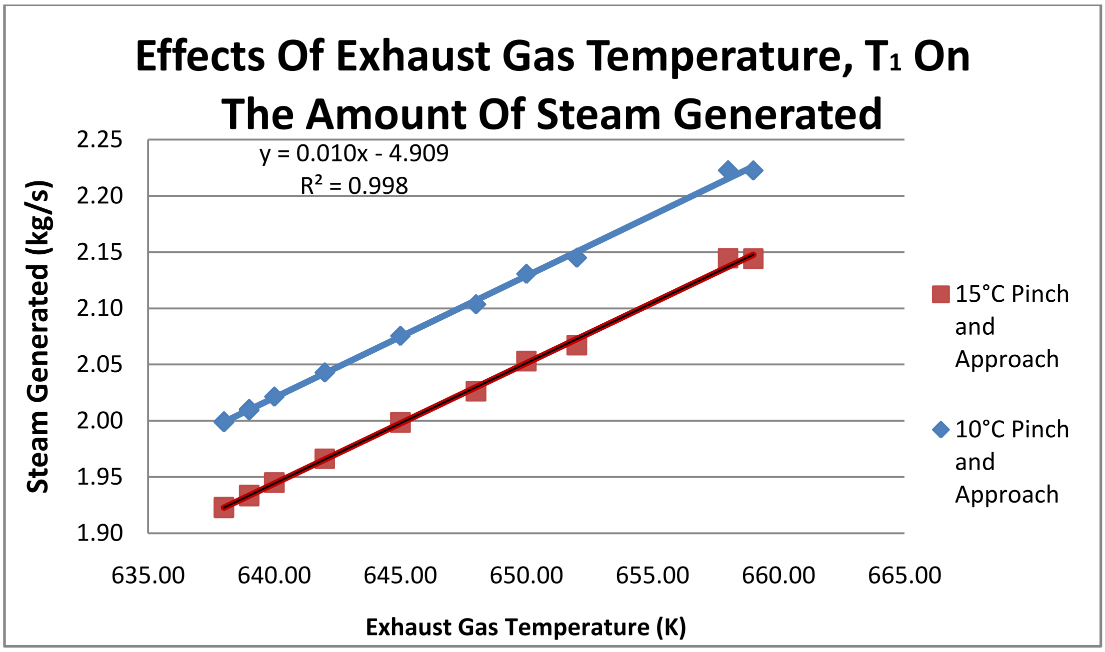

Figure 4.8: The effects of different pinch and approach point on the amount of steam generated by the HRSG obtained from Microsoft Excel spreadsheet

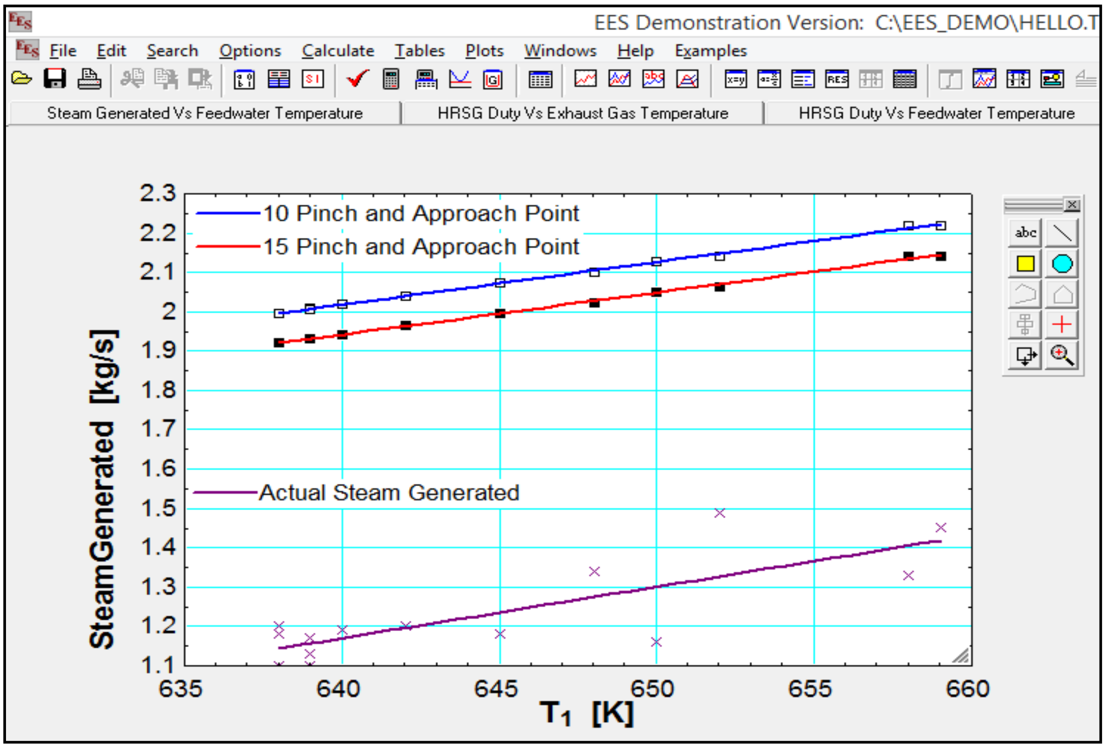

Figure 4.9: The effects of different pinch point and approach point on the amount of steam generated by the HRSG obtained from EES software

CHAPTER 5

CONCLUSION AND RECOMMENDATION

This study was carried out to study the parameters that could affect the steam generation of a HRSG and the parameters that were studied are the exhaust gas temperature entering the HRSG, the feedwater temperature entering the HRSG, the ambient temperature of the surrounding, and the pinch and approach point. These parameters were analyzed with a Microsoft Excel spreadsheet and graphs were plotted to show the relationship between the parameters and the amount of steam generated. Besides that, a mathematical model was created using EES software to do a parametric study on the steam generation of HRSG. From the results, the increase in exhaust gas temperature entering the HRSG will cause more steam to be produced. No relationship was found between the feedwater temperature and the amount of steam generated. The higher the ambient temperature, the lesser steam will be produced. Lower pinch and approach point will yield more steam. This model can be used to evaluate the performance of HRSG and to improve the amount of steam generated by HRSG.

For further research purposes, a few recommendations can be used to improve the experiment such as to study the effects of multi-pressure HRSG with single pressure HRSG, the different arrangement of the components of the HRSG, or the difference in performance of water tube HRSG and fire tube HRSG. All these factors are also important but were unable to be included in this study because of the limited scope of study. It is also recommended that the study be done over a longer period of time such as weeks or months. Due to constraints, this research was only done with one day data which may not be sufficient enough. Further research can also be extended to the study of gas turbines which may affect the performance of HRSG significantly because it drives the HRSG and also to steam absorption chillers where the steam produced by the HRSG may be used to produce chilled water for air conditioning.

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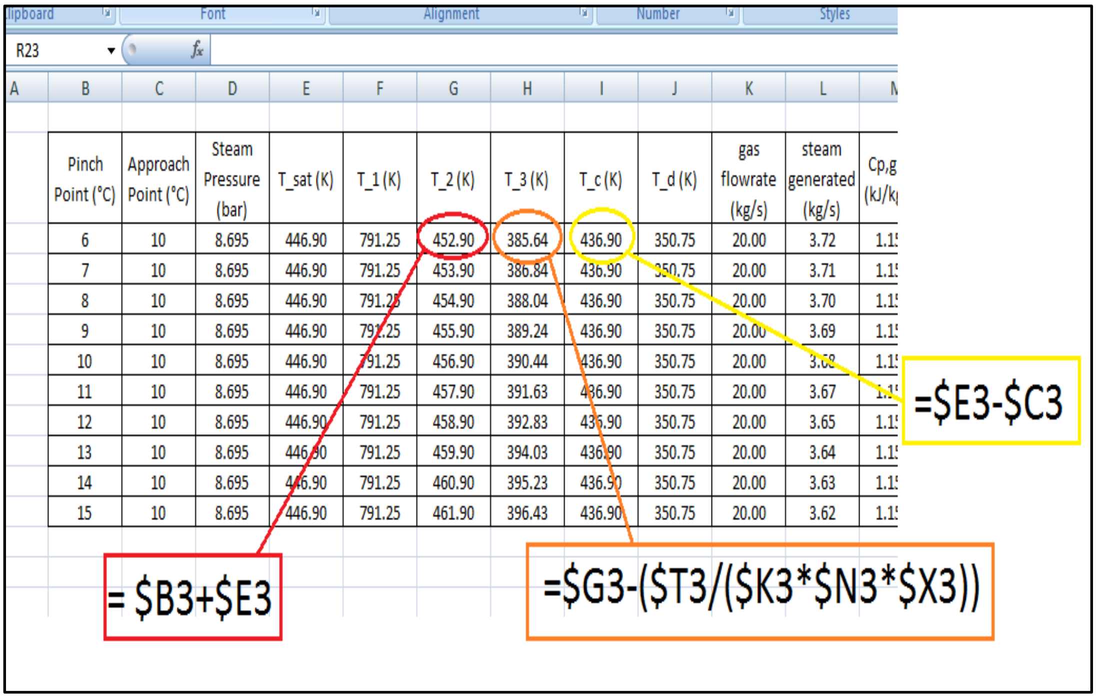
APPENDICES

Appendix 1

Spreadsheet model that was developed with Microsoft Excel

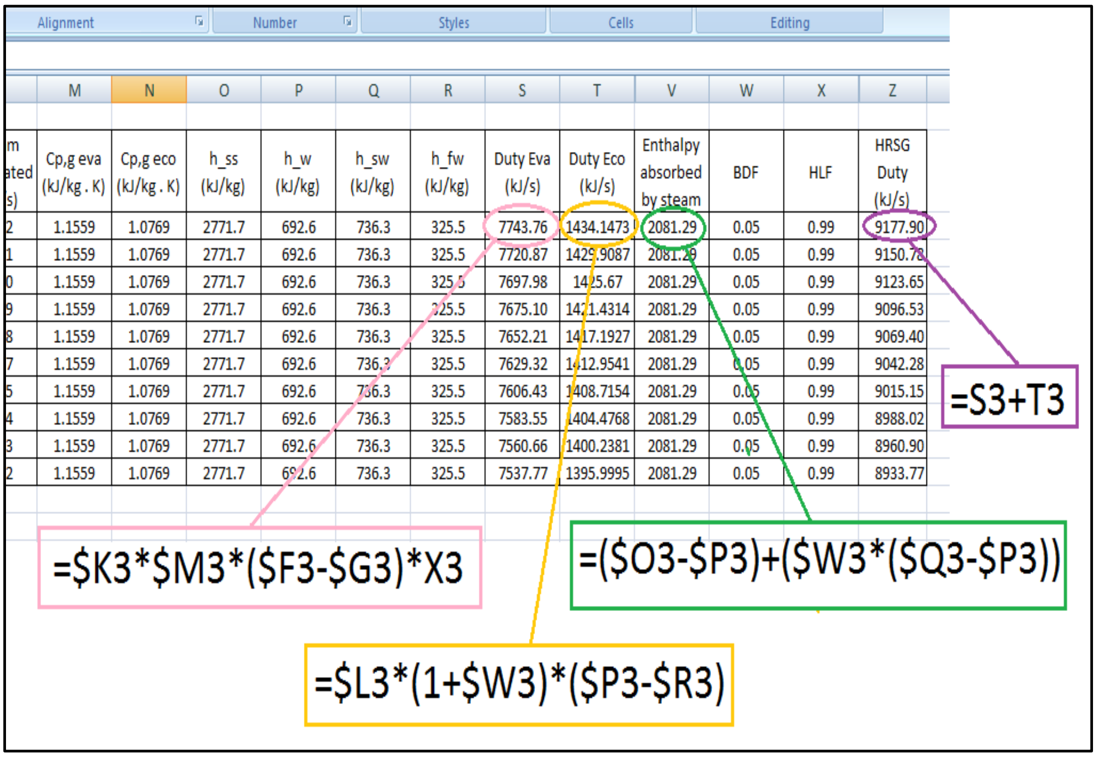


Pinch Point (°C)	Approach Point (°C)	Steam Pressure (bar)	T_sat (K)	T_1 (K)	T_2 (K)	T_3 (K)	T_c (K)	T_d (K)	gas flowrate (kg/s)	steam generated (kg/s)	Cp,g (kJ/k
6	10	8.695	446.90	791.25	452.90	385.64	436.90	350.75	20.00	3.72	1.1
7	10	8.695	446.90	791.25	453.90	386.84	436.90	350.75	20.00	3.71	1.1
8	10	8.695	446.90	791.25	454.90	388.04	436.90	350.75	20.00	3.70	1.1
9	10	8.695	446.90	791.25	455.90	389.24	436.90	350.75	20.00	3.69	1.1
10	10	8.695	446.90	791.25	456.90	390.44	436.90	350.75	20.00	3.68	1.1
11	10	8.695	446.90	791.25	457.90	391.63	436.90	350.75	20.00	3.67	1.1
12	10	8.695	446.90	791.25	458.90	392.83	436.90	350.75	20.00	3.65	1.1
13	10	8.695	446.90	791.25	459.90	394.03	436.90	350.75	20.00	3.64	1.1
14	10	8.695	446.90	791.25	460.90	395.23	436.90	350.75	20.00	3.63	1.1
15	10	8.695	446.90	791.25	461.90	396.43	436.90	350.75	20.00	3.62	1.1

=$E3-$C3

= $B3+$E3

=$G3-($T3/($K3*$N3*$X3))



m ated s)	Cp,g eva (kJ/kg . K)	Cp,g eco (kJ/kg . K)	h_ss (kJ/kg)	h_w (kJ/kg)	h_sw (kJ/kg)	h_fw (kJ/kg)	Duty Eva (kJ/s)	Duty Eco (kJ/s)	Enthalpy absorbed by steam	BDF	HLF	HRSG Duty (kJ/s)
2	1.1559	1.0769	2771.7	692.6	736.3	325.5	7743.76	1434.1473	2081.29	0.05	0.99	9177.90
1	1.1559	1.0769	2771.7	692.6	736.3	325.5	7720.87	1429.9087	2081.29	0.05	0.99	9150.78
0	1.1559	1.0769	2771.7	692.6	736.3	325.5	7697.98	1425.67	2081.29	0.05	0.99	9123.65
9	1.1559	1.0769	2771.7	692.6	736.3	325.5	7675.10	1421.4314	2081.29	0.05	0.99	9096.53
8	1.1559	1.0769	2771.7	692.6	736.3	325.5	7652.21	1417.1927	2081.29	0.05	0.99	9069.40
7	1.1559	1.0769	2771.7	692.6	736.3	325.5	7629.32	1412.9541	2081.29	0.05	0.99	9042.28
5	1.1559	1.0769	2771.7	692.6	736.3	325.5	7606.43	1408.7154	2081.29	0.05	0.99	9015.15
4	1.1559	1.0769	2771.7	692.6	736.3	325.5	7583.55	1404.4768	2081.29	0.05	0.99	8988.02
3	1.1559	1.0769	2771.7	692.6	736.3	325.5	7560.66	1400.2381	2081.29	0.05	0.99	8960.90
2	1.1559	1.0769	2771.7	692.6	736.3	325.5	7537.77	1395.9995	2081.29	0.05	0.99	8933.77

=$S3+T3

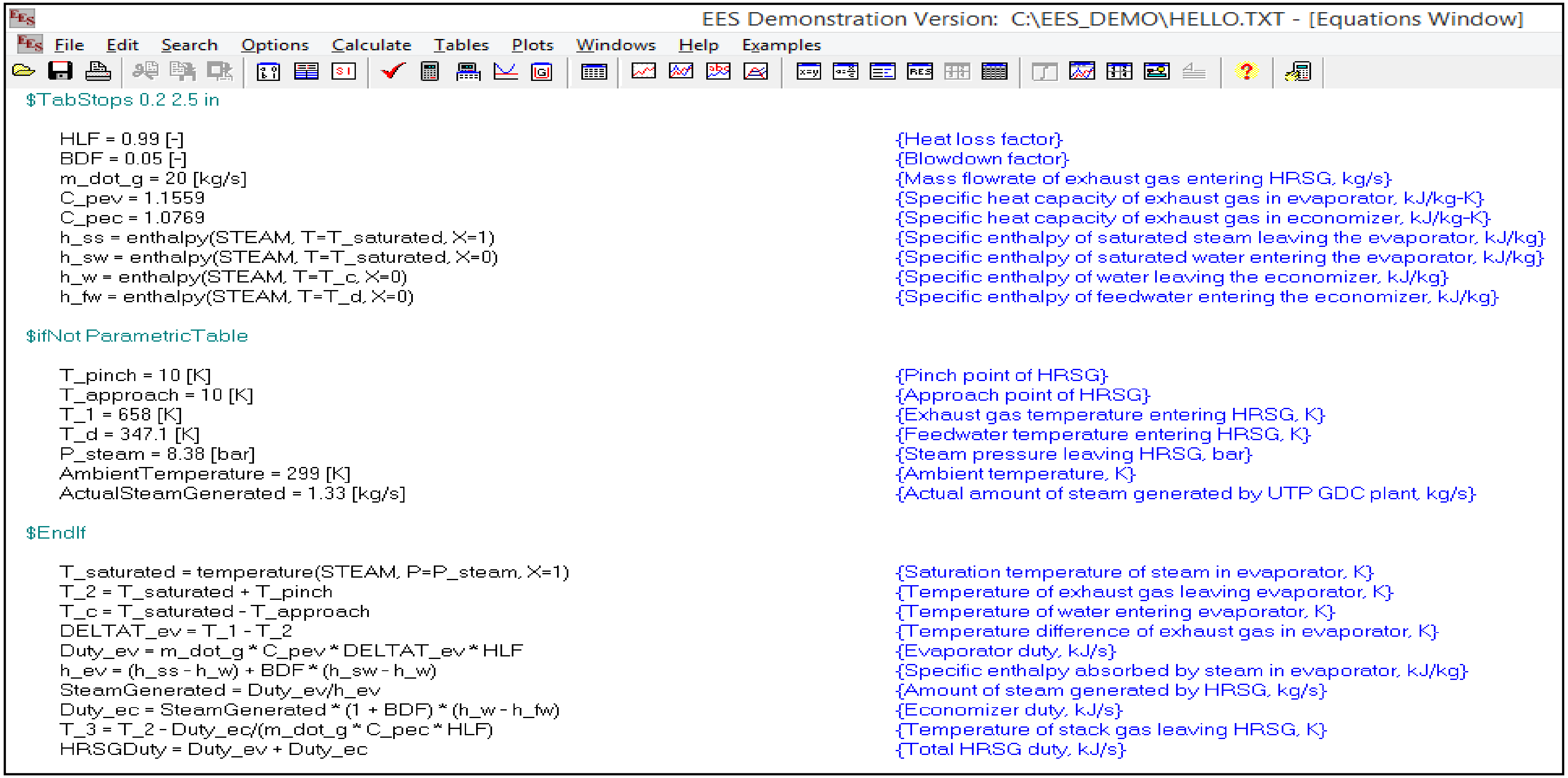
=$K3*$M3*($F3-$G3)*X3

=($O3-$P3)+($W3*($Q3-$P3))

=$L3*(1+$W3)*($P3-$R3)

Appendix 2

Mathematical model written in EES software



```
$TabStops 0.2 2.5 in

    HLF = 0.99 [-]                                            {Heat loss factor}
    BDF = 0.05 [-]                                            {Blowdown factor}
    m_dot_g = 20 [kg/s]                                       {Mass flowrate of exhaust gas entering HRSG, kg/s}
    C_pev = 1.1559                                            {Specific heat capacity of exhaust gas in evaporator, kJ/kg-K}
    C_pec = 1.0769                                            {Specific heat capacity of exhaust gas in economizer, kJ/kg-K}
    h_ss = enthalpy(STEAM, T=T_saturated, X=1)                {Specific enthalpy of saturated steam leaving the evaporator, kJ/kg}
    h_sw = enthalpy(STEAM, T=T_saturated, X=0)                {Specific enthalpy of saturated water entering the evaporator, kJ/kg}
    h_w = enthalpy(STEAM, T=T_c, X=0)                         {Specific enthalpy of water leaving the economizer, kJ/kg}
    h_fw = enthalpy(STEAM, T=T_d, X=0)                        {Specific enthalpy of feedwater entering the economizer, kJ/kg}

$ifNot ParametricTable

    T_pinch = 10 [K]                                          {Pinch point of HRSG}
    T_approach = 10 [K]                                       {Approach point of HRSG}
    T_1 = 658 [K]                                             {Exhaust gas temperature entering HRSG, K}
    T_d = 347.1 [K]                                           {Feedwater temperature entering HRSG, K}
    P_steam = 8.38 [bar]                                      {Steam pressure leaving HRSG, bar}
    AmbientTemperature = 299 [K]                              {Ambient temperature, K}
    ActualSteamGenerated = 1.33 [kg/s]                        {Actual amount of steam generated by UTP GDC plant, kg/s}

$EndIf

    T_saturated = temperature(STEAM, P=P_steam, X=1)          {Saturation temperature of steam in evaporator, K}
    T_2 = T_saturated + T_pinch                               {Temperature of exhaust gas leaving evaporator, K}
    T_c = T_saturated - T_approach                            {Temperature of water entering evaporator, K}
    DELTAT_ev = T_1 - T_2                                     {Temperature difference of exhaust gas in evaporator, K}
    Duty_ev = m_dot_g * C_pev * DELTAT_ev * HLF               {Evaporator duty, kJ/s}
    h_ev = (h_ss - h_w) + BDF * (h_sw - h_w)                  {Specific enthalpy absorbed by steam in evaporator, kJ/kg}
    SteamGenerated = Duty_ev/h_ev                             {Amount of steam generated by HRSG, kg/s}
    Duty_ec = SteamGenerated * (1 + BDF) * (h_w - h_fw)       {Economizer duty, kJ/s}
    T_3 = T_2 - Duty_ec/(m_dot_g * C_pec * HLF)               {Temperature of stack gas leaving HRSG, K}
    HRSGDuty = Duty_ev + Duty_ec                              {Total HRSG duty, kJ/s}
```

Appendix 3

The results obtained from UTP GDC plant on 10th of June 2015 when pinch and approach point are set to 10°C

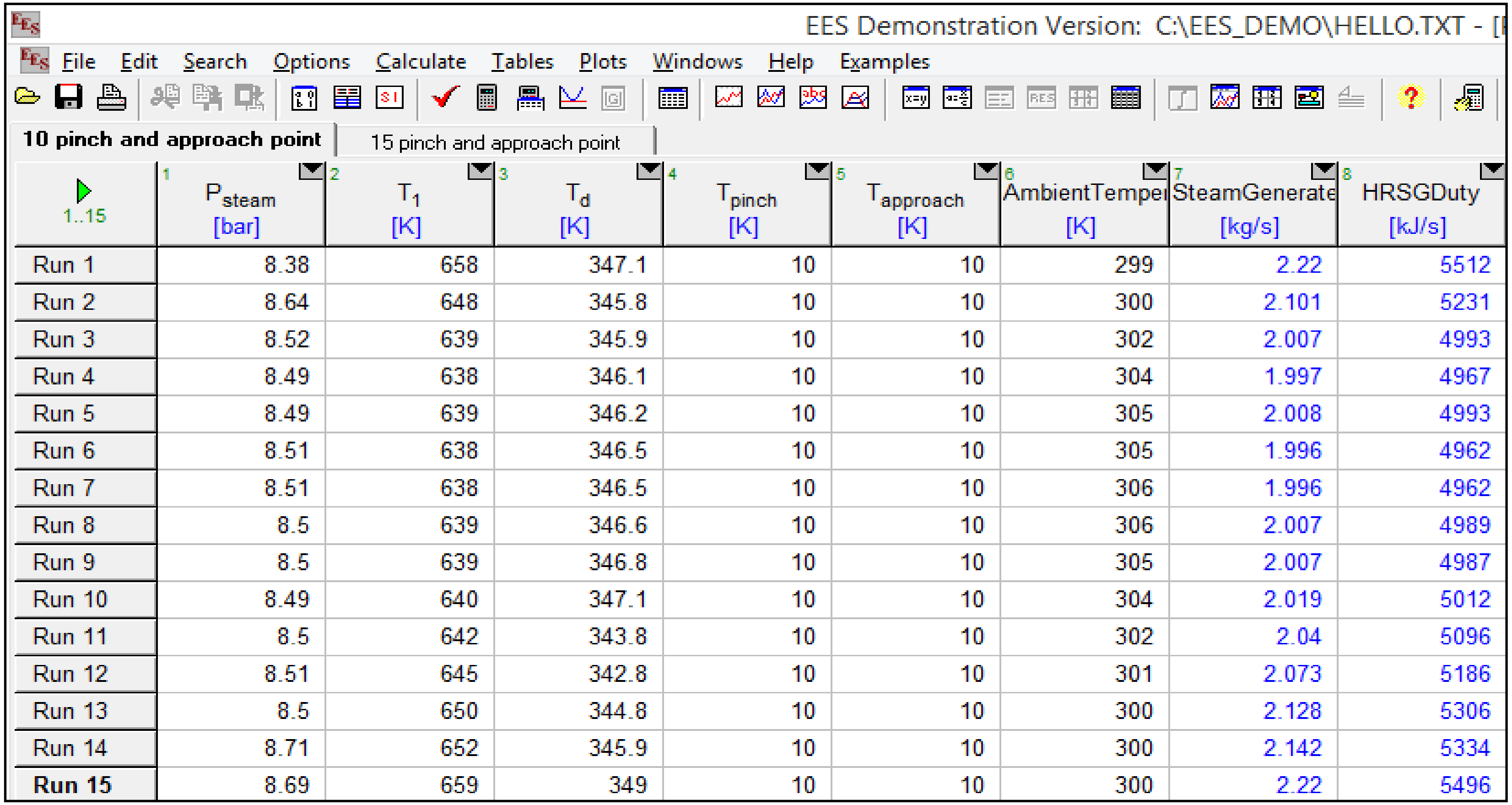
Time	Pinch Point (°C)	Approach Point (°C)	Steam Pressure* (bar)	T_sat (K)	T_1* (K)	T_2 (K)	T_3 (K)	T_c (K)	T_d* (K)	steam generated (kg/s)	Enthalpy absorbed by steam (kJ/s)	HRSG Duty (kJ/s)	Ambient Temperature* (°C)
0800	10	10	8.38	445.35	658.00	455.35	414.24	435.35	347.10	2.22	2086.59	5514.63	26
0900	10	10	8.64	446.63	648.00	456.63	416.58	436.63	345.80	2.10	2082.19	5233.72	27
1000	10	10	8.52	446.04	639.00	456.04	418.09	436.04	345.90	2.01	2084.29	4996.57	29
1100	10	10	8.49	445.89	638.00	455.89	418.26	435.89	346.10	2.00	2084.69	4970.26	31
1200	10	10	8.49	445.89	639.00	455.89	418.09	435.89	346.20	2.01	2084.69	4996.71	32
1300	10	10	8.51	445.99	638.00	455.99	418.50	435.99	346.50	2.00	2084.39	4964.92	32
1400	10	10	8.51	445.99	638.00	455.99	418.50	435.99	346.50	2.00	2084.39	4964.92	33
1500	10	10	8.50	445.94	639.00	455.94	418.30	435.94	346.60	2.01	2084.59	4992.22	33
1600	10	10	8.50	445.94	639.00	455.94	418.38	435.94	346.80	2.01	2084.59	4990.53	32
1700	10	10	8.49	445.89	640.00	455.89	418.27	435.89	347.10	2.02	2084.69	5015.93	31
1800	10	10	8.50	445.94	642.00	455.94	416.51	435.94	343.80	2.04	2084.59	5099.12	29
1900	10	10	8.51	445.99	645.00	455.99	415.48	435.99	342.80	2.08	2084.39	5189.64	28
2000	10	10	8.50	445.94	650.00	455.94	415.25	435.94	344.80	2.13	2084.59	5308.98	27
2100	10	10	8.71	446.97	652.00	456.97	416.02	436.97	345.90	2.14	2080.99	5336.79	27
2200	10	10	8.69	446.87	659.00	456.87	415.91	436.87	349.00	2.22	2081.39	5499.40	27

T_sat	Saturation temperature of steam	T_3	Stack gas temperature leaving economizer
T_1	Exhaust gas temperature entering evaporator	T_c	Temperature of water entering the evaporator
T_2	Exhaust gas temperature leaving evaporator	T_d	Temperature of feedwater entering the economizer

*Actual data collected

Appendix 4

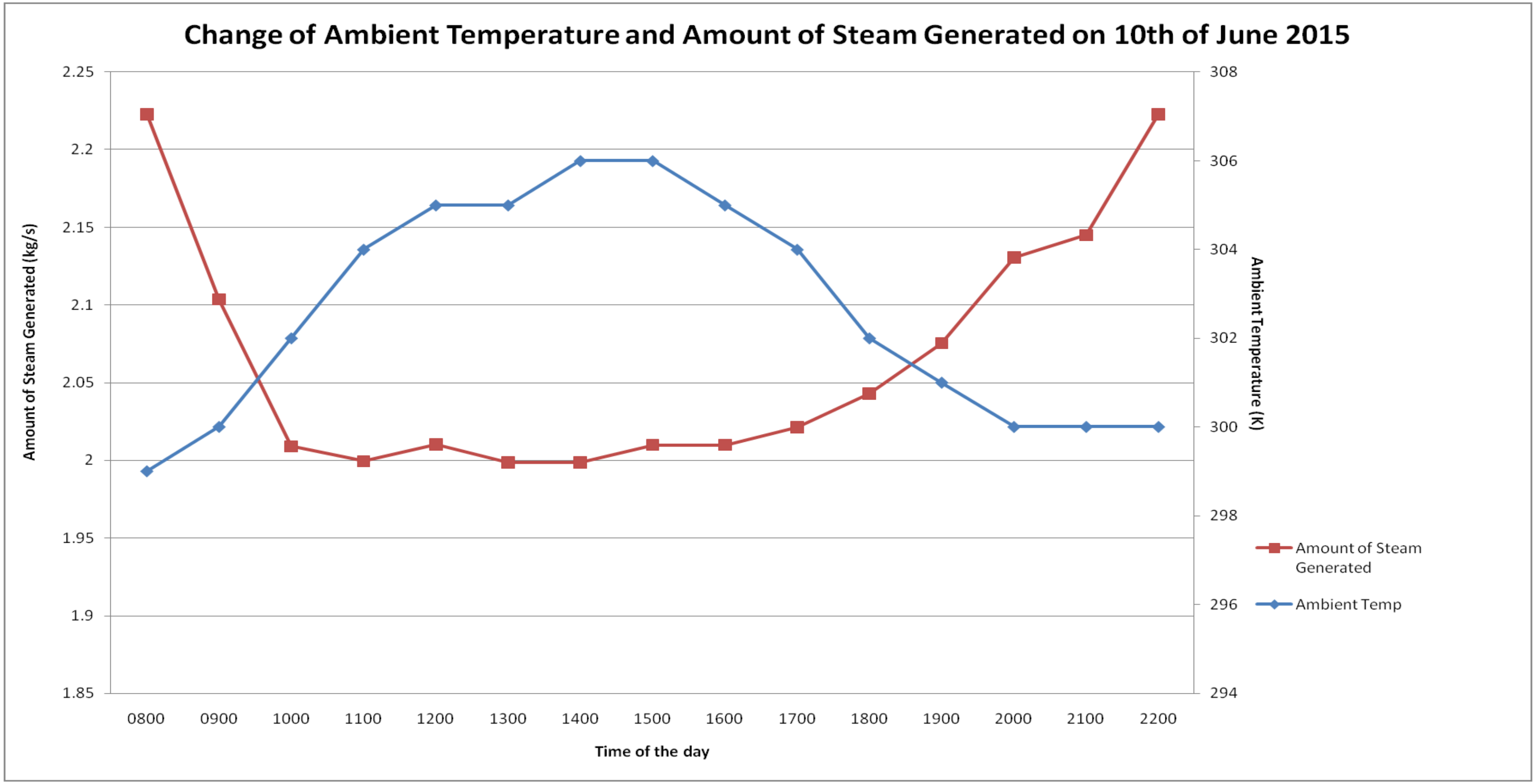
The parametric table from EES software used to solve for the data collected from UTP GDC plant on 10th of June when pinch and approach are set to 10 K



1..15	1 P_{steam} [bar]	2 T_1 [K]	3 T_d [K]	4 T_{pinch} [K]	5 $T_{approach}$ [K]	6 AmbientTemper [K]	7 SteamGenerate [kg/s]	8 HRSGDuty [kJ/s]
Run 1	8.38	658	347.1	10	10	299	2.22	5512
Run 2	8.64	648	345.8	10	10	300	2.101	5231
Run 3	8.52	639	345.9	10	10	302	2.007	4993
Run 4	8.49	638	346.1	10	10	304	1.997	4967
Run 5	8.49	639	346.2	10	10	305	2.008	4993
Run 6	8.51	638	346.5	10	10	305	1.996	4962
Run 7	8.51	638	346.5	10	10	306	1.996	4962
Run 8	8.5	639	346.6	10	10	306	2.007	4989
Run 9	8.5	639	346.8	10	10	305	2.007	4987
Run 10	8.49	640	347.1	10	10	304	2.019	5012
Run 11	8.5	642	343.8	10	10	302	2.04	5096
Run 12	8.51	645	342.8	10	10	301	2.073	5186
Run 13	8.5	650	344.8	10	10	300	2.128	5306
Run 14	8.71	652	345.9	10	10	300	2.142	5334
Run 15	8.69	659	349	10	10	300	2.22	5496

Appendix 5

The hourly ambient temperature and the amount of steam generated during the operation hours of the HRSG on 10th of June 2015



Appendix 6

The results obtained from UTP GDC plant on 10th of June 2015 when pinch and approach point are set to 15°C

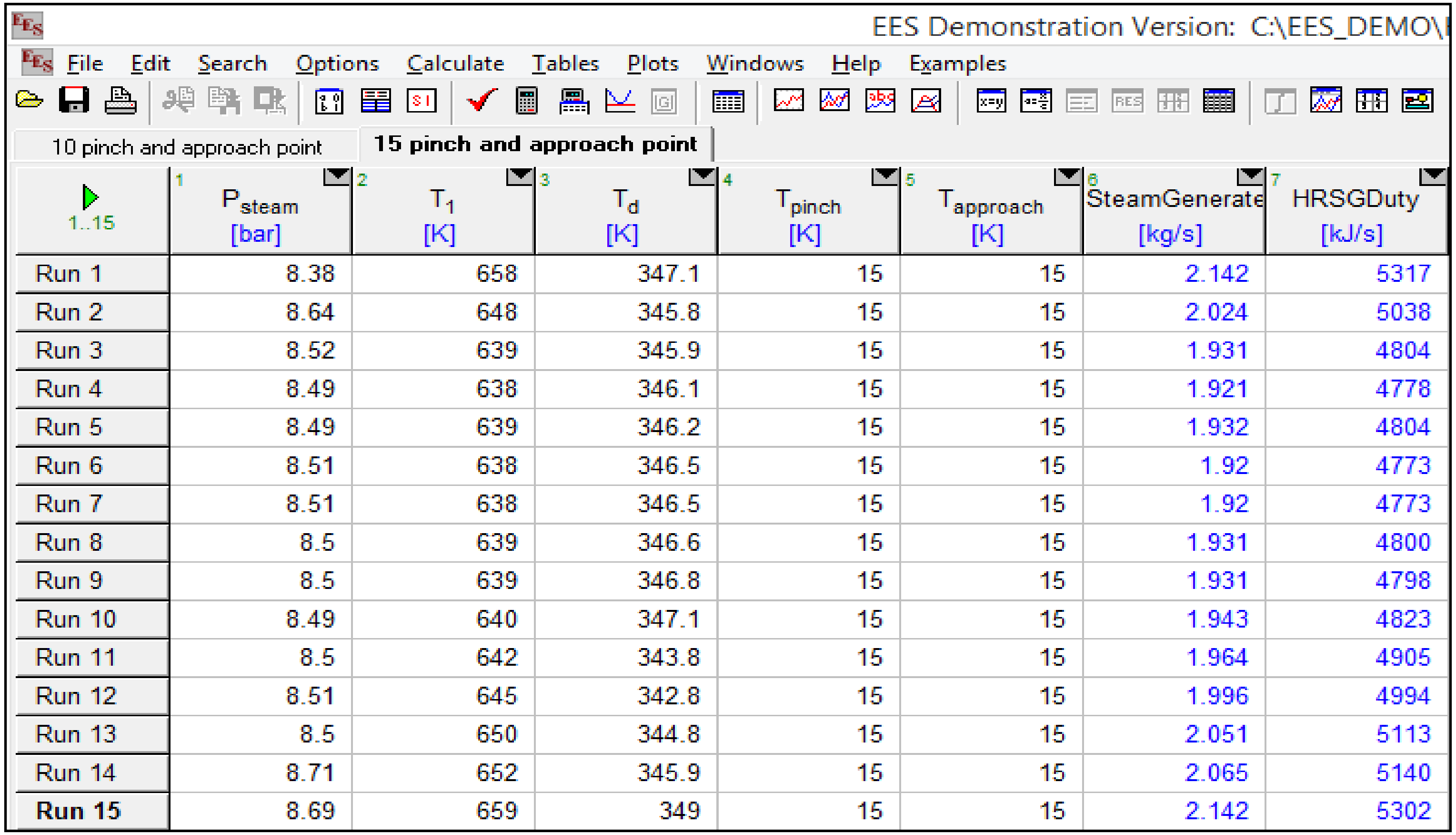
Time	Pinch Point (°C)	Approach Point (°C)	Steam Pressure* (bar)	T_sat (K)	T_1* (K)	T_2 (K)	T_3 (K)	T_c (K)	T_d* (K)	gas flowrate (kg/s)	steam generated (kg/s)	HRSG Duty (kJ/s)	Ambient Temperature* (°C)
0800	15	15	8.38	445.35	658.00	460.35	422.98	430.35	347.10	20.00	2.14	5320.47	26
0900	15	15	8.64	446.63	648.00	461.63	425.23	431.63	345.80	20.00	2.03	5041.55	27
1000	15	15	8.52	446.04	639.00	461.04	426.59	431.04	345.90	20.00	1.93	4807.46	29
1100	15	15	8.49	445.89	638.00	460.89	426.76	430.89	346.10	20.00	1.92	4781.30	31
1200	15	15	8.49	445.89	639.00	460.89	426.60	430.89	346.20	20.00	1.93	4807.48	32
1300	15	15	8.51	445.99	638.00	460.99	426.99	430.99	346.50	20.00	1.92	4776.08	32
1400	15	15	8.51	445.99	638.00	460.99	426.99	430.99	346.50	20.00	1.92	4776.08	33
1500	15	15	8.50	445.94	639.00	460.94	426.80	430.94	346.60	20.00	1.93	4803.12	33
1600	15	15	8.50	445.94	639.00	460.94	426.88	430.94	346.80	20.00	1.93	4801.50	32
1700	15	15	8.49	445.89	640.00	460.89	426.77	430.89	347.10	20.00	1.95	4826.71	31
1800	15	15	8.50	445.94	642.00	460.94	425.09	430.94	343.80	20.00	1.97	4908.20	29
1900	15	15	8.51	445.99	645.00	460.99	424.12	430.99	342.80	20.00	2.00	4997.48	28
2000	15	15	8.50	445.94	650.00	460.94	423.94	430.94	344.80	20.00	2.05	5116.01	27
2100	15	15	8.71	446.97	652.00	461.97	424.72	431.97	345.90	20.00	2.07	5143.40	27
2200	15	15	8.69	446.87	659.00	461.87	424.65	431.87	349.00	20.00	2.14	5305.28	27

T_sat	Saturation temperature of steam	T_3	Stack gas temperature leaving economizer
T_1	Exhaust gas temperature entering evaporator	T_c	Temperature of water entering the evaporator
T_2	Exhaust gas temperature leaving evaporator	T_d	Temperature of feedwater entering the economizer

*Actual data collected

Appendix 7

The parametric table from EES software used to solve for the data collected from UTP GDC plant on 10th of June when pinch and approach are set to 15 K



1..15	1 P_{steam} [bar]	2 T_1 [K]	3 T_d [K]	4 T_{pinch} [K]	5 $T_{approach}$ [K]	6 SteamGenerate [kg/s]	7 HRSGDuty [kJ/s]
Run 1	8.38	658	347.1	15	15	2.142	5317
Run 2	8.64	648	345.8	15	15	2.024	5038
Run 3	8.52	639	345.9	15	15	1.931	4804
Run 4	8.49	638	346.1	15	15	1.921	4778
Run 5	8.49	639	346.2	15	15	1.932	4804
Run 6	8.51	638	346.5	15	15	1.92	4773
Run 7	8.51	638	346.5	15	15	1.92	4773
Run 8	8.5	639	346.6	15	15	1.931	4800
Run 9	8.5	639	346.8	15	15	1.931	4798
Run 10	8.49	640	347.1	15	15	1.943	4823
Run 11	8.5	642	343.8	15	15	1.964	4905
Run 12	8.51	645	342.8	15	15	1.996	4994
Run 13	8.5	650	344.8	15	15	2.051	5113
Run 14	8.71	652	345.9	15	15	2.065	5140
Run 15	8.69	659	349	15	15	2.142	5302