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Causal Model for Peak and Off Peak Waste Heat Recovery for Chilled Water Production

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Abstract: The objective of this study is to develop a causal model for estimating the amount of chilled water that can be produced from generated waste heat during off peak period of a district cooling plant. The methodology adopted is to calculate the amount of waste heat generated by the gas turbines of the plant during peak and off peak operations. Ten months of 2009 historical data of waste heat generated during peak and off peak periods were analyzed. The chilled water produced by absorption cooling for the ten months during peak period was also analyzed. Mathematical models using the causal relationship of the waste heat generated with the chilled water produced during the peak period for the ten months were formulated. Three models were formulated using the data namely linear, quadratic and exponential. The R^2 values obtained are 0.5034, 0.784 and 0.5128 for the linear, quadratic and exponential respectively. Since the R^2 value for the quadratic model is the highest, the quadratic model is used to evaluate the amount of chilled water that could be generated from the off peak waste heat. From the calculation, it is estimated that an average of 520,310 RTh of chilled water could be produced monthly from the off peak waste heat. This is 79.7% of the chilled water produced during peak period. Based on these findings the waste heat during off peak if converted to chilled water using absorption process will lead to economic benefits as well as reduced emission to atmosphere. Further detail study will be undertaken to enhance the model and to establish the design configuration of the system to recover the off peak waste heat for chilled water production by absorption process.

Key words: Waste heat, chilled water, absorption cooling, district cooling plant

INTRODUCTION

Waste heat is produced during energy conversion process. The normal waste heat temperature produced ranges from 370 to 540°C (UNEP, 2006). This category of waste heat could be utilized to produce chilled water or hot water. In the case of district cooling plants the steam is used for operating steam absorption chiller. It is a normal practice the waste heat recovery from gas turbines as in the district cooling is confined to day time, i.e., during peak period. While during night time operation, i.e., off peak period, the waste heat from the gas turbines is not recovered. The waste heat is emitted to the atmosphere. This is being practiced by Gas District Cooling (GDC) plant of University Teknologi PETRONAS (UTP) (Gilani *et al*., 2006). However, if the off peak waste heat is used to produce chilled water and the chilled water is stored to thermal energy storage system, the chilled could then be made available during peak period. This would support the peak period chilled water requirements as well as provide economic benefits (Dincer, 2002; Hussain *et al*., 2004; Khan *et al*., 2004).

The objective of this study is to establish a causal model for peak and off peak waste heat recovery for chilled water production. This would enable the evaluation of economic feasibility of investment on off peak waste heat recovery using absorption cooling to produce chilled water which could be used to support peak period requirements.

Since chilled water is not produced during off peak period it is difficult to estimate the amount of chilled water that could be produced during off peak period. Causal relationship was used to address this issue by using mathematical model which established relationship of peak waste heat and chilled water using regression. The model was then applied to estimate the amount of chilled water that can be produced by off peak waste heat.

MATERIALS AND METHODS

Universiti Teknologi PETRONAS Gas District Cooling plant (GDC) plant is a co-generation plant. The exhaust heat, in this case termed as waste heat, of the gas turbines is being recovered to produce chilled water.

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Waste heat recovery using heat recovery steam generator is only applicable during peak period from 6 am in the morning to 6 pm in the evening. During off peak operation the waste heat is not recovered. In order to estimate the potential amount of chilled water that could be produced during off peak hours the following methodology is used:

- Acquisition and analysis of the gas turbine waste heat produced during peak and off-peak hours at UTP gas district cooling plant. The peak was considered as the period from 6 am to 6 pm, while the off peak was taken from 6 pm to 6 am. The UTP district cooling plant operates two turbines, each of 5.2 MW at ISO condition
  - The amount of waste heat generated in terms of MW was evaluated at 66.6% which was based on the plant data on May 2009. While the remaining 33.4% is emitted to the environment
  - Established a mathematical model between chilled water and waste heat for the peak period using regression
  - The relationship was used to evaluate the amount of chilled water that can be produced from the waste heat during off peak period

The main equation used for calculation of waste heat is given as Abdul Karim and Waden (2011):

$$Q_{ex} = \dot{m}_g cp_g T_{ex} \quad (1)$$

Where, cp_g is the specific heat of exhaust gas, T_{ex} is the temperature of exhaust gas and $\dot{m}_{gf}$ is mass flow rate of exhaust heat and is defined in equation (Rahman *et al*., 2011):

$$\dot{m}_g = \dot{m}_a + \dot{m}_f \quad (2)$$

where, $\dot{m}_a$ is mass flow air and $\dot{m}_{gf}$ is the fuel flow rate.

In this study the least square approach is used to develop the model. Three models are selected for this study namely linear, quadratic and exponential.

Linear model: Equation 3 is the general linear equation model to relate the chilled water and the waste heat.

$$f(x) = p_1x+p_2 \quad (3)$$

where, x representing the independent variable (waste heat) and f(x) representing the chilled water output, the dependent variable. p_1 and p_2 are the coefficients of the linear model.

Quadratic model: Quadratic model is a nonlinear model of the basic form in which the functional part of the model is not linear with respect to the unknown parameters and the method of least squares is used to estimate the values of the unknown parameters. The general equation is given by:

$$f(x) = p_1x^2+p_2x+p_3 \quad (4)$$

Exponential model: Exponentials are often used when the rate of change of a quantity is proportional to the initial amount of the quantity. It is generally used to model the data that increases or decreases at a high rate.

$$f(x) = ae^{bx} \quad (5)$$

where, a and b are coefficients for exponential model. If the coefficient associated with e is negative, f(x) represents exponential decay. If the coefficient is positive, f(x) represents exponential growth.

RESULTS

Figure 1 shows the waste heat generated by Turbine A and Turbine B of the GDC plant, using 66.6% recovery of the total waste heat generated. This amount was used as the basis for the calculation as it is the practice at the plant to capture the waste heat for conversion to chilled water. The remaining 33.4% is emitted to atmosphere.

The total waste heat generated during peak and off peak periods are 85.05 and 52.82 GWh respectively. While the minimum and maximum waste heat generated during peak period are 6.57 and 9.34 GWh. For the case of off peak waste heat generated, the minimum and maximum are 4.79 and 5.88 GWh.

Figure 2 and 3 show the amount of waste heat generated specifically for each turbine, namely Turbine A and Turbine B.

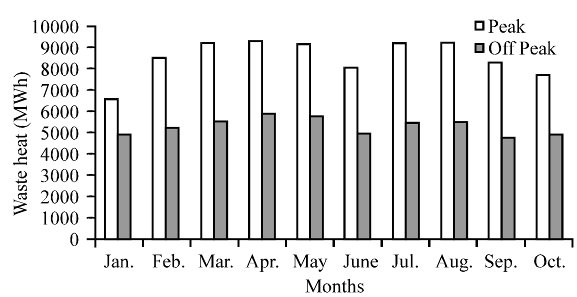

Fig. 1: Total waste heat during peak and off peak periods generated for year 2009

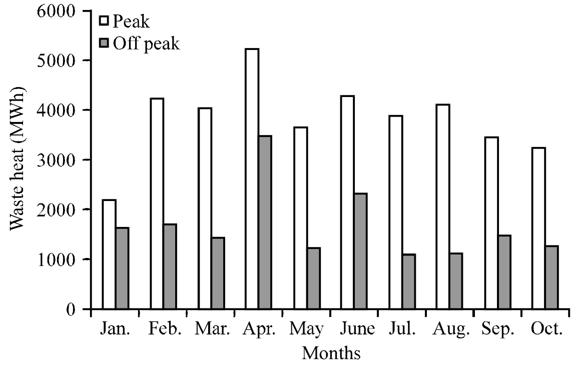

Fig. 2: Waste heat during peak and off peak periods generated by turbine A for year 2009

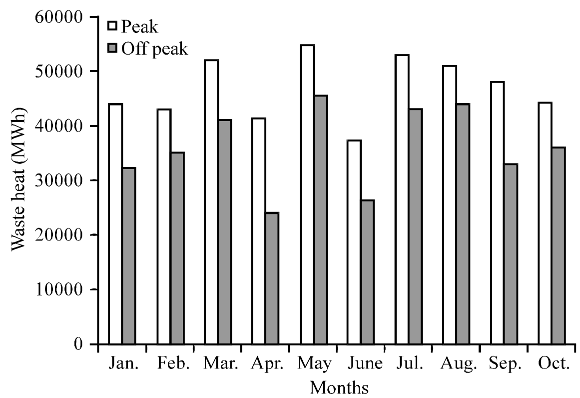

Fig. 3: Waste heat during peak and off peak periods generated by turbine B for year 2009

The total waste heat generated during peak and off peak periods by Turbine A are 38.11 and 16.58 GWh respectively. The minimum and maximum waste heat generated during peak period, are 2.17 and 5.19 GWh. While the minimum and maximum off peak waste heat generated are 1.08 and 3.45 GWh.

The total waste heat generated during peak and off peak periods by Turbine B are 46.95 and 36.24 GWh, respectively. The minimum and maximum waste heat generated during peak period are 3.75 and 5.49 GWh. While the minimum and maximum off peak waste heat generated are 2.44 and 4.55 GWh.

Linear, quadratic and exponential equations were used to curve fit the data. Results of the curve fitting for the three models are as shown in Fig. 4-6 with 95% confidence bound for the coefficients. The values for the coefficients are included in Table 1. The intervals indicate 95% chance that the new observations are contained within the lower and upper prediction bounds. The goodness of fit statistics for the models is included in Table 2.

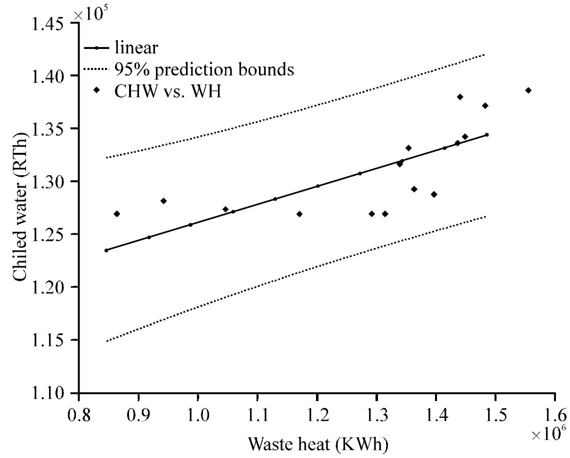

Fig. 4: Linear least square fitting model

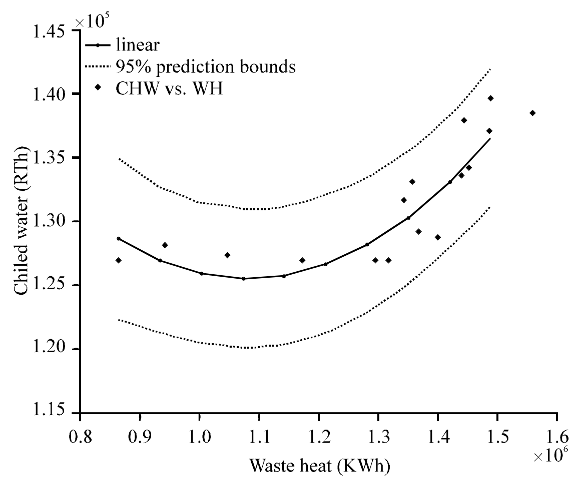

Fig. 5: Quadratic least square fitting model

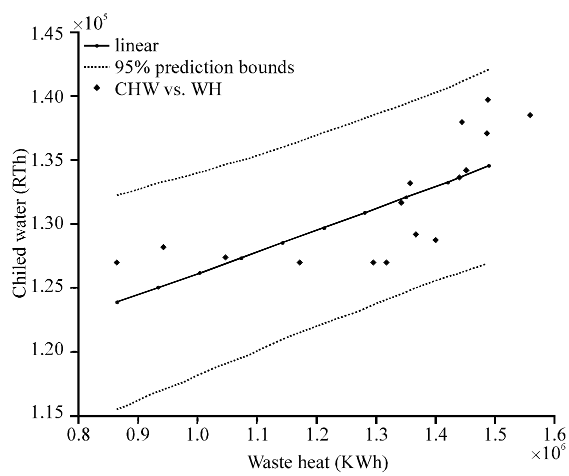

Fig. 6: Exponential least square fitting model

Table 1: Coefficients and confidence interval for the linear, quadratic and exponential models

		95% confidence interval		
Cof.	Equation	Cof. value	Lower	Upper
p_1	$f(x) = p_1x+p_2$	0.0170	0.0077	0.0263
p_2		1.091e+005	9.68e+004	1.21e+005
p_1	$f(x) = p_1x^2+p_2x+p_3$	6.75e-008	-3.355e-008	1.015e-008
p_2		-0.1459	-0.2281	-0.064
p_3		2.043e+005	1.557e+005	2.529 e+005
a	$f(x) = ae^{bx}$	1.104e+005	9.98e+004	1.21 e+005
b		1.329 e-007	6.076 e-008	2.05e-007

Table 2: Goodness of fit statistics for the models

Data Set	CW vs. WH	CW vs. WH	CW vs. WH
Equation	linear	quadratic	Expo
SSE	1.7e+008	7.57e+007	1.7e+008
R^2	0.5034	0.784	0.5128
# Coeff.	2	3	2

- The liner model is represented by:

$$f(x) = 0.01703x+1.091e+005 \quad (6)$$

Goodness of fit values:
SSE: 1.739e+008
R-square: 0.5034

- The quadratic model is represented by:

$$f(x) = 6.751e\text{-}008x^2+\text{-}0.1459x+2.043e+005 \quad (7)$$

Goodness of fit values:
SSE: 7.566e+007
R-square: 0.784

- The exponential model is represented by:

$$f(x) = 1.104e+005e^{132e\text{-}007x} \quad (8)$$

Goodness of fit values:
SSE: 1.7064e+008
R-square: 0.5128
CW: Chilled water
WH: Waste heat

Sum of Squares Due to Error (SSE) measures the total deviation of the response values from the fit to the response values. A value is small or closer to 0 indicates a better fit. In this case the quadratic fitting is the best fit compared to linear and exponential.

Since the quadratic model is the best fit, the quadratic model was used to calculate the amount of chilled water that could be produced from off peak waste heat. Table 3, 4 and 5 show that the amount of chilled water that was obtained using quadratic model from the off peak waste heat. The assumption used 66.6% waste heat recovery from the total off peak waste heat generated.

Table 3: The estimated total amount of chilled water that can be produced from waste heat during off peak period by both turbine A and B

Months, 2009	Off peak WH (MWh)	Estimated CHW (RTh)
January	3206	430545
February	3443	502202
March	3663	575704
April	3884	655908
May	3813	629623
June	3255	444589
July	3561	540872
August	3638	566997
September	3163	418286
October	3233	438372

Table 4: The estimated total amount of chilled water that can be produced from waste heat during off peak period by turbine A

Months, 2009	Off peak WH (MWh)	Estimated CHW (RTh)
January	1065	125488
February	1110	125531
March	942	126770
April	2273	221534
May	807	130522
June	1509	137888
July	715	134474
August	728	133881
September	960	126452
October	829	129734

Table 5: The estimated total amount of chilled water that can be produced from waste heat during off peak period by Turbine B

Months, 2009	Off peak WH (MWh)	Estimated CHW (RTh)
January	2141	201441
February	2333	231284
March	2721	307167
April	1610	144407
May	3006	375811
June	1745	155302
July	2846	335817
August	2910	351491
September	2203	210541
October	2404	243738

The average monthly amount of chilled water that can be produced from off-peak waste heat by both the turbine A and turbine B is 520,310 RTh. This is 79.7% of the chilled water produced during the peak period.

DISCUSSION

The analysis of the waste heat generated by Turbine A and Turbine B indicate that substantial waste heat was generated by both turbines during peak and off peak periods during the study period. Using the causal relationship of the peak waste heat generated with chilled water produced, three models namely linear, quadratic and exponential were formulated. The models are all having R^2 values greater than 0.5. Since the R^2 value for the quadratic model is the highest, the quadratic model was used to estimate the amount of chilled water that can be produced from the off peak waste heat. The amount of chilled water that can be produced is 520,310 RTh monthly. Hence it is justified to further evaluate, in terms of life cycle analysis, the feasibility of investing absorption cooling and thermal energy storage system, the recovery of the waste heat generated during off peak period.

CONCLUSION

The current practice of the plant is to emit the waste heat to atmosphere during off peak period. Study indicates that substantial amount of waste heat is available during off peak period. This amount could be put to beneficial use by converting to chilled water. Further study on technical and economic feasibility of recovery of the off peak waste heat for chilled water using absorption process is recommended.

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