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Research Article
Transient Simulation of a Waste Heat Recovery from Gas Turbine Exhaust

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Abstract

Background and Objective: Waste Heat Recovery (WHR) system enables to recover the exhaust heat from gas turbine to produce a useful energy. However, the amount of exhaust heat recovered from the turbine is depending on the various operating variables i.e., ambient temperature and fuel flow rate. Hence, this study focuses on the effect of operating variable on WHR system using transient simulation. **Materials and Methods:** The TRNSYS simulation environment is adopted to develop the WHR system model to understand the system's transient operation and evaluate the operating variables of waste heat recovery system. The effect of ambient temperature and mass flow rate on operating variables has been studied by considering academic institution waste heat recovery system which is driven by a gas turbine has a capacity of 5.2 MW. **Results:** Results indicate that 20% variation of ambient temperature (°C) could lead to 0.7% changes in power generated and 1.7% changes in steam generation. With respect to fuel flow rate, 10% changes of fuel flow rate could lead to about 4 and 8.7% changes on turbine power and steam generated, respectively. **Conclusion:** This transient study of the waste heat recovery could be useful to the operator to carry out the performance analysis and design of the control WHR system for safe and optimum performance operation.

Key words: TRNSYS, waste heat recovery, ambient temprature, fuel flow rate, gas turbine, heat recovery, steam generator, compressor, combustion chamber

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Waste Heat Recovery (WHR) system mitigates loss of energy by recovering waste heat produced during power generation. In conventional power generation, the main purpose of the power generation system is to convert the fuel or other type of energy into electricity. However, the amount energy converted from fuel energy to electricity is very low[1,2]. The large portion of the fuel energy goes out as exhaust heat or waste heat. In order to reduce loss of energy, WHR system assist to reduce this waste heat loss by using the part of the waste heat to produces steam and chilled water. During the operation of a conventional power plant, a large quantity of heat is rejected in the atmosphere either through the cooling circuits or with the exhaust gases. Most of this heat can be recovered and used to cover thermal needs, thus increasing the energy efficiency from 30-50% of a power plant to 73-90% of a cogeneration system[3,4].

The performance assessment of WHR system has come to involve three tasks which are design, off design and transient analysis[5]. Various efforts have been done in the past for developing the simulation model for design and off design behaviour of the WHR systems keeping into consideration the desired outcomes i.e., type of applications, work outputs and the optimized conditions for achieving maximum thermal efficiency and the component efficiencies within the system. The design and the off design performance analysis of single shaft waste heat recovery has been studied by Baheta and Gilani[6], Wahab and Ibrahim[7]. A waste heat recovery is basically operated on its design conditions. However, it also operates on the so called off-design conditions due to the variation in a power load, process requirement or operating mode. Savola and Keppo[8] eveloped an off design simulation based on the part load performance of four small-scale (1-20 MW) combined heat and power plants. The purpose of his study is to simulate the electricity production as the district heat load decreases in small-scale combined heat and power plants and to create a linear mathematical model of the power production as a function of the district heat load. Consonni and Silva[9] highlighted on the off-design operation of plants where a waste-to-energy system fed with municipal solid waste is integrated with a natural gas-fired combined cycle. Sanaye and Rezazadeh[10] prepared a developed thermal model for predicting the working conditions of Heat Recovery Steam Generation (HRSG) elements during transient start up procedure. Descombes and Boudigues[11] studied waste heat recovery aiming to increase the availability of the combined cycles and cogeneration.

Most researchers focused on the steady state simulation which consider the design and off design point however the steady state simulation does not show the real phenomena particularly during the start-up and shutdown phase. Thus, it is required to develop the transient behaviour of the system which could help the operator to capture the real phenomena to identify optimum and reliable performance of waste heat recovery system. Knowing the transient performance helps to study the effect of ambient condition and mass flow rate which are important in waste heat recovery design and operation. In this study, the transient behaviour of WHR has been developed using TRNSYS simulation environment. This model helps to analyse the operating variables through change in time. Basically, the WHR system consists of five major components including the compressor, combustion chamber, turbine, generator and heat recovery steam generation unit. A schematic diagram for a waste recovery system is shown in Fig. 1. In Fig. 1, air is drawn from the atmosphere and is compressed to a high pressure in a

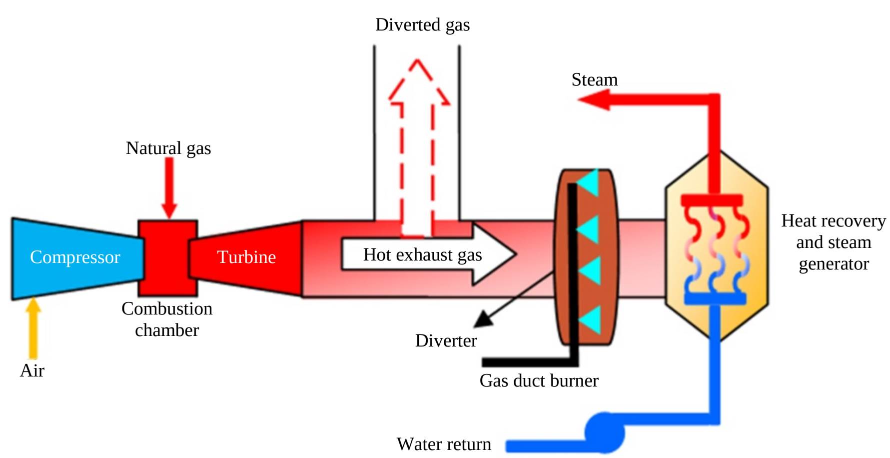

Fig. 1: Waste heat recovery system

compressor. The high pressure air enters a combustion chamber, in which fuel is sprayed onto the compressed air and the fuel-air mixture is burned at constant pressure. The gases leaving the combustion chamber at high pressure and high temperature are directed towards the turbine blades so as to rotate the turbine shaft.

In general, nearly half of the work output of the rotating turbine shaft is used to rotate the compressor shaft and the rest is used to produce electricity. Again, after expansion in the turbine to provide the required power, the flue gas is passed through the HRSG where it exchanges heat with water flowing through the HRSG which is supplied from the pump. The gases leaving the turbine are released into the atmosphere. These gases contain carbon dioxide, nitrous oxides, sulfur oxides and particulate matter. The temperature of the exhaust gases can also be very high. Hence, it is very essential to optimize the performance of WHR system to mitigate the effect of exhaust gases. Thus, this study focuses on the performance analysis of WHR by considering various operation parameters such as mass flow rate, fuel flow rate and exhaust gas flow under transient conditions.

MATERIALS AND METHODS

The transient simulation model for WHR was formulated to analyse the performance assessment of waste heat recovery system using TRNSYS 17 software. The TRNSYS 17 was able to study transient behaviour of WHR system performance. The TRNSYS enables the users to form or develop their particular models using standard components or users' created components. In this study, the WHR model was developed using the format of standard components in TRNSYS 17 which consist of inputs, constant parameters and outputs. Figure 2 shows that steps adopted to assess the performance analysis of WHR systems using TRNSYS 17. Weather-load conditions and set points data were collected for WHR system. The weather data were taken from where WHR system operated at Ipoh-Malaysia. Weather-load conditions and set points data was used as inputs for a compressor, turbine and combust or/and heat recovery. Each input of the components has linked to determine the variables which are transferred from one component to another.

The associated mathematical equation used for to determine the operating variables of the main component of WHR system such as compressor, combustion chamber, turbine and heat and steam generation recovery are presented in the following[12,13].

Compressor: The absorbed power and final temperature by the compressor can be estimated using Eq. 1 and 2, respectively:

$$W = \frac{P_{in} V_a \gamma \left[\left(\frac{P_{out}}{P_{in}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]}{(\gamma - 1)\eta_{ac} \times \eta_{mc}} \quad (1)$$

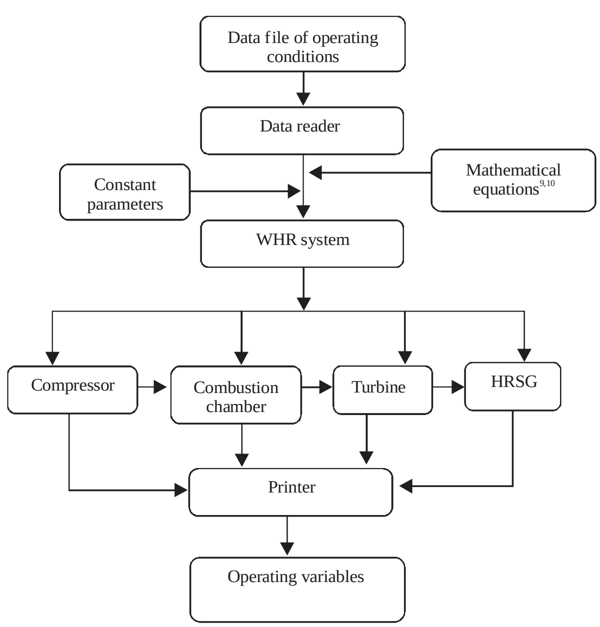

Fig. 2: Simulation procedures for performance analysis of waste heat recovery

$$T_{out} = T_{in}\left[\frac{\left(\frac{P_{out}}{P_{in}}\right)^{\frac{\gamma-1}{\gamma}}-1}{\eta_{ac}}+1\right] \quad (2)$$

Where:

W = Absorbed power
P_{in} = Inlet pressure
P_{out} = Outlet pressure
T_{in} = Inlet temperature
T_{out} = Outlet temperature
V_a = Flow rate (at inlet condition)
γ = Cp/Cv
η_{ac} = Adiabatic efficiency
η_{mc} = Mechanical e efficiency

Combustion chamber: Energy must be supplied to the heating device in order to heat the air stream from its inlet condition to its outlet condition. The temperature of the air at the exit of the combust or can be calculated using Eq. 3:

$$T_{out} = \left[\frac{LHV}{Q\times C_{pexg}}+T_{inlet}\right] \quad (3)$$

Turbine: Energy is produced by the turbine as the air expands from its inlet pressure to its specified outlet pressure. The power generated and final temperatures of turbine are show in Eq. 4 and 5, respectively:

$$W = \eta_{ac}\times\eta_{mc}\frac{P_{in}V_a\gamma\left[1-\left(\frac{P_{out}}{P_{in}}\right)^{\frac{\gamma-1}{\gamma}}\right]}{(\gamma-1)} \quad (4)$$

$$T_{out} = T_{in}\left[\frac{\left(\frac{P_{out}}{P_{in}}\right)^{\frac{\gamma-1}{\gamma}}-1}{\eta_{ac}}+1\right] \quad (5)$$

Heat recovery and steam generator: In a cogeneration environment, the gas turbine is coupled to HRSG. This is to enable the exhaust from the turbine to be used to generate steam. The most important variables should consider during the conversation of the exhaust heat into steam are pinch point and approach pinch point. The pinch point is the difference between the exhaust gas temperature leaving the evaporator and the temperature of the saturated steam. The approach point is the difference between the temperature of saturated steam and the temperature of the water entering the evaporator. Figure 3 shows the temperature trend of HRSG operating at a single pressure, indicating the pinch point and approach point[14].

Once the pinch point is chosen, the temperature of the gas leaving the evaporator (t_{g2}) and the approach point gives the temperature of the water leaving the economizer (s2), since the saturation temperature is known. The energy balance across the evaporator and economizer, as shown in Eq. 6-8:

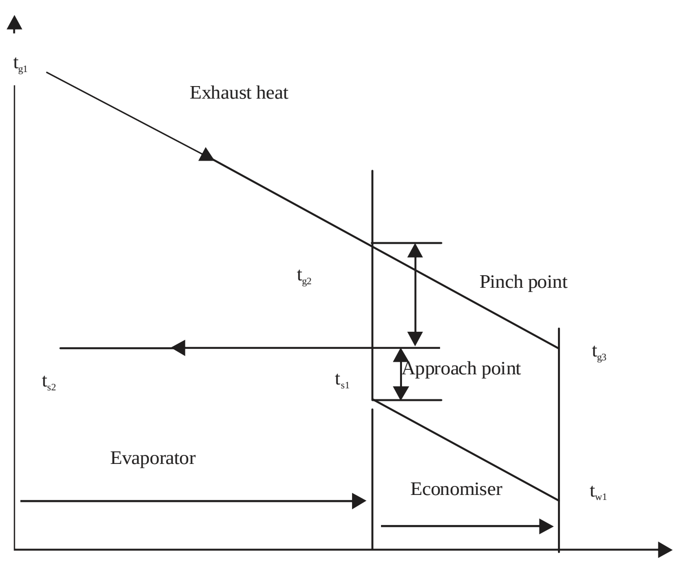

Fig. 3: HRSG Temperature profile and steam generation[11]

$$\dot{m}_s = \frac{\dot{m}_{g1} C_{pg} (t_{g1}\ t_{g2})}{(h_{s2}\ h_{s1})} \quad (6)$$

$$\dot{m}_s = \frac{\dot{m}_{g1} C_{pg} (t_{g2}\ t_{g3})}{(h_{s1}\ h_{w1})} \quad (7)$$

$$PP = (t_{g2}-t_{s1}) \quad (8)$$

where, t_{g1} is the exhaust gas temperature which comes from combustion chamber, t_{g3} is the gas temperature leaving the economizer, $\dot{m}$ is mass flow rate of steam produced by HRSG, C_{pg} is specific heat of exhaust gas, t_{g2} is temperature exit from evaporator, h_{w1}, h_{s1} and h_{s2} are enthalpy of water entering the economizer, entering and exit from the evaporator, respectively and PP is pinch point value. The value of h_{s1} and h_{s2} are calculated based on the saturated condition of steam pressure.

RESULTS AND DISCUSSION

The WHR individual components were created based on the campus district cooling plant. This campus district cooling plant uses two gas turbines which have a capacity of 4.2 MW each. In this gas district cooing plant, each elements model as individual component models is called types. These models of individual components are then connected within TRNSYS. The associated mathematical model in the each component model can be described in TRNSYS simulation engine[9,10]. A schematic model of WHR TRNSYS simulation is as shown in Fig. 4. In Fig. 4, material and information flows are indicated by connections between two components. It is important to properly specify the required variables for each component while creating a simulation studio. For such systems, the TRNSYS simulation is generally represented which define the behaviour of the thermodynamic system in respect of all kind of flows involved in the process it is undergoing. The energy flows and energy transformations can be represented in a unified manner along with their interactions as shown in Fig. 4.

Simulation of system's performance was carried out for one year duration. Simulated performance of the system throughout the year is presented in Fig. 5-8 for temperature, power and fuel flow rate of fuel and exhaust gas and steam flow rate respectively steady state performance of the system is also presented for comparison as shown in Table 1. For this calculation, ISO standard ambient conditions of 15°C and 1 atm are assumed and all produced heat is assumed to be consumed by the maximum respective loads.

Figure 5 shows the plot of variation of air temperature at compressor exit (T_out_compressor), follows ambient temperature variation, ranging from 370-404°C (for steady

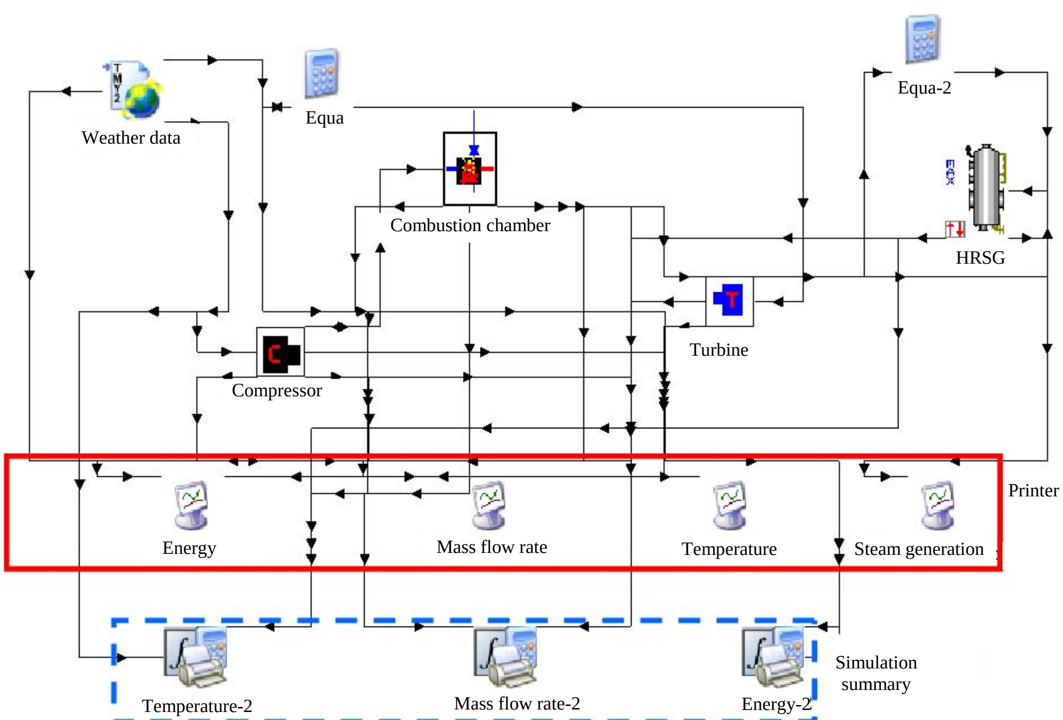

Fig. 4: Schematic simulation models

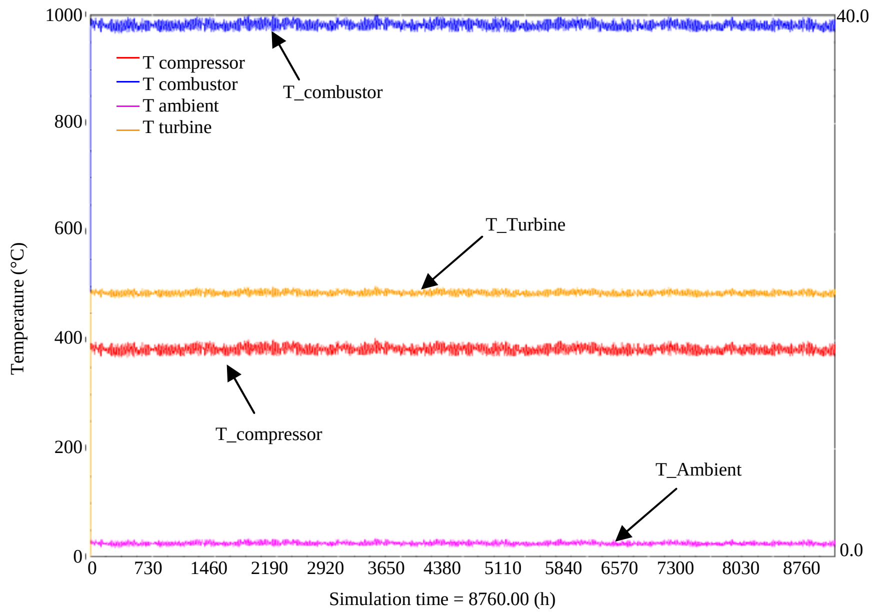

Fig. 5: Temperature profile for compressor combust or and turbine

Table 1: Summary of steady state and transient simulation results

	Steady state		Transient	
	Temperature (°C)	Power (kJ h^{-1})	Temperature (°C)	Power (MJ h^{-1})
Compressor	333	2.6×10^7	Max = 404	Max = 28.7
			Min = 370	Min = 27.3
Combustor	972	5.3×10^7	Max = 996	Max = 5.5×10^7
			Min= 960	Min = 5.07×10^7
Turbine	450	4.29×10^7	Max = 491	Max = 42.7
			Min = 468	Min = 43.9

state the corresponding temperature is 333°C). For the temperature at turbine inlet (Temperature out combustion chamber), the plot shows ranges between 960-996°C (for steady state the corresponding temperature is 972°C). The temperature at gas turbine exit (Temperature out gas turbine) varies from 468 and 491°C (steady state temperature is 450°C).

Figure 6 shows that the variation of fuel use and exhaust gas fuel through time. The fuel use is varied between 1023 and 1089 kg h^{-1} while the exhaust gas flow varies 76936 and 77089 kg h^{-1}. The steam generated through time. The generated steam varies between 10765 and 11433 kg h^{-1}.

Figure 7 shows the plot of power absorbed by the compressor and turbine varies through time. The power absorbed by compressor varies between 27.3 and 28.7 MJ h^{-1} while the ISO condition is 2.6×10^7 J h^{-1}. The power generated from the gas turbine system ranges from 42.7 and 43.9 MJ h^{-1} while the power in ISO condition is 4.29×10^7 J h^{-1} because of different air density entering into gas turbine system.

Figure 8 shows the variation of steam production through time. The steam production varies between 10750-111150 kg h^{-1}.

Effect of ambient temperature and fuel use on power and steam generation: The data extracted from the transient simulation results from Fig. 5-8 to study the effect of ambient temperature and fule injection on power and steam generation. Figure 9 shows that the varation of turbine power with respect to ambient temperature. As can be seen in plot, the turbine power deceases while the ambient temperature increases. Twenty percent variation of ambient temperature could result about 0.7% change in turbine power with correlated coefficient (R^2) 0.85. In fact the increment of ambient temperature leads lower the air density and increase the compressor work which in turn to lower power output of turbiune. Rahman *et al.*[15] and Ibrahim and Rahman[16] have observed similar profile on the relationship between ambient temperature and power output of gas turbine power plant. Ambient temperature also affect the steam generation. The steam generation increases with increase of ambient temperature as shown in Fig. 10 and similar trend also observed with Baheta and Gilani[17]. Twenty percent change in ambient temperature may results 1.7% changes in steam generation.

Figure 11 shows that the effect of ambient temperature on exhaust gas mass flow rate. The exhaust gas flow deceases while the ambient temperature increases. Twenty percent variation of ambient temperature could results 0.06% changes

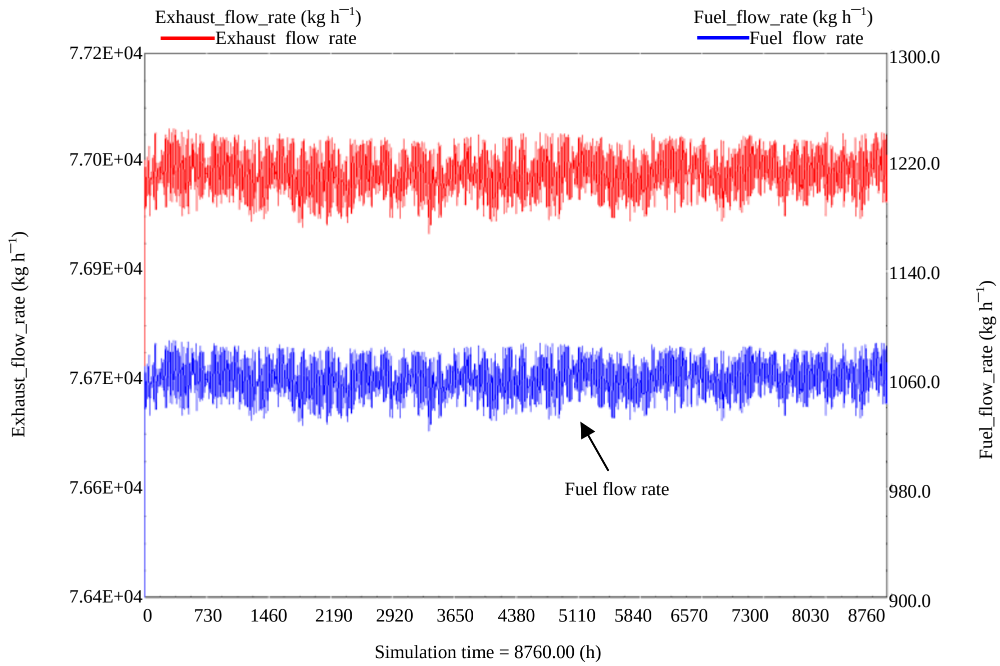

Fig. 6: Variation of fuel and exhaust mass flow rate with time

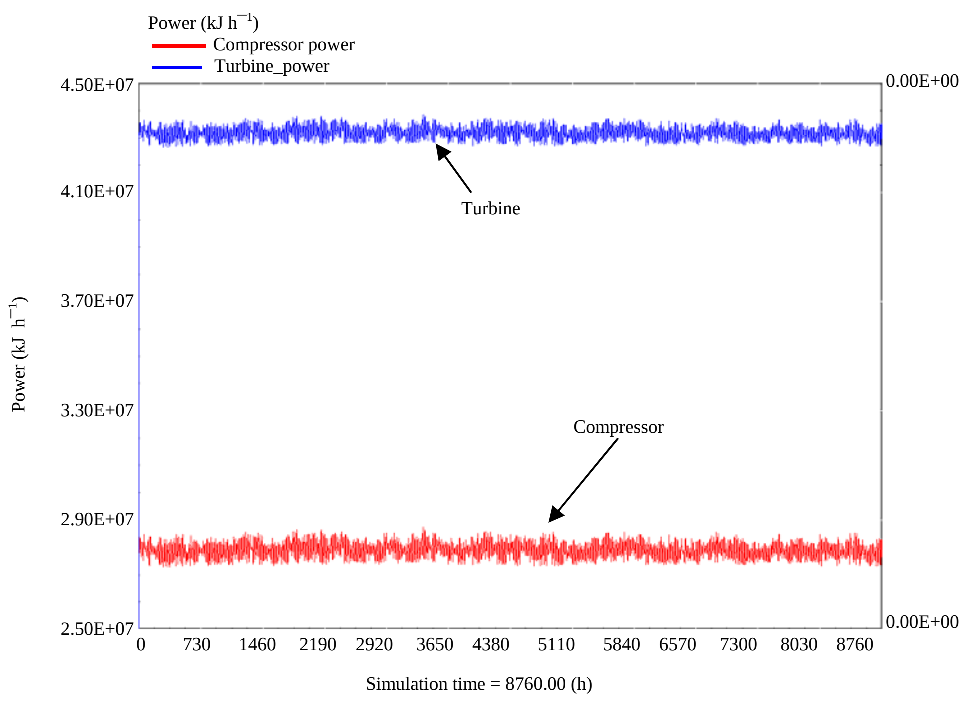

Fig. 7: Power absorbed by compressor and turbine

in exhaust fuel gas flow with correlated cofficent 1. Figure 12 indicates that the ambient temperature has direct effect on the turbine exit temperature. The ambient temperature increase the turbine exit temperature increases. According to Fig. 12, 10% change of the ambient temperature would causes a change of about 1% turbine exit temperature.

The changes in fuel flow rate also influence on the power produced and steam generated as indicated Fig. 13 and 14.

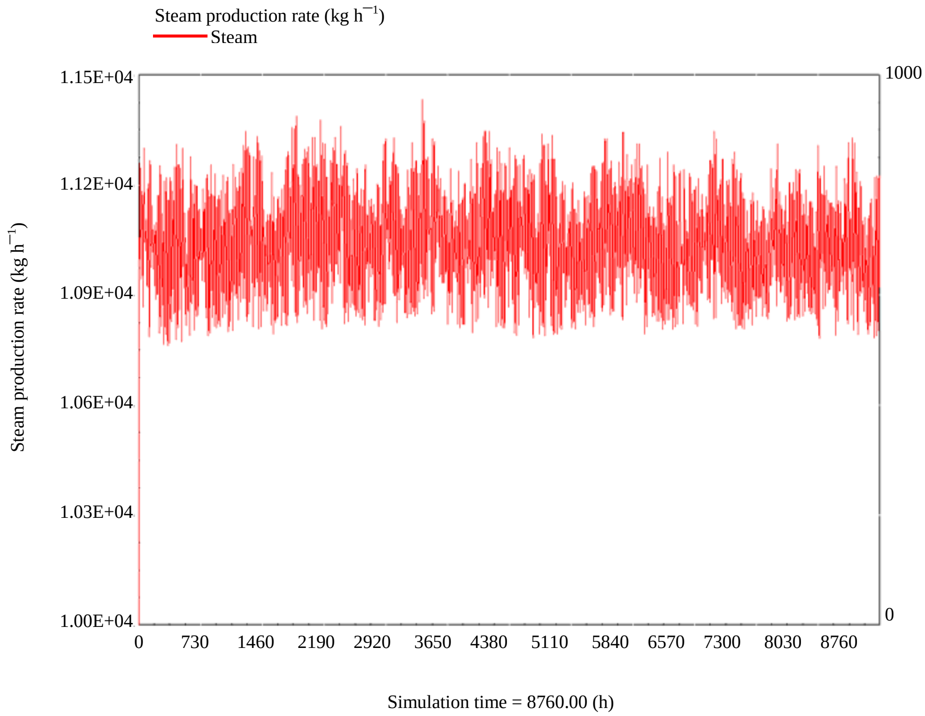

Fig. 8: Variation of rate of steam generated with time

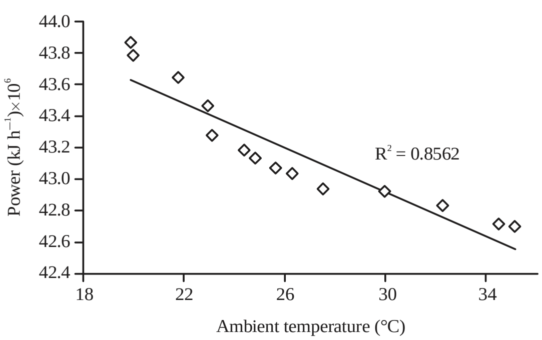

Fig. 9: Variation of ambient temperature on turbine power

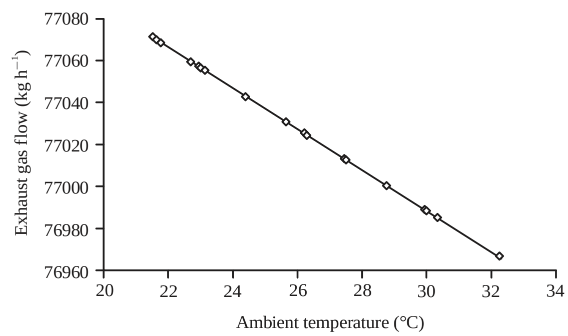

Fig. 11: Effect of ambient temperature on exhaust gas flow

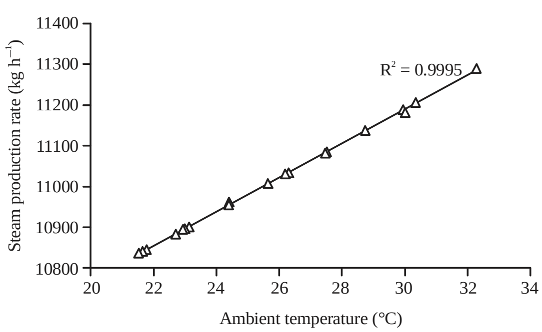

Fig. 10: Effect of ambient temperature on steam generated

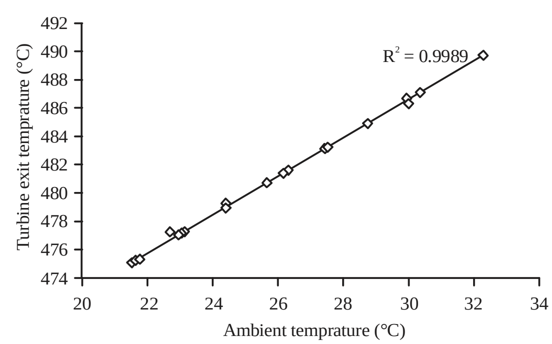

Fig. 12: Effect of ambient temperature on turbine exit temperature

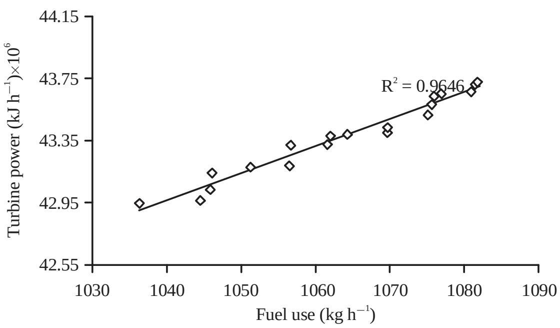

Fig. 13: Variation of mass fuel flow rate on turbine power

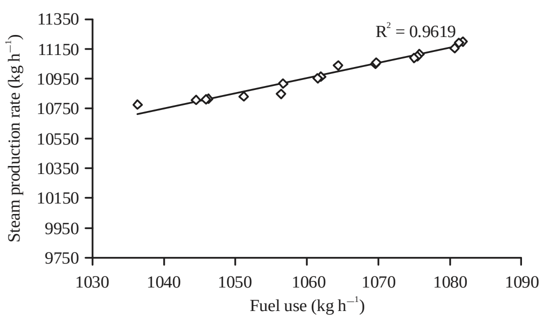

Fig. 14: Effect of fuel flow rate on steam generation

When the mass fuel flow rate increase the power absorbed by the turbine and steam generation also increases. As can be observed in Fig. 13 and 14, the 10% variation of fuel flow rate could results 3.6 and 8.7% changes in power and steam generation. In general, the simulation results show that the ambient conditions and mass flow rate may influence the turbine power and steam generated from HRSG. Therefore, the ambient temperature and mass flow rate should be monitored intruder to obtain the desire generated power and steam.

CONCLUSION

In this study, the transient simulation model of WHR system was developed. The simulation model enables to determine quantitatively the effect of ambient temperature and fuel flow rate on the production of power and steam generation. The results indicate that the increase of ambient temperature and fuel flow rate would have effect on turbine power and steam generated by waste heat recovery. Thus, the results prove that the operating condition of the waste heat recover has to be regulated for optimum production of useful energy. Hence, this study enables the operator to set the optimum operation conditions for the waste heat recovery system.

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