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Parametric study on the effects of pinch and approach points on heat recovery steam generator performance at a district cooling system

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ABSTRACT

Heat recovery steam generators are important equipment at district cooling plants. The capability of heat recovery steam generators in generating steam influences the steam absorption chiller's performance. The steam generation capability of the heat recovery steam generators in turn is linked to the values of pinch point and approach point. Hence, a study on the pinch point and approach point for the heat recovery steam generators would be useful in understanding the effects of varying pinch point and approach point values to the heat recovery steam generators' performance. In relation to this subject, a parametric study on the heat recovery steam generators was done. The study covered the effects of the pinch point and approach point on the following: mass flow rate of steam generated; exhaust heat temperature leaving the heat recovery steam generators; and the efficiencies of the heat recovery steam generators. The first law of thermodynamics was used for the analysis. Four scenarios were covered in the study: the effects of the pinch point and approach point on steam generation; the effects of the pinch point and approach point on the exhaust heat temperature leaving the heat recovery steam generators; the effects of the pinch point and approach point on the efficiency of the heat recovery steam generators; and the effects of the exhaust heat temperature of the gas turbine on the mass flow rate of steam. Operating data at Universiti Teknologi PETRONAS gas district cooling plant were used to validate the model. The results from the first scenario indicated that higher pinch point and approach point led to a decrease in the steam being generated. For the second scenario, the increase in pinch point and approach point resulted in higher exhaust heat temperature leaving the heat recovery steam generators. Meanwhile, for the third scenario, it was noted that there was only a minimal variation of the efficiency of the heat recovery steam generator when the pinch point and approach point were increased. The findings of the fourth scenario indicated that with higher gas turbine exhaust heat temperatures, there was an increase in steam being generated. Therefore, the findings could be useful for the plant to set the operating parameters for operating heat recovery steam generators.

Keywords: Approach point; efficiency; heat recovery steam generator; pinch point.

INTRODUCTION

Heat Recovery Steam Generator (HRSG) is normally installed at district cooling plants. At the district cooling plant, the HRSG is coupled with an absorption chiller to generate chilled water for cooling purposes. The HRSG generates steam using the Gas Turbine

(GT) exhaust heat. The steam is used by the Steam Absorption Chiller (SAC) to generate chilled water. Performance of HRSG affects the overall performance of the district cooling plant [1]. Many studies on the performance of HRSG have been undertaken [2-7]. Hongcung et al. [8] modeled a comprehensive algorithm modeling of a multi-pressure HRSG based on the heat exchangers layout. They developed a general model and analyzed the thermodynamic performance of three different heat exchangers layout to find the mass flow rates of steam and the heat efficiency. Hussam and Alexander [9] proposed a split concept for boilers and HRSGs to reduce the heat exchange area and the requirement of power recycled. Mahmoud and Adel [10] analyzed a thermodynamic comparison of HRSG exhaust gas temperatures between 350°C to 650°C. The authors noted that the optimal pressures were achieved by increasing the pressure level. Increasing the pressure level also led to a decrease in the value of pinch point (PP). Tyagi and Khan [11] investigated the effects of turbine exhaust temperature, stack temperature and ambient temperature on the efficiency of a combine cycle plant and concluded that the stack temperature was the most dominating factor that contributed to the increase in the efficiency of the combine cycle plant. Using a numerical approach, reference [12] reported that the following factors affected the performance of the HRSG: mass flow rate of exhaust heat and steam; temperature of exhaust heat and steam; pressure and the compositions of gas and water used in the HRSG; water and air temperature; the geometry of the HRSG and the fluctuating of the GT conditions.

In order to determine the performance of HRSG, thermodynamic analysis has to be carried out. Butcher and Reddy [13] studied the performance of a waste heat recovery power generation system based on the temperature profiles across HRSG, network output, second law efficiency and entropy generation. The effect of PP on the performance of HRSG was also investigated. The authors reported that when the PP increased, the steam generated from HRSG decreased due to the reduced heat transfer in HRSG. However, when the waste heat temperature from the GT increased, the steam generation rate increased due to more energy input to the HRSG. The variation of PP for the case of the first law efficiency was not so much compared to the second law efficiency. Normally, HRSG is designed for a set of conditions. Unfortunately, in the real situation, HRSG is operated in different parameters due to the plant's constrains such as steam demand and different ambient conditions which can affect the entire plant's performance. Ganapathy [14] reported on the performance of HRSG based on the capability of steam generated. Meanwhile, the capability of steam generated is affected by the conditions of the exhaust heat from GT. There are two variables that directly affect the steam and gas temperature profiles, namely PP and AP. It is desirable to have the best range of PP that increases the mass flow rate of steam. The PP and AP are thus important parameters that influence the HRSG performance. This study was done to investigate these factors on the operating HRSGs available at a district cooling plant.

MATERIALS AND METHODS

In the present work, an HRSG equipped with an economizer and evaporator was considered. The HRSG was the unfired type. Performance of the HRSG was evaluated based on the mass flow rate of steam generated and the efficiency of the HRSG. The mass flow rate of steam generated by HRSG could be evaluated if the PP and AP are known. PP and AP are important parameters which influence the temperatures within the economizer and evaporator. The related temperatures are shown in Figure 1. Figure 1 shows the typical gas and steam temperature profiles in an HRSG consisting of an evaporator and economizer operating at a single pressure. The exhaust heat enters the evaporator at T_{g1} and flows through the evaporator and economizer and is discharged from HRSG into the environment at T_{g3}. Water enters the economizer at temperature T_{w1} and is sensibly heated at T_{w2}, after which it enters the evaporator. The water boils in the evaporator at the saturation temperature T_s and leaves the evaporator as saturated steam at T_{s4}. The steam is then delivered to SAC to generate chilled water.

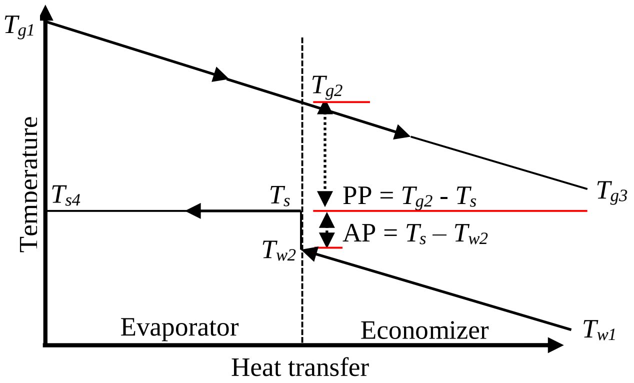

Figure 1.Typical temperature profiles for a single pressure HRSG.

Eq. (1) and Eq. (2) show the relationship of PP and AP to T_{g2}, T_s and T_{w2}. By knowing the PP, AP and T_s , the values of T_{g2} and T_{w2} could be obtained. The values of T_{g2} and T_{w2} were then used in Eq.(4) and Eq. (6).

$$\mathrm{PP} = T_{g2} - T_s \quad (1)$$

$$\mathrm{AP} = T_s - T_{w2} \quad (2)$$

Mass flow rate of steam generated

Eq. (3) was used to calculate the mass flow rate of steam generated [14].

$$\text{Mass flow rate of steam generated} = \frac{\text{Evaporator duty}}{\text{Enthalpy absorbed by steam in evaporator}} \quad (3)$$

Evaporator duty is required to be calculated in order to evaluate the mass flow rate of steam generated. The evaporator duty was calculated using Eq. (4);

$$\text{Evaporator duty} = \dot{m}_{exhaust\ gas} \times (1 - hl) \times Cp_{g(evap)@Tg1} \times (T_{g1} - T_{g2}) \quad (4)$$

where $\dot{m}_{exhaust\ gas}$ is the mass flow rate of exhaust heat from GT, *hl* is the percentage of heat loss, T_{g1} is the exhaust heat from GT, and T_{g2} is the temperature of exhaust heat entering the economizer. $Cp_{g(evap)}$ is the specific heat gas of evaporator and was calculated as [15];

$$Cp_g = 0.991615 + (6.99703 \times 10^{-5} \times T) + (2.7129 \times 10^{-7} \times T^2) - (1.22442 \times 10^{-10} \times T^3 \quad (5)$$

Eq. (6) was used to evaluate enthalpy absorbed by steam in the evaporator [14];

$$\text{Enthalpy absorbed by steam in the evaporator} = \left(h_s - h_{w@Tw2(fluid)} + bl \times \left(h_{w@Tw2(vapor)} - h_{w@Tw2(fluid)}\right)\right) \tag{6}$$

where *bl* is the blow down factor and h_s, $h_{w@Tw2(fluid)}$ and $h_{w@Tw2(vapor)}$ are the enthalpy of steam, saturated water entering evaporator and saturated water in vapor state respectively.

Gas temperature leaving HRSG

For the evaluation of gas temperature leaving HRSG, Eq. (7) was used [14];

$$T_{g3} = T_{g2} - \text{Gas temperature drop} \tag{7}$$

where the T_{g2} was obtained from Eq. (1). The temperature drop was expressed as [14];

$$\text{Gas temperature drop} = \frac{\text{Economizer duty}}{\left(\dot{m}_{exhaust\ gas} \times Cp_{g(econ)} \times (1 - hl)\right)} \tag{8}$$

$$\text{Economizer duty} = \dot{m}_{steam} \times (1 + bl) \times \left(h_{w@Tw2(fluid)} - h_{w@Tw1}\right) \tag{9}$$

where $\dot{m}_{steam}$ is the mass flow rate of steam obtained from Eq. (3), $h_{w@Tw2(fluid)}$ is the enthalpy of saturated water entering the evaporator and $h_{w@Tw1}$ is the enthalpy of feed water.

Performance of HRSG

HRSG efficiency is also an important factor which influences the efficiency of a district cooling plant. Using mass and energy balance equations, Eq. (10) was used to evaluate the efficiency of the HRSG [14];

$$\eta_{\text{HRSG}} = \frac{\text{Energy given to steam}}{(\text{gas flow} \times \text{inlet enthalpy}) + \text{fuel input on LHV basis}} \tag{10}$$

Substituting the parameters Eq. (10) becomes;

$$\eta_{\text{HRSG}} = \frac{\dot{m}_{steam}\left(h_{steam} - h_{w@Tw1}\right)}{\left(\dot{m}_{exhaust\ gas} Cp_g \left(T_{g1} - T_{g3}\right)\right) + \left(\dot{m}_{fuel} \times LHV\right)} \tag{11}$$

where $\dot{m}_{fuel}$ is the mass flow rate of fuel and *LHV* is the Low Heating Value of the GT fuel.

In this study, the mass flow rate of steam, the temperature of exhaust gas leaving HRSG and the efficiency of HRSG were determined by varying the values of PP and AP. The results were used to determine the values of PP and AP that generated the maximum steam rate, the lowest temperature of exhaust heat leaving HRSG and the highest efficiency of HRSG.

Case Study

HRSG at Universiti Teknologi Petronas (UTP) was taken as a case study as shown in Figure 2. The HRSG capacity is 12 tons/hr. The HRSG is normally operated from 7 a.m to 11.00 p.m daily and it is operated using exhaust gas from the GT at the plant. In this study, it was assumed that 66.6% of the exhaust gas are captured by the HRSG. This was based from the study by M. Amin et al. [16]. The HRSG generates steam which is used to produce chilled water by the absorption process. The chilled water is used for meeting the cooling demand of UTP campus as well as the plant. The following assumptions were used for the analysis [13];

(i) System is at a steady state.
(ii) No pressure drops on steam side.
(iii) Pressure drop on the gas side does not affect its temperature.

The parameters in Table 1 were used to determine the temperature profile of the HRSG.

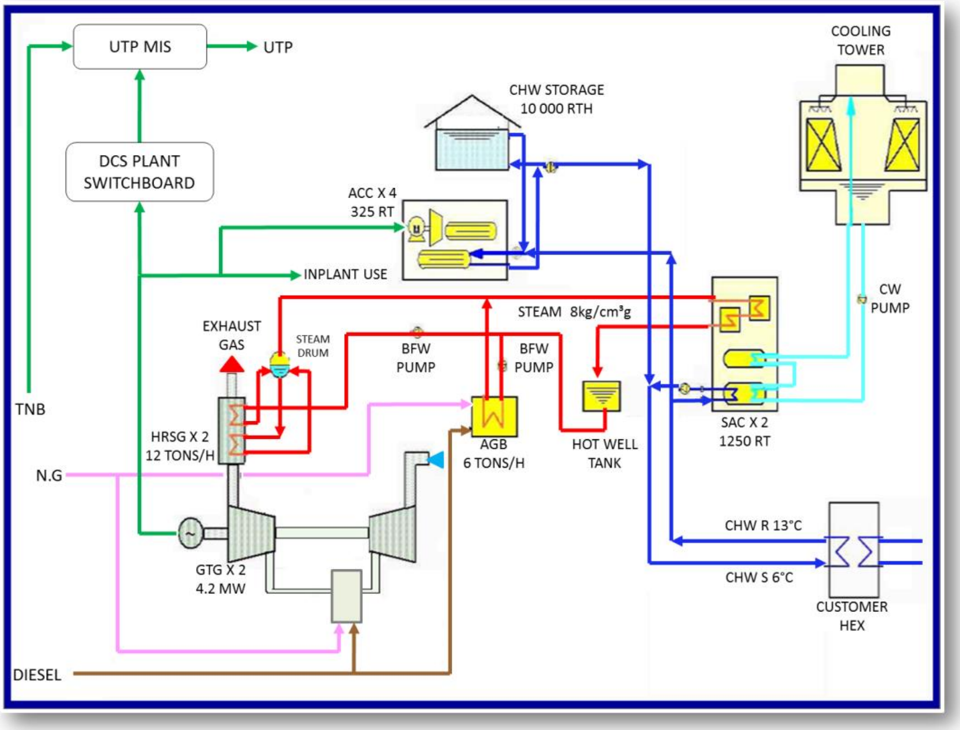

Figure 2. Universiti Teknologi Petronas' District Cooling System [17].

Table 1. UTP HRSG parameters [18].

Parameters		Value
Mass flow rate of exhaust gas	(kg/s)	19.30
Exhaust gas inlet temperature	(K)	648
Steam pressure	(bar)	8.69
Steam temperature	(K)	453
Feed water temperature	(K)	355.7
Blowdown factor	-	0.05
Heat loss factor	(%)	2

RESULTS AND DISCUSSION

Effects of PP and AP on Steam Generation

The plot of PP and AP on steam generation is shown in Figure 3. The plot was based on 70%, 50% and 30% of exhaust gas diverted to HRSG. For the case of varying PP values, the value of AP was maintained at 15 K. Meanwhile, for the case of varying AP values, the value of PP was maintained at 20 K. As the PP and AP increased, the mass flow rate of steam decreased. The same results were noted throughout all cases. This indicated that high PP and AP values resulted in lower steam being generated. The reason being, higher PP and AP led to the increase in the exhaust gas temperature entering the economizer in HRSG. This led to a reduction of heat transfer in the evaporator and hence lower the rate of steam being produced [19]. The summary of results for PP and AP are tabulated in Table 2 and Table 3 respectively. Table 2 indicates the decreasing steam generated with the increasing PP, with AP maintained at 15 K. Table 3 shows the decreasing steam generated with the increasing AP while PP was maintained at 20 K.

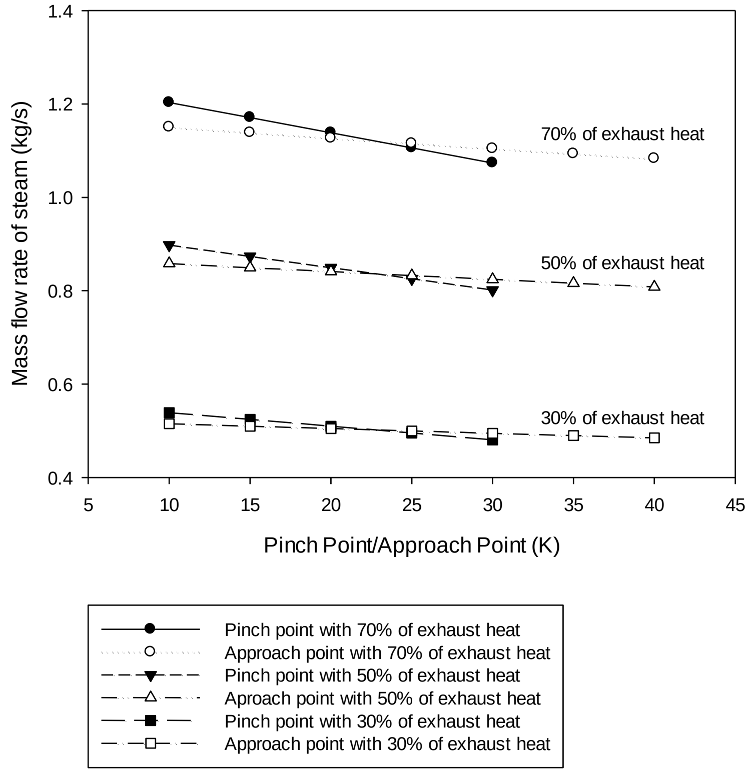

Figure 3. Effects of PP and AP of HRSG on the mass flow rates of steam.

Table 2. Mass low rate of steam with PP varied from 10 K to 30 K with AP at 15 K.

AP (K)	PP (K)	Mass flow rate of steam (kg/s)		
		70% of exhaust heat	50% of exhaust heat	30% of exhaust heat
	10	1.20	0.90	0.54
	15	1.17	0.87	0.52
15	20	1.14	0.85	0.51
	25	1.11	0.83	0.50
	30	1.07	0.80	0.48

Table 3. Mass flow rate of steam with AP varied from 10 K to 40 K with PP at 20 K.

PP (K)	AP (K)	Mass flow rate of steam (kg/s)		
		70% of exhaust heat	50% of exhaust heat	30% of exhaust heat
20	10	1.15	0.86	0.52
	15	1.14	0.85	0.51
	20	1.13	0.84	0.50
	25	1.12	0.83	0.50
	30	1.10	0.82	0.49
	35	1.09	0.82	0.49
	40	1.08	0.81	0.48

Effects of PP and AP on Exhaust Heat Temperature Leaving HRSG

Figure 4 presents the effects of PP and AP on the exhaust heat temperature leaving the HRSG in three different mass flow rates of exhaust heat entering the HRSG. Equation (7) was used for evaluating the temperature of exhaust heat leaving the HRSG. This could be explained by the fact that the amount of gas temperature drop in the HRSG was constant, which led to a higher exhaust heat temperature leaving the HRSG. Therefore, a straight line was achieved for the PP approach evaluation. In contrast, for the AP approach, the results showed that the temperature drops were different between 30%, 50% and 70%. The results of the temperature drops are summarized in Table 4 and Table 5. This was noted from the results on the temperature of exhaust heat leaving the HRSG.

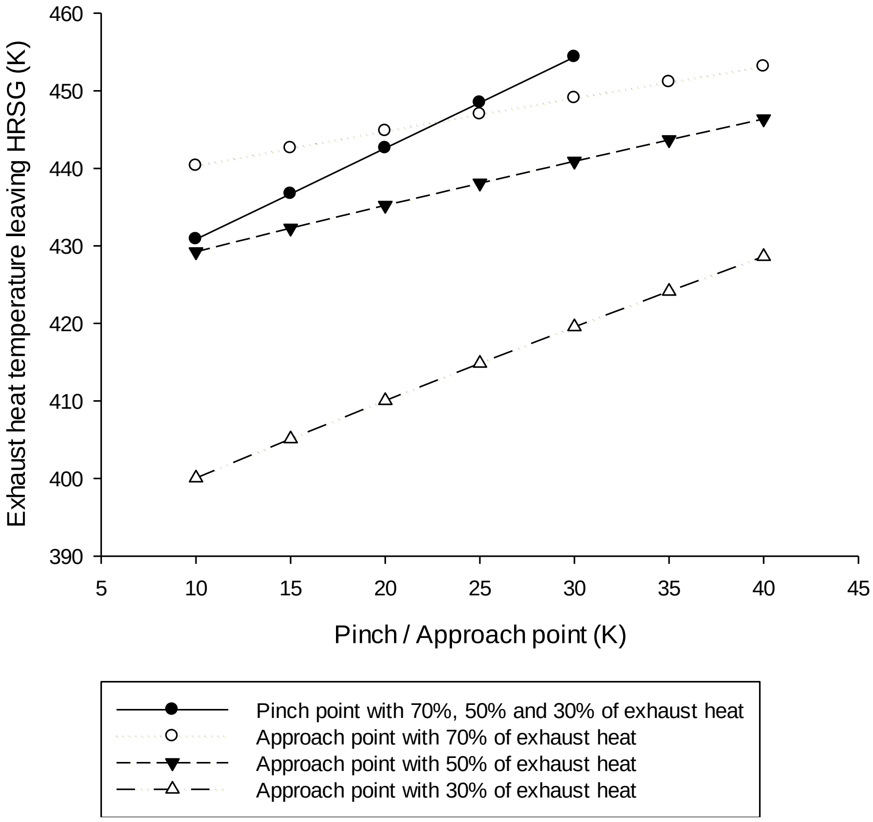

Figure 4. Effects of PP and AP of HRSG on exhaust heat temperatures leaving HRSG.

Table 4. Temperature drops at the economizer decrease with the increase of PP.

Pinch Point (K)	Temperature drop (K) 70%, 50% and 30% of exhaust heat
10	32.16
15	31.28
20	30.40
25	29.52
30	28.64

Table 5. Temperature drops at the economizer decrease with the increase of AP for cases 70%, 50% and 30% of exhaust heat diverted into HRSG.

Approach Point (K)	Temperature drop (K)		
	70% of exhaust heat	50% of exhaust heat	30% of exhaust heat
10	32.66	43.77	72.94
15	30.40	40.74	67.89
20	28.19	37.78	62.96
25	26.04	34.89	58.15
30	23.94	32.07	53.46
35	21.88	29.32	48.86
40	19.87	26.63	44.38

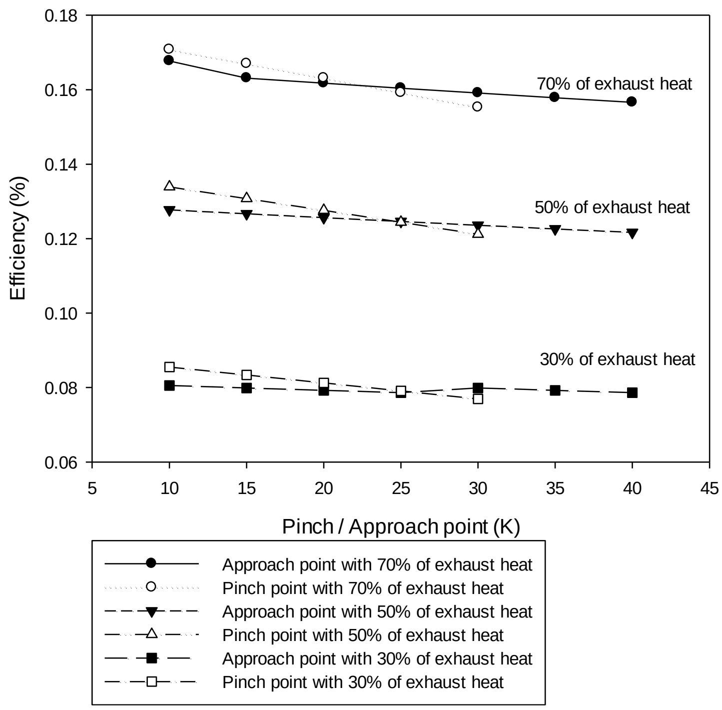

Figure 5. Effects of PP and AP on the efficiency of HRSG.

Effects of PP and AP on the Efficiency of HRSG

Figure 5 shows the plot of HRSG efficiencies for cases of different values of PP and AP as per Table 8 and Table 9. The plot indicated that as the values of PP and AP increased, the efficiencies of HRSG decreased. The results showed that the maximum efficiency obtained was at 70% of exhaust heat diverted into HRSG. The range of HRSG performance was about 0.17% to 0.16% for the case of 70% of exhaust heat captured into HRSG, and similar results were reported by literature [19]. Hence, the variation in AP had a minimal effect on the efficiency of HRSG.

Table 8. Effects of PP on the efficiency of HRSG.

PP (K)	AP (K)	Efficiency (%)		
		70% of exhaust heat	50% of exhaust heat	30% of exhaust heat
10		0.1708	0.1339	0.0855
15		0.1670	0.1308	0.0834
20	15	0.1631	0.1276	0.0812
25		0.1592	0.1244	0.0791
30		0.1553	0.1212	0.0769

Table 9. Effects of AP on the efficiency of HRSG.

AP (K)	PP (K)	Efficiency (%)		
		70% of exhaust heat	50% of exhaust heat	30% of exhaust heat
10		0.1677	0.1278	0.0805
15		0.1631	0.1267	0.0799
20		0.1617	0.1257	0.0792
25	20	0.1604	0.1246	0.0786
30		0.1591	0.1236	0.0799
35		0.1578	0.1227	0.0792
40		0.1566	0.1217	0.0786

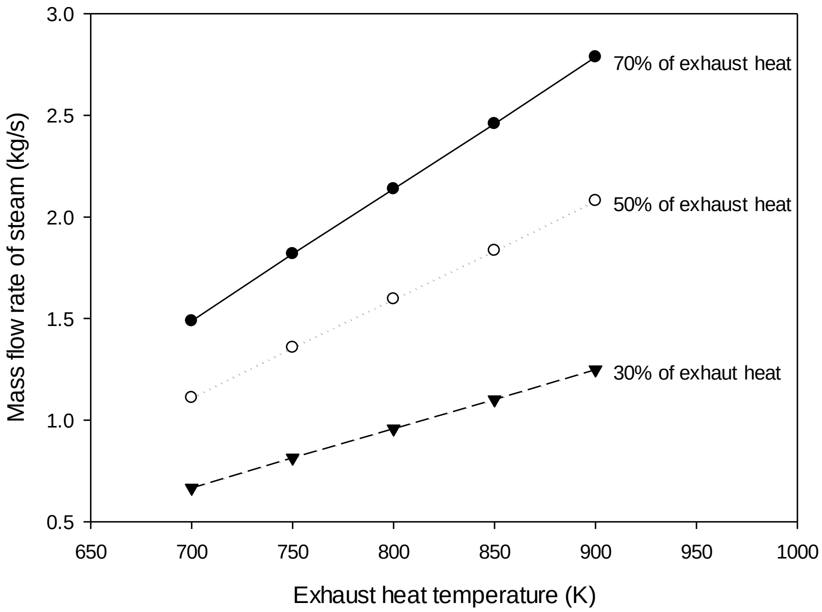

Figure 6. Effects of GT exhaust heat temperature on mass flow rate of steam.

Effects of Exhaust Heat Temperature of GT on the Mass Flow Rate of Steam

Figure 6 shows the effects of GT exhaust heat temperature on the mass flow rate of generated steam by HRSG. The results indicated that the mass flow rate of steam increased as the temperature of GT exhaust heat increased. Hence, the exhaust heat temperature from the GT influenced the mass flow rates of steam generated by the HRSG due to more energy input into the HRSG. The results and trends on the effects of PP and AP to the mass flow rate of steam generated and the efficiency of HRSG correlated with the findings from a published literature by [13].

CONCLUSIONS

Based on the analysis of this study, PP and AP influenced the mass flow rate of steam, exhaust heat temperature leaving HRSG and efficiency of HRSG. As PP and AP increased, the mass flow rate of steam and efficiency of HRSG decreased. With the increase of PP and AP, the temperature leaving HRSG was increased. The maximum mass flow rate of steam was obtained when 70% of exhaust heat from GT was diverted into HRSG. When the mass flow rate of steam generated was high, the efficiency of HRSG was improved. For this case study, in order to get the optimal mass flow rate of exhaust heat and efficiency of HRSG, the best range of the PP and AP was in between 10 K to 20 K. This was supported by the literature that the positive pinch point was 10 K to 20 K for the best heat recovery capacity of HRSG.

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