PARAMETRIC INVESTIGATION STUDY OF COUNTER-FLOW EVAPORATOR FOR WASTE HEAT RECOVERY

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ABSTRACT

Organic Rankine cycle system (ORC) may be used to recover waste heat from an internal combustion engine (ICE). The evaporator design in such a system is a very important task. For a successful ORC system, the amount of heat that can be received in the evaporator should be determined.

In this paper, the performance of a counter-flow evaporator used to recover exhaust waste heat from a diesel engine is presented. First, depending on the measured data, the exhaust heat of the diesel engine is evaluated. Then, a mathematical model of the evaporator is developed based on the detailed geometry and the specific ORC working conditions. The evaporator is subdivided into three zones, i.e preheater, boiler and superheater. The results show that the percentage heat flux for preheater zone is approximately 47.4% from total heat while for boiler zone it is 38.01% and for superheater zone is 14.59%. Furthermore, the heat transfer rate of each zone is proportional to that of the overall heat transfer rate when the engine operating condition changes. Consequently the percentage area for preheater zone is approximately 71% from the total area while for the boiler zone it is 26%; for superheater zone it is 3 % (in case of evaporation temperature 120ºC and superheating degree 10ºC). Results were compared with literatures and shows a very good agreement.

1. INTRODUCTION

One of the methods to improve the thermal efficiency of an internal combustion engine is the usage of, Organic Rankine cycles (ORCs) to recover the waste heat. Many studies analyzing the ORC performances have been conducted recently [1–7]. The available heat which is called as waste heat is transferred to the organic working fluid by an evaporator in an ORC, where the organic working fluid changes from a liquid state to a vapor state under a high pressure. Then, the organic working fluid, which has a high enthalpy, is expanded in an expander, and output power is generated. Therefore, the evaporator is an important part of the ORC for an engine waste-heat recovery system. In this study, the parametric investigation of a counter-flow evaporator designed to recover the exhaust waste heat from a diesel engine is evaluated theoretically. The working fluid R245fa is selected as the working fluid. A mathematical model of the evaporator is developed according to the detailed dimensions of the designed evaporator and the specified ORC working conditions.

2. SYSTEM DESCRIPTION

The schematic of an ORC for exhaust heat recovery of a diesel engine is shown in Figure 1. The pressure of fresh air is increased by the compressor. Then, the air enters the engine cylinders, which combusts with the injected fuel. After expanding in the cylinders, the high-temperature gas is exhausted to the turbine to be expanded further. In the turbine outlet, the temperature of the exhaust gas is still high between 170 ºC and 480 ºC depending on the load variations [8]. This high-temperature waste heat can be use as a heat source for ORC, for

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evaporating the working fluid in the evaporator. The evaporator, which will be used in this study is of counter - flow type.

3.NUMERICAL APPROACH

The approach used in this work draws inspiration from the work of Vargas et al. [9] where such an evaporator is assumed to be divided into three zones i.e. a preheater (Pr) , a boiler (B) and a superheater (Sp) as shown in Figure 2.

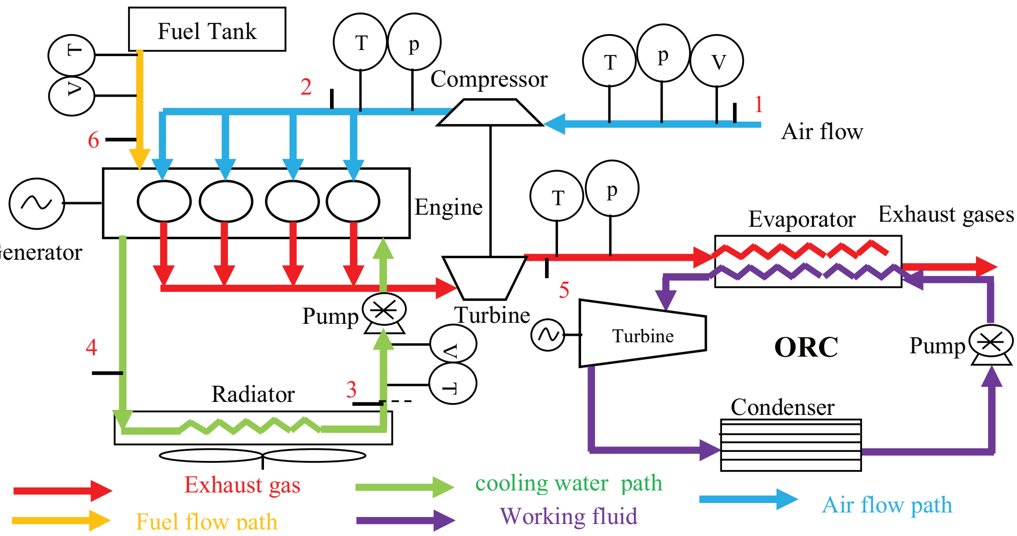

Figure 1: Schematic diagram for ICE and

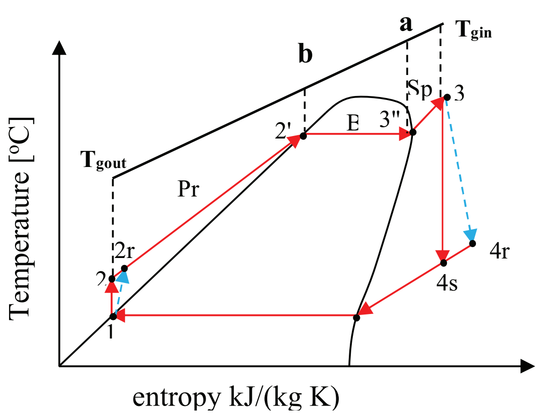

Figure 2: T-s diagram for ORC.

4. MATHEMATICAL MODEL

The mathematical model was developed based on a set of thermodynamic equations written for each zone of the evaporator and corresponding inlet and outlet parameters.

Firstly, the thermodynamic properties of the exhaust gas and the working fluids are calculated for each zone, based on the corresponding temperature and pressure levels.

Secondly, according to the energy balance, the heat transfer rate for each zone is obtained. Then, depending on the relative correlations, the heat transfer coefficients are estimated. Finally, the heat transfer area of each zone is determined.

The waste heat from exhaust gas can be determined as:

$$\dot{Q}_g = \dot{m}_g\, c_{p,g}(T_{g,in} - T_{g,out}) = \dot{m}_{ref}(h_{out} - h_{in}) = \dot{m}_{ref}(h_3 - h_{2r}) \quad [kW] \tag{1}$$

where $\dot{m}_g$ is the exhaust gases mass flow rate in [kg/s]; $\dot{m}_{ref}$ is the refrigerant mass flow rate in [kg/s]; h_3, h_{2r} are the enthalpies of refrigerant on the inlet to evaporator and outlet from evaporator, respectively in [kJ/kg K].$c_{p,g}$ is the specific heat at constant pressure of exhaust gases in [kJ/(kg K)] and $T_{g,in}$, $T_{g,out}$ are the temperatures of exhaust gases at inlet to the evaporator and outlet from evaporator, respectively in [K]. Table 1 shows the measurement data which are used in this study. The enthalpies of refrigerant on the inlet to evaporator (point 2r) and outlet from evaporator (point 3) depend on the properties of working fluid and can be calculated by using the EES program [10]. With some changes at equation (1), the refrigerant mass flow rate can be calculated as:

$$\dot{m}_{ref} = \frac{\dot{Q}_g}{(h_3 - h_{2r})} \tag{2}$$

The exhaust gases mass flow rate and the temperature of exhaust gases at inlet to the evaporator are calculate from experimental work as shown in Figure 1 [8] but the temperature of exhaust gases at evaporator outlet is assumed to be 140^{o}C [11].

Table 1: Main parameters used in the study.

Property	Value	Unit
Exhaust gases temperature at inlet evaporator [$T_{g,in}$]	480	^{o}C
Exhaust gases temperature at outlet evaporator [$T_{g,out}$]	140	^{o}C
Exhaust gases mass flow rate [m_g]	192.6	kg/s
Expander efficiency [η_{ex}]	0.9	—
pump efficiency [η_p]	0.9	—
Ambient temperature [T_{amb}]	22	^{o}C
Inside diameter of evaporator inner tube [d_i]	0.08	m
Outside diameter of evaporator inner tube [d_o]	0.09	m
Outside diameter of evaporator outer tube [d]	0.1	m

The specific heat at constant pressure of exhaust gases is depending on the medium temperature for each zone and the percentage volume of components for exhaust gases and is determined from Ref.[12,13,14]. Now the heat transfer rates of all zones are obtained from the following equations:

$$\dot{Q}_{pr} = \dot{m}_{ref}\left(h_2' - h_{2r}\right); \dot{Q}_b = \dot{m}_{ref}\left(h_3'' - h_2'\right); \dot{Q}_{sp} = \dot{m}_{ref}\left(h_3 - h_3''\right) \; [kW] \tag{3}$$

There are two sides in evaporator tube; the refrigerant side and exhaust gases side, so many equations are used to determine the heat transfer coefficients [15,16,17]. Then the overall heat transfer coefficient is determined as:

$$U_{overall} == \frac{H_{ref} * H_g}{H_{ref} + H_g} \tag{4}$$

The log mean temperature difference (LMTD) method is often used to predict the performance of a heat exchanger [18]. The LMTD is defined as:

$$\Delta T_{m,j} = \frac{\Delta T_{max} - \Delta T_{min}}{\ln\left(\frac{\Delta T_{max}}{\Delta T_{min}}\right)} \tag{5}$$

Then, the heat transfer area for each zone is calculate as:

$$A_j = \frac{Q_j}{U_j \, \Delta T_{m,j}} \tag{6}$$

where j represents preheater or boiler or superheater zones.

5. RESULTS

Based on the mathematical model, a program has been developed in EES [10,13]. The program input data is from Table 1. The results are presented in Figures (3-6). From Figure 3 it can be observed that the amount of heat for preheater and boiler zones decreases with superheating degree and for superheater zone is increasing. In conditions of constant heat input in the evaporator, the superheating increase leads to a increase of the heat received in the superheater zone and a corresponding decrease of the heat input in the preheater and boiler zones. Also, the percentage heat flux for preheater zone is approximately 47.4% from total heat while for boiler zone it is 38.01% and for superheater zone is 14.59% (with 30 ºC superheating degree).

Figure 4 shows effect of inlet turbine temperature (ITT) on the heat flux for each zone of evaporator. It can be seen another style which is the heat flux for preheater and superheater zones is increasing with (ITT) but the heat flux for boiler zone is decreasing.

Figure 5 shows effect of superheating degree on the area for all zones. It can be observed from this figure that increase in superheating degree leads to increase in the area of superheater and preheater zones while the area of boiler is decreasing. The high value is for preheater zone while the lower value is for superheater zone. In another side the effect of (ITT) on the heat exchange area of each zone is shown in Figure 6 and from this figure it can be seen a slight increase in area of superheater zone with (ITT) but in preheater zone there is marked increases. In another way in the boiler zone the area is decreasing.

From Figure 7 it can be observed that the overall heat transfer coefficient for all zones is decreasing with superheating degree and the high value is associated with the boiler zone while the lower value is for preheater zone.

Finally the effect of ITT on overall heat transfer coefficient of each zone can be seen in Figure 8 and clearly shows a slight increasing in preheater zone and high increasing in superheater zone while decreasing in boiler zone.

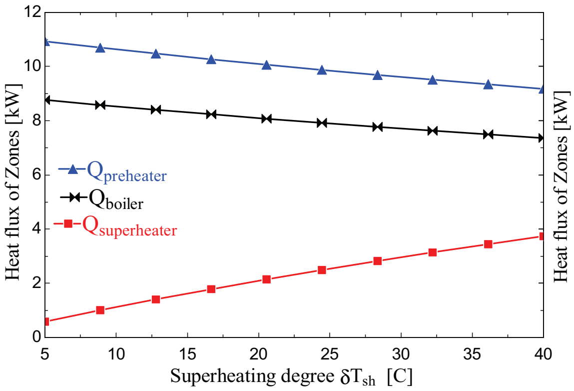

Figure 3. Effect of (SD) on the heat flux at T_c=27ºC T_{ev}=120 ºC.

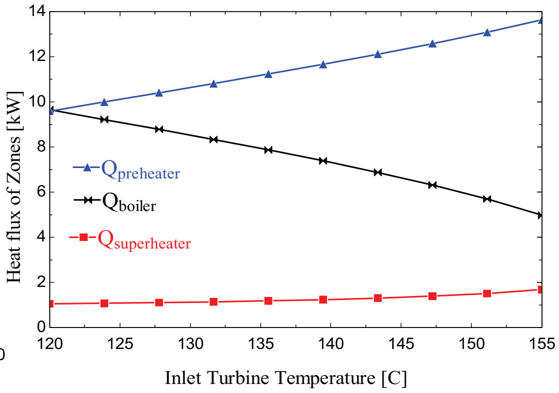

Figure 4. Effect of (ITT) on the heat flux of zone at T_c=27ºC, SD=10ºC.

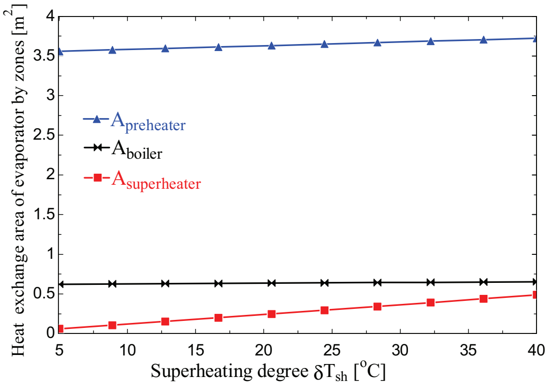

Figure 5. Effect of (SD) on the area of zone at T_c=27°C T_{ev}=120 °C.

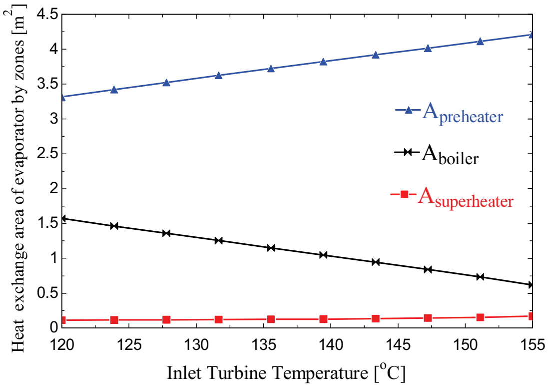

Figure 6. Effect of (ITT) on the area of zones at T_c=27°C, SD=10°C.

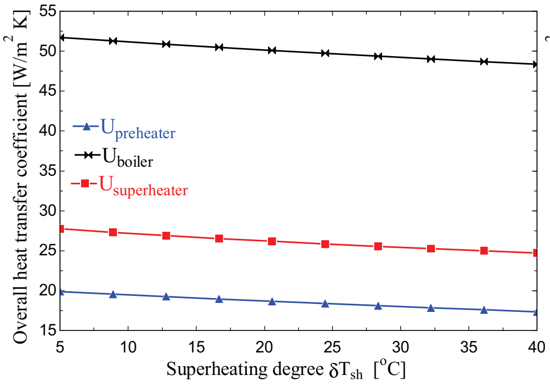

Figure 7. Effect of (SD) on the heat transfer coefficient at T_c=27°C T_{ev}=120 °C.

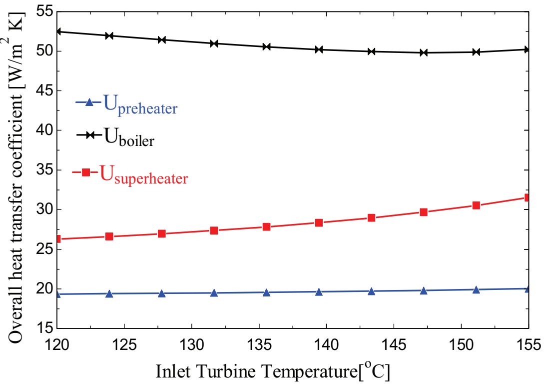

Figure 8. Effect of (ITT) on the heat flux of zone at T_c=27°C, SD=10°C.

6. Comparison

To check the validity of the results, it was necessary to compare the results with literature. The present model and calculation procedure were successfully validated by comparison with results found in Ref. [12]. The input data used in comparison are as follow: The exhaust gases temperature at evaporator outlet is 197 °C ; exhaust gases Temperature at the evaporator inlet is 528 °C; evaporation temperature T_{ev}= 131.5 °C; Degree of superheat is 35 K; Mass flow rate of exhaust gases is 0.188 kg/s. The comparison with Ref.[12] shows very good agreement.

6. CONCLUSIONS

In this study, the heat transfer characteristics of an ORC system combined with diesel engine were analyzed by using measured data such as flue gas mass flow rate and exhaust gas temperature at evaporator outlet. A mathematical model was created and developed with regard to the preheated zone, the boiler zone, and the superheated zone of a counter flow evaporator. The performance of the evaporator was evaluated under variations of superheating degree and inlet turbine temperature. Based on our analysis, the following points can be concluded:

1. The heat transfer rate of the preheated zone is the largest and is more than half of the overall heat transfer rate. The heat transfer rate of the boiler zone is higher than that of the

superheated zone. Furthermore, the heat transfer rate of each zone is proportional to that of the overall heat transfer rate when the engine operates in variable condition. In conditions of constant heat input ($\dot{Q}_g$) in the evaporator, the superheating increase leads to a increase of the heat received in the superheater zone ($\dot{Q}_{sp}$)and a corresponding decrease of the heat input in the preheater ($\dot{Q}_{pr}$) and boiler zones ($\dot{Q}_b$). Also, the percentage heat flux for preheater zone is approximately 47.4% from total heat while for boiler zone it is 38.01% and for superheater zone is 14.59% (with 30 ^{o}C superheating degree).

2. The area of superheater and preheater zones are increased with superheating degree while the area of boiler is decreased with superheating degree and high value was for preheater zone while the lower value was for superheater zone .The percentage area for preheater zone is approximately 71% from total area while for boiler zone it is 26% and for superheater zone it is 3 % (for evaporation temperature 120 ^{o}C and superheating degree 10 ^{o}C).

Acknowledgments

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