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EXERGOECONOMIC POWER COST RATES MODEL FOR ONSHORE AND OFFSHORE GAS TURBINES

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ABSTRACT

Both the onshore and offshore power generating plants use gas turbines for power generation. The normal practice is to evaluate feasibility of the plants using rate of return approach. This approach does not incorporate the energy and exergy analysis. The more appropriate approach is to apply the exergoeconomic method. By adopting this method both the economic as well as exergetic analysis are incorporated in the evaluation. This study investigated the application of exergoeconomic method to evaluate the cost rates of electricity produced by the gas turbines for both the onshore and offshore power generating plants. The methodology incorporates cost rates associated to capital investment, operation and maintenance and exergy transfers into and out of the turbine. The cost rates for the capital investment of the turbine cover the capital recovery cost. The cost rates for the operations cover the fuel cost and the maintenance cost rates cover the maintenance cost throughout the whole life of the turbine. The cost rates associated with exergy transfers include all the cost rates due to entering and exiting material streams as well as both heat and work interactions with the surrounding and exergy destructions. Data for the study were obtained from the operating onshore and offshore gas turbines. The exergetic cost rates were established using the first and second law themodynamics. EES and Mathlab were used to analyse the model. In both cases the cost rates decrease with increased of power output assuming ten per cent interest rates and service life of twenty years. For future study sensitivity analysis on interest rates, service life, CAPEX and OPEX will be done.The model could them provides more accurate costing of power rates for industrial application.

Keywords: electricity cost rates; exergoeconomic; offshore gas turbine; onshore gas turbine.

INTRODUCTION

Gas turbines (GT) are commonly used for power generation for both the onshore and offshore power generating systems. GT offers a number of advantages. The advantages include less installation cost, less installation time, quick starting and stopping, and fast response to load changes. However, the GT have certain disadvantages. The disadvantages include like large compressor work, large exhaust loss, sensitivity to machine inefficiencies, relatively lower cycle efficiency and costly fuel. Due to these disadvantages it is important to ensure that the GT installations to be appropriately evaluated in terms of thermoeconomic or exergoeconomic feasibility so as to ensure optimum benefits. It is noted that this approach was not done for the case of understudied onshore and offshore GT installations. Due to this reason this study is to establish an exergoenomic model which can be used to evaluate the power rates for both the onshore and offshore GT.

Exergoeconomic assessments for onshore GT have been undertaken by various authors [1-3]. Ahmadi and Dincer [4] undertaken a comprehensive thermodynamic and exergoeconomic analysis of GT power plant. The concept adopted is based on the first and second laws of thermodynamic and the Net Present Value (NPV). It is noted that among the main component which contributes to the power cost rates is the cost of fuel [5-7] besides the capital and operation and maintenance (O&M) costs. Hence, if the cost of gas is not taken into account in determining the power rates, the calculated power rate does not represent the true power rates.

METHODOLOGY

In order to develop an exergoeconomic model of the offshore power generating, thermodynamic and economic approach was adopted.

Thermodynamic model

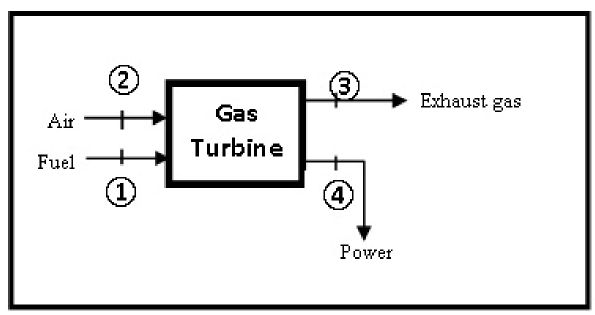

Figure-1. Configuration of GT model.

The model adopted both the first and second thermodynamic laws and NPV. The first law was used for energy balance; the second law evaluated the exergy balance while the NPV was used for evaluating the exergetic cost components. For the performance evaluation of the GT, the model as shown Figure-1 was used for analysis. The model indicates two inputs and two outputs. The two inputs are air and fuel. The outputs are exhaust gas and power. A closed system power cycle was adopted for the model. The power cycle is characterised both by the addition of energy, by heat transfer and rejection of energy by heat transfer. Equation (1) was used to evaluate the thermal efficiency for the model [8]:

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$$Q_{cycle} = Q_{in} - Q_3 \tag{1}$$

where Q_{in} and Q_3 denote the total energy added and rejected respectively. Using the Q_{cycle} the thermal efficiency of the turbine is defined by Equation (2) [8]:

$$\eta_{th} = \frac{\dot{W}_{nett}}{Q_{in}} \tag{2}$$

Where W_{nett} is the work net produced by turbine and Q_{in} heat transfer into the GT. The energy added, Q_{in} is the products of mass flow rate of fuel and Low Heating Value (LHV) of fuel. Hence Equation (2) could be rewritten as follows:

$$\eta e = \frac{\dot{W}_{nett}}{\dot{m}_{fuel} \times LHV} \tag{3}$$

The mass flow rate of exhaust gas generated by GT is the sum of mass flow rate of fuel and air.

$$\dot{m}_{exgas} = \dot{m}_{fuel} + \dot{m}_{air} \tag{4}$$

where $\dot{m}_{exgas}$ is the mass flow rate of exhaust gas, $\dot{m}_{fuel}$ is the mass flow rate of fuel and $\dot{m}_{air}$ is the mass flow rate of air.

For the second law of thermodynamic, exergy balance as per Equation (5) was used [9].

$$\dot{E}_Q + \sum_i \dot{m}_i \dot{e}_i = \sum_e \dot{m}_e \dot{e}_e + \dot{E}_w + \dot{E}_D \tag{5}$$

where, i and e denotes inlet and outlet of control volume and $\dot{E}_D$ is the exergy destruction. $\dot{E}_Q$ and $\dot{E}_w$ are the exergy transfer by heat and exergy transfer by work respectively.

The model was developed based on input and output enthalpy and exergy in each line of the GT component. For the exergy analysis, the exergy rate at the state where the fuel enters GT is expressed by Equation (6);

$$\dot{E}_{fuel} = \dot{m}_{fuel}\ ex_{fuel} \tag{6}$$

where ex_{fuel} was calculated using fuel specific exergy equation. For the evaluation of specific fuel exergy, the corresponding ratio of simplified exergy is defined as Equation (7) as reported by [6] and [10];

$$\xi = \frac{ex_{fuel}}{LHV} \tag{7}$$

A general gaseous fuel with composition, C_aH_b Equation (8) was used to evaluate the value of ξ.

$$\xi = 1.033 + 0.0169\frac{b}{a} - \frac{0.0698}{a} \tag{8}$$

Thus, the specific exergy of fuel is expressed as Equation (9);

$$ex_{fuel} = \xi \times LHV \tag{9}$$

The amount of exergy transfer by heat was evaluated using Equation (10) [11]:

$$\dot{E}_Q = \left(1 - \frac{T_0}{T_i}\right)\dot{Q}_i \tag{10}$$

where, T_0 and T_i are the ambient temperature and inlet temperature respectively. $\dot{Q}_i$ is inlet heat transfer rate. Exergy transfer by work is the useful work potential. It is also a form of mechanical energy, thus it can be converted to work entirely. So that, the exergy transfer by work is expressed by Equation (11) [4];

$$\dot{E}_W = \dot{W} \tag{11}$$

where, $\dot{W}$ is the work output.

Exergy for a flowing stream which is the specific exergy is determine by adding the exergy of non-flow exergy and flow exergy. The specific exergy at a steady flow system can be evaluated by Equation (12) [12]:

$$ex = (h - h_0) - T_0(s - s_0) \tag{12}$$

where, ex denotes the specific exergy, h is enthalpy and s is entropy. While ($_0$) refers to ambient condition. By neglecting the kinetic and potential exergies, the exergy rate for all streams are presented in Table-1.

Table-1. Summary of the exergy rate for GT model.

Stream	Identification	Exergy rate equation	Eqn
1	Fuel	$\dot{E}_1 = \dot{m}_{fuel}\ ex_{fuel}$	(6)
		$ex_{fuel} = \xi \times LHV$	(9)
		$\xi = 1.033 + 0.0169\frac{b}{a} - \frac{0.0698}{a}$	(8)
2	Air	$\dot{E}_2 = 0$ At this stream, $T_2 = 0$ and $P_2 = 0$.	(13)
3	Exhaust gas	$\dot{E}_3 = \dot{m}_{exgas} Cpg T_0 \left(\frac{T_3}{T_0} - 1 - \ln\frac{T_3}{T_0}\right)$	(14)
4	Power	$\dot{E}_4 = \dot{W}$	(11)

Economic model

For a system operating at steady state, the cost rate associated with exergy stream and other remaining cost rates are expressed by Equation (13);

$$\dot{C}_{P(total)} = \dot{C}_{F(total)} + \dot{Z}_K \tag{13}$$

where, $\dot{C}$ denotes the cost rate (RM/h) associated with exergy stream while $\dot{Z}$ represent the cost rate due to capital and operation and maintenance cost. $\dot{C}_{P(total)}$ is the total cost rate of the products generated and $\dot{C}_{F(total)}$ is the total cost rate of fuel. $\dot{Z}_K$ is the sum of the cost rates associated with the capital investment and the operation and maintenance costs.

$$\dot{Z}_K = \dot{Z}_{CI(K)} + \dot{Z}_{OM(K)} \tag{14}$$

$$\dot{Z}_{CI(K)} = CI_{(K)} + CRF \tag{15}$$

$$\dot{Z}_{OM(K)} = C(OM)_{(K)} \tag{16}$$

where, $CI_{(K)}$ is the turbine capital cost and $C(OM)_{(K)}$ is the present worth of the operation and maintenance costs. The turbine cost was annualized by using the capital recovery factor (CRF).

$$CRF = \frac{i(1+i)n}{(1+i)n-1} \tag{17}$$

where i denotes annual interest rate and n is the number of period undertaken in years.

Exergoeconomic model

For the case of exergy costing, a cost was calculated based on each exergy stream. Equation (18) to Equation (20) which are related exergy costing equations for entering and exiting stream expressed by i and o respectively.

$$\dot{C}i = ci\,\dot{E}i \tag{18}$$

$$\dot{C}_0 = c_0\,\dot{E}_0 \tag{19}$$

$$\dot{C}_w = c_w\,\dot{E}_w \tag{20}$$

Here, $\dot{C}i$, $\dot{C}_0$ and $\dot{C}_w$ denote the average costs per unit of exergy tranfer rate and the unit of $\dot{C}i$, $\dot{C}_0$ and $\dot{C}_w$ are Ringgit Malaysia per hour (RM/h). The cost equations for each exergy stream are tabulated in Table-2.

Table-2. Summary of the equations for the exergoeconomic model for GT.

Exergoeconomic model	Equation
Cost balance:	
$\dot{C}_1 + \dot{C}_2 + \dot{Z}_{GT} = \dot{W}_4 + \dot{C}_3$	(23)
$c_1\dot{E}_1 + c_2\dot{E}_2 + \dot{Z}_{GT} = c_4\dot{E}_4 + c_3\dot{E}_3$	(24)
Auxiliary exergoeconomic relation; $c_2 = 0$, $c_3 = 0$	
Variable calculated from cost balance;	
$C_{power} = \dfrac{c_1\dot{E}_1 + \dot{Z}_{GT}}{\dot{E}_4}$	(25)

Case study

The exergoeconomic model was used to evaluate two turbine installations; one at onshore power generating plant and the other at offshore power generating plant. The onshore turbine was 4.2 MW capacity installed at cogenerating plant. The offshore turbine was installed at a platform and it was used to generate power in open cycle mode. Since it was operated at the platform the natural gas used for the fuel was not priced. The onshore turbine used the gas supplied by the Malaysia Peninsular Pipeline. The gas price was based on market price. In this study for comparison purposes the price of gas to offshore turbine was assumed the same as the price of gas for onshore turbine. Other data for both turbines used for this study are listed in Table-3. The pressure ratios for the onshore and offshore GT were 11.7 and 18.32 respectively. The maximum power generated by the onshore and offshore GT were 3.7 MW and 15.5 MW respectively. In terms of mass flow rate of fuel, the onshore GT was 0.231kg/s, while the offshore GT was 2.012 kg/s.

Table-3. The GT used for case study.

Performance parameter	Onshore	Offshore
Total pressure ratio	11.7	18.2
Average power generated	3.7 MW	15.5 MW
Fuel type	Liquefied natural gas	Liquefied natural gas
Mass flow rate of fuel used	0.231 kg/s	2.012 kg/s

RESULTS AND DISCUSSION

Figure-2 and Figure-3 show the plots of power rates versus mass flow rates of fuel for the onshore and offshore GT respectively. Both plots indicate decreasing power rates with increasing mass flow rates of fuel. For both of these cases the price of fuel was assumed RM14.07 per GJ. The decreasing trends of power rates with increasing of mass flow rates of fuel also noted for the case when the price of fuel is zero for the case of offshore GT as indicated by the plots in Figure-4.

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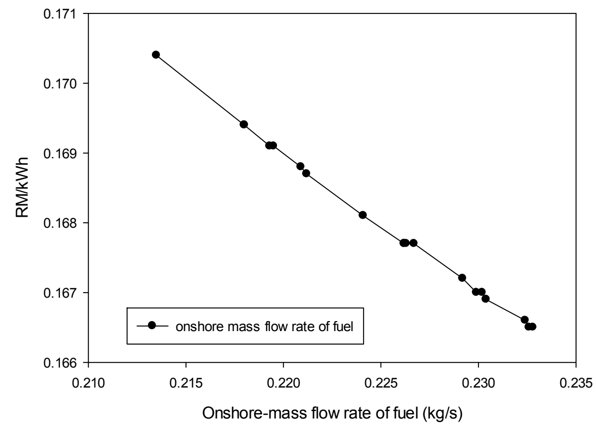

Figure-2. Power rates versus mass flow rates of fuel for onshore GT (cost of fuel RM14.07 per GJ).

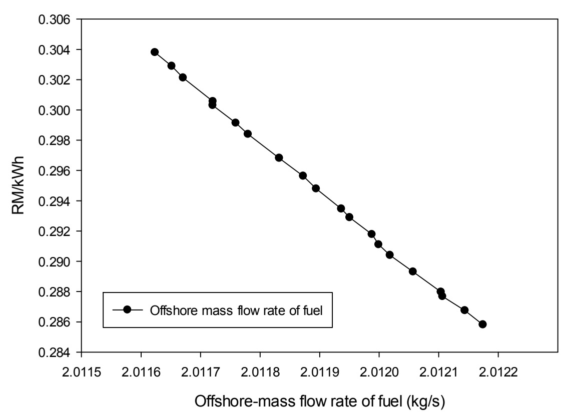

Figure-3. Power rates versus mass flow rates of fuel for offshore GT (cost of fuel RM14.07 per GJ).

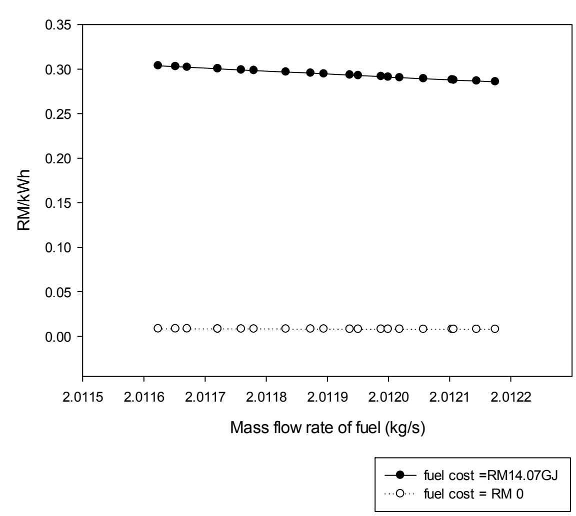

Figure-4. Power rates versus mass flow rates of fuel for offshore GT.

Figure-5 shows the plot of power rates versus power for onshore GT. The evaluated power cost rate was RM660.06 per hour which the specific cost of power was RM47.50 per GJ with 3.86 MW power which is higher than that of the evaluated specific cost of fuel which is RM14.41, indicating that the electricity power rates is higher than the fuel rates. This is in agreement to the findings by Xu D. *et al*. [13]. Figure 6 shows the plot of power rates to generated power for offshore GT. The plot indicates decreasing trend of power rates with respect to generated power. The possible reason is due to the cost of capital is being shared to higher units of power produced and hence the power rates decreased. The average power rate was RM 0.17/kWh for the onshore GT. While the average power rates for offshore GT was RM 0.30/kWh as seen from Figure-6.

It is noted that the average power rates for the offshore GT was very much higher than the average power rates for the onshore GT. One possible reason is the offshore GT is operating with high mass flow rates of fuel, since it was operating at 67 per cent capacity. While the onshore GT was operating at higher capacity about 74 per cent its capacity.

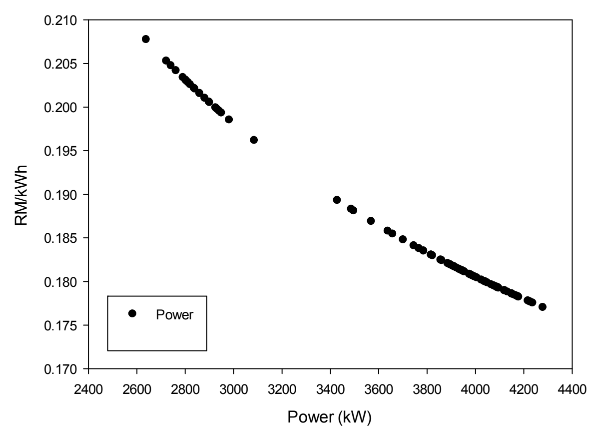

Figure-5. Power rates versus generated power for onshore GT (cost of fuel RM14.07 per GJ)

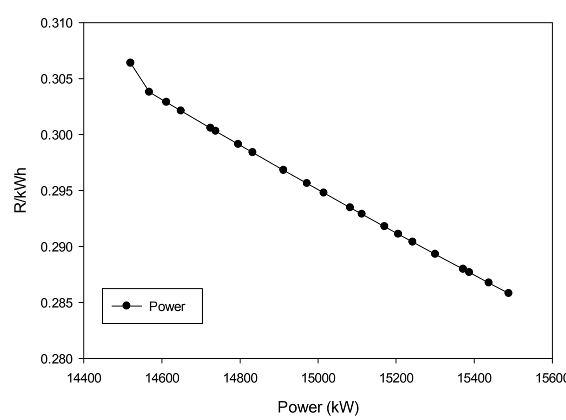

Figure-6. Power rates versus generated power for offshore GT (cost of fuel RM14.07 per GJ).

CONCLUSIONS

The developed exergoeconomic model enabled the power rates for the onshore and offshore gas turbines to be evaluated. For both cases the power rates decreases with increase of the mass flow rates of fuel. The evaluated power rates for onshore and offshore GT were 0.17 per kWh and RM0.30 per kWh respectively. This was based on cost of fuel RM14.07 per GJ. This value was obtained based on assumptions of 10 per cent interest rate and 20-year service life. For future study sensitivity analysis on the interest rate, service life as well as on CAPEX and OPEX will be undertaken to capture the changes in actual industrial environment.

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