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Energy and Exergy Analysis of an Organic Rankine Cycle Using Different Working Fluids from Waste Heat Recovery

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***Abstract* -** In this study, the energy and exergy analysis of organic Rankine cycle is performed for different dry working fluids which are R600a, R600, R245fa, R123 and R113. The organic Rankine cycle's performance parameters are evaluated depending on varied evaporation temperatures and the inlet temperatures of the waste hot fluid. Results show that the best performance results are obtained for R600a considering the thermal efficiency, exergy efficiency, net power and lower total irreversibility at the evaluations of both the increment of the evaporation temperature and the increment of the inlet temperature of waste hot fluid.

***Keywords* -** Energy, exergy, organic Rankine cycle, working fluid, waste heat recovery

INTRODUCTION

Nowadays, energy has become a major issue in ensuring that countries provide a competitive advantage. The technological innovations, increasing the permeability of international borders, capital mobility and development of communication cause increasing the amount and speed of energy use. For this reason, energy saving and making more efficient use of energy is a vital matter for the world development due to many environmental impacts and energy shortage. In recent years, the global warming has compelled the energy planners to develop a new energy conversion technology which produces electricity without causing environmental pollution.

One of the most important ways to transform on large scale thermal energy into power is the vapor Rankine cycle. Water is used as a working fluid in this cycle. There are several advantages for water using as working fluid. These are very good thermal/chemical stability; owing to very low viscosity, less pumping work required; owing to high latent and specific heat, good energy carrier; non-toxic; non-flammable and no threat to the environment and cheap and abundant [1]. However, many problems are encountered when using water as a working fluid: need of superheating to prevent condensation during expansion, risk of erosion of turbine blades, excess pressure in the evaporator, complex and expensive turbines [2]. Because of these reasons, water is used in high temperature applications and large centralized systems. An organic or non-conventional working fluid, which has higher molecular mass and lower ebullition/critical temperature than water, is more suitable in small and medium scale power plants and low temperature applications. This technology is "Organic Rankine Cycles".

The organic Rankine cycle (ORC) is established for converting heat to electricity. The most important feature of an ORC is its capability of utilization of various kinds of low-grade heat sources for power generation [3]. Owing to its low operating temperature, an organic Rankine cycle can suitably recover heat from various sources. Useable heat resources in ORC are solar energy, geothermal energy, biomass products, surface seawater and waste heat from various thermal processes.

An ORC has several advantages over conventional vapor power plant: less heat is needed during the evaporation process; the evaporation process takes place at lower pressure and temperature; the expansion process ends in the vapor region and hence the superheating is not required and the risk of blades erosion is avoided; the smaller temperature difference between evaporation and condensation also means that the pressure drop/ratio will be much smaller and thus simple single stage turbines can be used [1].

The challenges, when ORC is used in a process, are of low thermal efficiency, limited ways to improve the work output, selection of working fluids matching to available heat source and sink temperatures and their effects on environment [3]. The performance of an ORC system is strongly related to the working fluid. The working fluid determines thermal efficiency, safety, stability, environmental impact and economic profitability of the system in an ORC. In recent years, working fluid selection for ORC has drawn significant attention. Different performance evaluation criteria lead to different optimum working fluids. For this reason, a reasonable evaluation criterion is the key issue for working fluid selection.

Many studies on ORC have been presented in the literature. For example, Liu *et al.* [4] used total heat-recovery efficiency and heat availability instead of thermal efficiency as the evaluation criteria to optimize the working fluid and operating conditions for organic rankine cycle. Chen *et al.* [5] compared the system performance between a supercritical Rankine cycle using CO_2 as working fluid and a subcritical ORC using R123 as working fluid. Kanoglu and Bolatturk [6] assessed the thermodynamic performance of the Reno (Nevada, USA) binary plant. This plant uses geothermal fluid at 158 ^{o}C and isobutane as working fluid. Roy *et al.* [3] analyzed non-regenerative organic Rankine cycle, based on the parametric optimization, using R-12, R-123, R-134a and R-717 as working fluids superheated at constant pressure. Gao *et al.* [7] analyzed the performance of supercritical ORC driven by exhaust heat using 18 organic working fluids. Wang *et al.* [8] analyzed a double Organic Rankine Cycle for discontinuous waste heat recovery. Wang *et al.* [9] optimized the working fluid and parameters of ORC system with simulated annealing algorithm for 13 working fluids. Kaska [10] analyzed a waste heat driven organic Rankine cycle and assessed performance of the cycle and pinpoint sites of primary exergy destruction using actual plant data. Imran *et al.* [11] assessed the economic assessment of greenhouse gas (GHG) reduction through waste heat recovery using organic Rankine cycle (ORC). Zhu *et al.* [12] assessed the performances of ORC under saturated expansion using organic dry and isentropic fluids, and under superheated expansions using organic wet fluids.

The brief review above shows that the types of working fluids have a significant influence on the performance of ORC. In this paper, with the light of studies in literature, the energy and exergy analysis of subcritical organic Rankine cycle is performed for different dry working fluids which are R600a, R600, R245fa, R123 and R113. The organic Rankine cycle's performance parameters are evaluated depending on varied evaporation temperatures and the inlet temperatures of the waste hot fluid. The exergy efficiency, thermal efficiency, the total-heat-recovery efficiency, the irreversibility rate, the net power, the evaporation pressure, the outlet temperature of waste hot fluid or the evaporation temperature are calculated with the various evaporation temperatures and the inlet temperatures of the waste hot fluid. Results from the analyses show that both evaporation temperature and the inlet temperature of hot fluid have significant effect on the performance parameters of an ORC. Also the R600a working fluid produces higher thermal efficiency, exergy efficiency, net power and lower total irreversibility rate under accepted conditions in compared with other working fluid.

MATERIAL AND METHOD

A) Basic Organic Rankine Cycle

The schematic diagram of a simple ORC system is shown in Figure 1. It includes four components: evaporator, expander, condenser and pump. An ORC is composed of four phases:1-2: Pressure increase in the condensate in the feed pump from pressure p_1 to p_2; 2-3: Isobaric heating, evaporation and overheating of the working medium in the evaporator at pressure $p_2 = p_3$; 3-4: Expansion of the vapor working medium in an expansion machine from pressure p_3 to p_4; 4-1: Isobaric heat release, complete condensation and possible under-cooling of the working medium in the condenser at pressure $p_4 = p_1$.

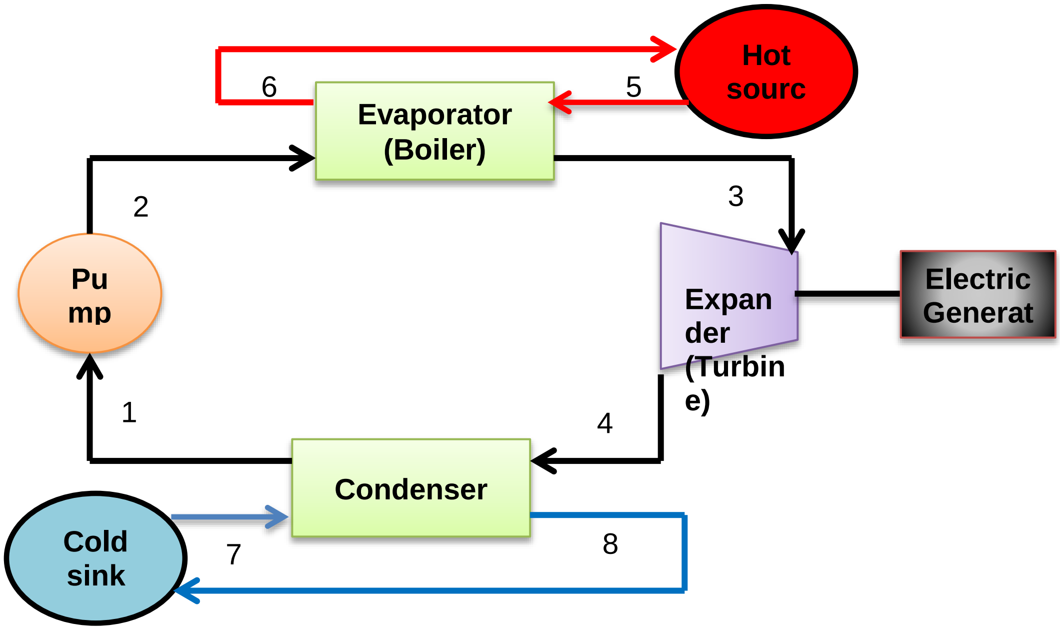

Figure 1: Schematic diagram of organic Rankine cycle

In this study, R600a, R600, R245fa, R123 and R113 dry fluids are selected as the working fluids. Table 1 shows the thermo-physical properties of the selected fluids. It can be seen from Table 1 that R600a has the lowest value of critical temperature. It is followed by R600, R245fa, R123 and R113 respectively.

Table 1: Thermo-physical properties of the selected fluids [13]

Parameters	**R600a**	**R600**	**R245fa**	**R123**	**R113**
Molecular mass (g/mol)	*58,12*	*58,12*	*134,05*	*152,93*	*187,38*
Maximum temperature (K)	*575,00*	*575,00*	*440,00*	*600,00*	*525,00*
Maximum pressure (MPa)	*35,00*	*12,00*	*200,00*	*76,00*	*200,00*
Critical point temperature (K)	*407,70*	*425,00*	*427,01*	*456,70*	*487,10*
Critical point pressure (MPa)	*3,63*	*3,80*	*3,65*	*3,66*	*3,39*
Critical point density (kg/m^3)	*225,50*	*228,00*	*519,43*	*550,00*	*560,00*
Boiling point temperature (^{o}C)	*-11,68*	*-0,5273*	*15,18*	*27,78*	*47,59*

B) System Description and Modeling

The analysis of an ORC based on thermodynamic laws and the energy, exergy analyses were performed for the working fluids investigated. For simplicity, the following assumption were made: all processes are operating at steady state; the thermal and friction losses in the pipes are negligible; the kinetic and potential energy changes are negligible; pressure drops of working fluid in the evaporator and condenser is neglected; there are only two pressures: an evaporating pressure p_e and a condensing pressure p_c; the inlet temperature of hot waste fluid in evaporator is 130 ^{o}C; the isentropic efficiency of turbine and the pump are 0,80; atmospheric condition is taken as 100 kPa and 293,15 K; The mass flow rate and the specific heat capacity of the waste hot fluid are 1 kg/s and 1 kJ/kgK respectively; the minimum temperature difference in the evaporator is 5 K; the cooling medium temperature T_L is 293,15 K.

For any steady state control volume, by neglecting the potential and kinetic energy changes, general expression of mass, energy and exergy balance equations is that:

Mass balance equation: $$\sum \dot{m_{in}} = \sum \dot{m_{out}} \tag{1}$$

Energy balance equation: $$\dot{E_{in}} = \dot{E_{out}} \tag{2}$$

$$\dot{Q} + \dot{W} = \sum \dot{m_{out}}\ h_{out} - \sum \dot{m_{in}}\, h_{in} \tag{3}$$

Exergy balance equation: $$\sum \dot{Ex_{in}} - \sum \dot{Ex_{out}} - \dot{Ex_d} = \Delta \dot{Ex_s} \tag{4}$$

Where for a steady-state system, $\Delta \dot{Ex_s}$ is zero. $$\dot{Ex_{in}} = \dot{Ex_{out}} \tag{5}$$

$$\dot{Ex_{heat}} + \dot{W} = \dot{Ex_{out}} - \dot{Ex_{in}} + \dot{I} \tag{6}$$

where, subscripts in and out represent the inlet and exit states, $\dot{Q}$ is heat input, $\dot{W}$ is work input, $\dot{Ex}$ is exergy rate and $\dot{I}$ is the irreversibility rate.

Process 1-2 (pump):

The isentropic efficiency: $\eta_p = (h_{2s} - h_1)/(h_2 - h_1)$ (7)

The pump power: $\dot{W}_p = \frac{\dot{m}_{wf}(h_{2s} - h_1)}{\eta_p} = \dot{m}_{wf}(h_2 - h_1)$

(8)

The irreversibility of the pump: $\dot{I}_p = \left(\dot{E}_1 - \dot{E}_2\right) + \dot{W}_p = \mathrm{T}_0 \Delta S_p$ (9)

Process 2-3 (evaporator):

During the above heat exchange, the temperature of hot fluid decreases from T_5 to T_6. The specific heat capacity C_p of the hot fluid at constant pressure is assumed to be constant.

The evaporator heat rate: $\dot{Q}_e = \dot{m}_{wf}(h_3 - h_2) = \dot{m}_{hf}(h_5 - h_6)$ (10)

$\dot{Q}_e = \dot{m}_{hf} Cp(T_5 - T_6)$ (11)

The irreversibility of the evaporator: $\dot{I}_e = T_0 \ \dot{m}_{wf} \left[(s_3 - s_2) - \frac{2(h_3 - h_2)}{(T_5 + T_6)}\right]$ (12)

Process 3-4 (expander):

The isentropic efficiency: $\eta_t = (h_3 - h_4)/(h_3 - h_{4s})$ (13)

The expander power: $\dot{W}_t = \dot{m}_{wf}(h_3 - h_{4s})\eta_t = \dot{m}_{wf}(h_3 - h_4)$ (14)

The irreversibility of the turbine: $\dot{I}_t = \left(\dot{E}_3 - \dot{E}_4\right) - \dot{W}_t = \mathrm{T}_0 \Delta S_t$ (15)

Process 4-1 (condenser):

The condenser heat rate: $\dot{Q}_c = \dot{m}_{wf}(h_4 - h_1)$ (16)

The irreversibility of the condenser: $\dot{I}_c = T_0 \ \dot{m}_{wf} \left[(s_1 - s_4) - \frac{(h_1 - h_4)}{T_L}\right]$

(17)

The net power output: $\dot{W}_{net} = \dot{W}_t - \dot{W}_p$ (18)

The thermal efficiency (η_{th}) of the ORC is the ratio of the net power output to the heat input. It can be expressed as:

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_e} = \frac{\dot{W}_t - \dot{W}_p}{\dot{Q}_e} \tag{19}$$

The exergy destruction rate of ORC:

$$\dot{I}_{cycle} = T_0 \; \dot{m}_{wf} \left[-\frac{2(h_3 - h_2)}{(T_5 + T_6)} - \frac{(h_1 - h_4)}{T_L} \right] \tag{20}$$

The exergy efficiency of ORC:

$$\eta_{exe} = \frac{\dot{W}_{net}}{\dot{W}_{net} + \dot{E}_d} = \frac{\dot{W}_{net}}{\dot{Q}_e\left(1 - \frac{2T_L}{(T_5 + T_6)}\right)} \tag{21}$$

The total heat-recovery efficiency, defined as the ratio of net power to the available energy in ideal case [14]:

$$\eta_r = \frac{(T_5 - T_6)}{(T_5 - T_0)} \, \eta_{th} \tag{22}$$

RESULTS AND DISCUSSION

A) The Analysis of Various Evaporation Temperatures

The evaparation temperature and the inlet temperature of hot fluid effect the performance analysis of an organic Rankine cycle. Therefore, we focused on two variables in this study. Firstly, the evaporation temperature was increased from 70 ^{o}C to 110 ^{o}C with a 5 ^{o}C and then the exergy efficiency, thermal efficiency, the total-heat-recovery efficiency, the irreversibility rate, the net power, the outlet temperature of waste hot fluid and the evaporation pressure were calculated for the various evaporation temperatures. The inlet temperature of the waste hot fluid was 130 ^{o}C.

According to the analysis, the thermal efficiency, the outlet temperature of waste hot fluid and the evaporation pressure increase when the evaporation temperature increases for the R600a working fluid. Nevertheless, the total heat-recovery efficiency, the total cycle the irreversibility rate, the net power decrease with the evaporation temperature. The exergy efficiency is parabolic-like function with evaporation temperature.

When compared the net power of the working fluids, according to Figure 2 for all of the working fluids, the net power increases before and then decreases with the increase of the evaporation temperature. In addition, the highest net power is obtained for the R600a working fluid with 10,52 kW. This is followed by R600, R245fa, R123 and R113 respectively.

Results from Figure 3 show that total irreversibility rate or exergy destruction decreases with evaporation temperature. The minimum total irreversibility rate is obtained for the R600a working fluid. Also, it is calculated in analysis that the components with greater exergy destructions to lower one are evaporator, expander, condenser and pump.

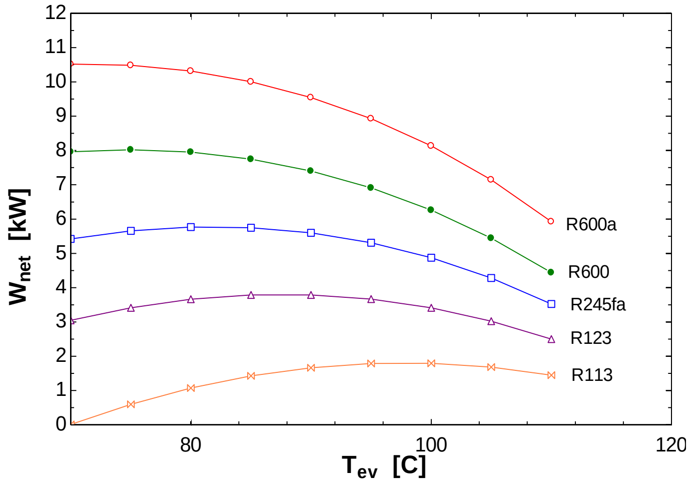

Figure 2: Comparison of the net power

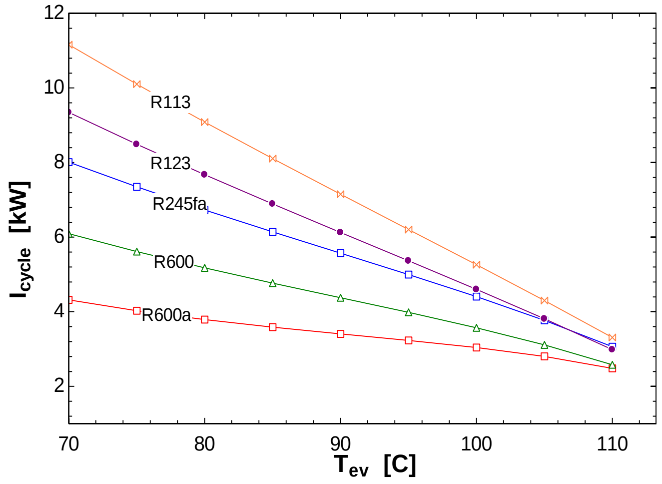

Figure 3: Comparison of the irreversibility rate

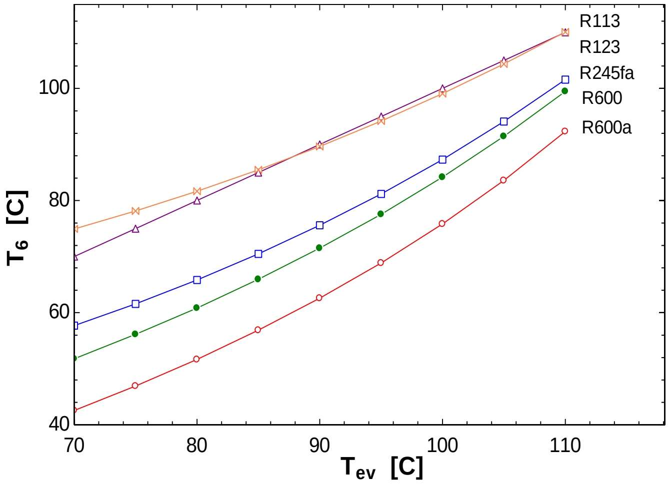

Figure 4: Comparison of the outlet temperature of hot fluid

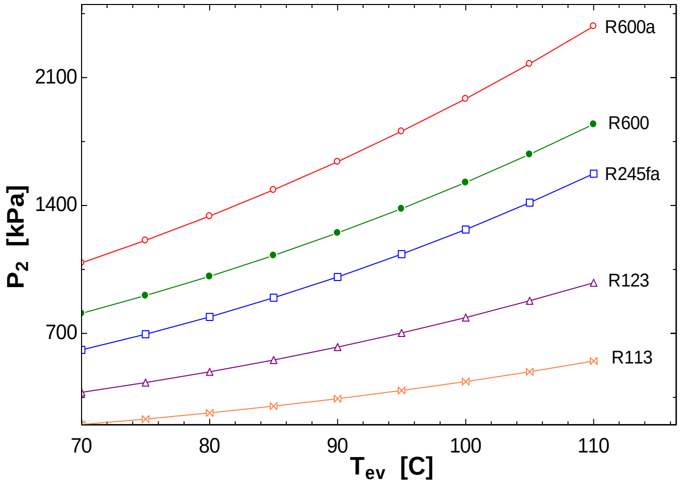

Figure 5: Comparison of the evaporation pressure

According to Figure 4, when the evaporation temperature increases in the analysis of ORC, the outlet temperature of hot fluid increases dramatically for all of the working fluids. Otherwise the lowest values are calculated for the R600a working fluid. In other words, the R600a organic fluid benefits from the heat of the waste hot fluid to use in the evaporator.

According to the results of calculations, Figure 5 shows that the evaporation temperature has important effect on the evaporation pressure which increase with evaporation temperature. In addition, the increase of evaporation pressure effects the energy and exergy efficiency of ORC. It can be seen that from Figure 6, the highest evaporation pressure value are calculated for R600 a working fluid which followed by R600, R245fa, R123 and R113.

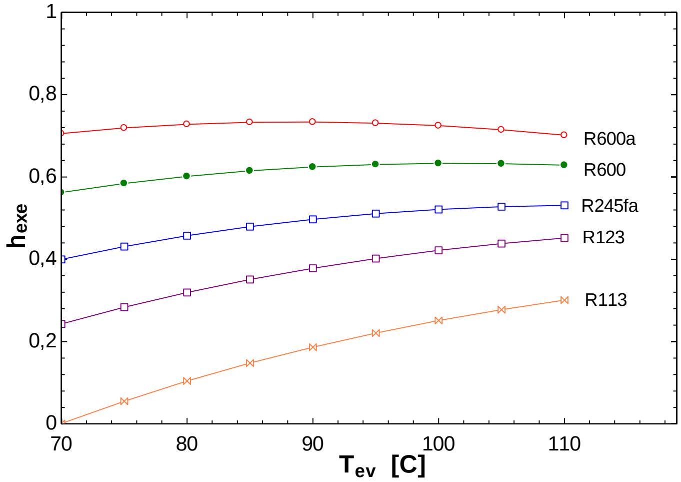

Figure 6: Comparison of the exergy efficiency

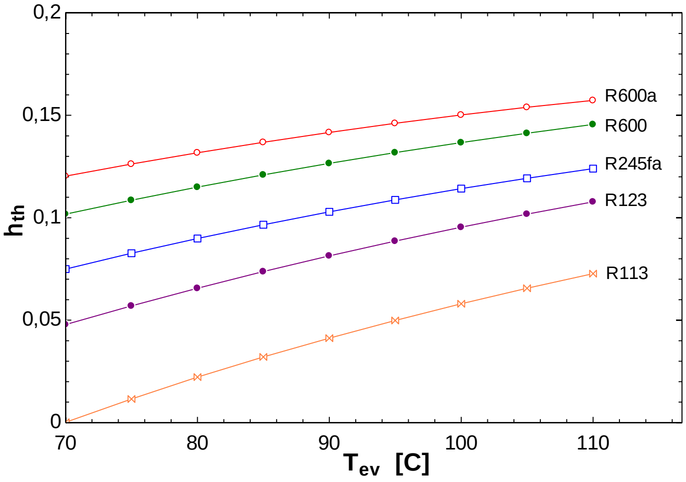

Figure 7: Comparison of the thermal efficiency

Figure 6 and Figure 7 show the comparison of the exergy efficiency and thermal efficiency for organic working fluids. The working fluids with greater both exergy efficiency and thermal efficiency to lower one are R600a, R600, R245fa, R123 and R113. When the thermal efficiency is evaluated with the net power (Fig.3), the thermal efficiency increases with the increment of the net power however the net power decreases, the thermal efficiency still increases which shows that the effect of the increase of evaporation temperature on the decrease of the heat absorbed by the working fluid (Qev) is greater than on the decrease of the net power (Wnet).

The total heat-recovery efficiency which has the same trend with the net power is calculated in its higher value for R600a working fluid as shown in Figure 8. As Equation (22), Figure 4 and Figure 8 are commented together, it can be seen that the increase of the outlet temperature of the hot fluid is more effective than the increase of the thermal efficiency on the total heat-recovery efficiency.

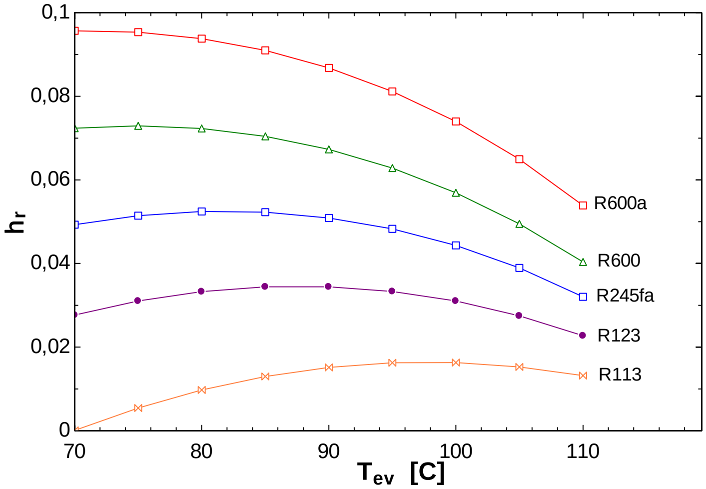

Figure 8: Comparison of the total heat-recovery efficiency

B) The Analysis of Various Inlet Temperatures of Hot Fluid

After the evaporation temperature has been examined, the effect of the various inlet temperatures of hot fluid on the performance of an ORC is evaluated in this section. The evaporation temperature was assumed to be 70 ^{o}C. The outlet temperature of the hot fluid was increased from 100 ^{o}C to 140 ^{o}C with a 5 ^{o}C and then the exergy efficiency, the total-heat-recovery efficiency, the irreversibility rate, the net power and the outlet temperature of waste hot fluid were calculated for the various inlet temperatures.

According to the analysis, the thermal efficiency and the evaporation pressure did not change with the inlet temperature of hot fluid. In addition, the exergy efficiency, the outlet temperature of waste hot fluid and the evaporation pressure decrease when the inlet temperature of hot fluid increases for all of the working fluids. On the other hand, the total heat-recovery efficiency, the total cycle the irreversibility rate, the net power increase with the inlet temperature of hot fluid.

According to Figure 9 for all of the working fluids, the net power increases with the increment of the inlet temperature of hot fluid. In addition, the maximum net power is obtained in 140 ^{o}C for the R600a working fluid with 12,27 kW. This is followed by R600, R245fa, R123 and R113 respectively.

Results from Figure 10 show that total irreversibility rate or exergy destruction increases with the inlet temperature of the hot fluid. The minimum total irreversibility rate is calculated for the R600a working fluid. The value of the total exergy destruction is calculated as be 0,46 kW and 4,45 kW at the inlet temperature of hot fluid 100 °C and 140 °C respectively.

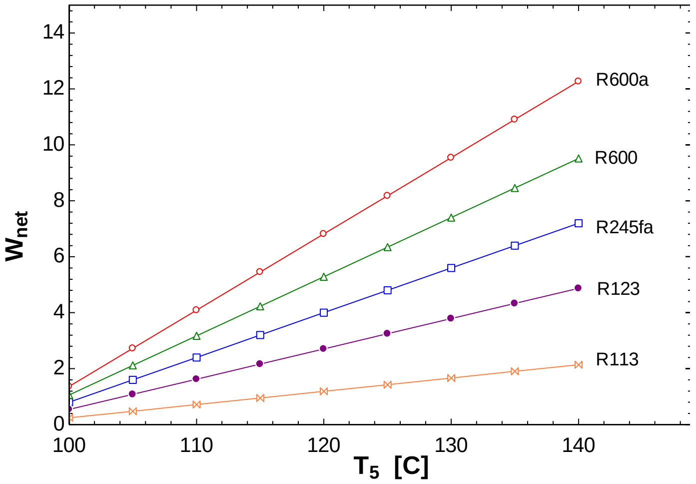

Figure 9: Comparison of the net power

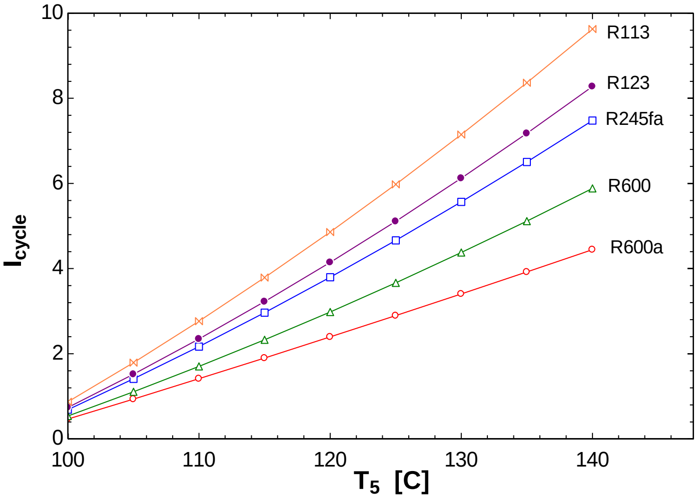

Figure 10: Comparison of the total irreversibility rate

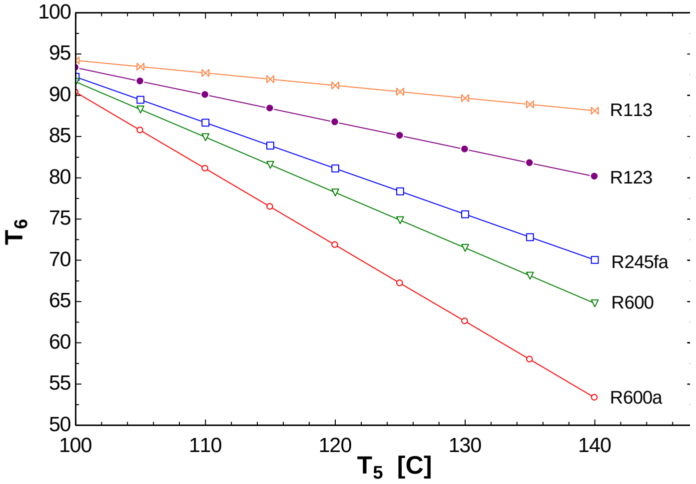

Figure 11: Comparison of the outlet temperature of hot fluid

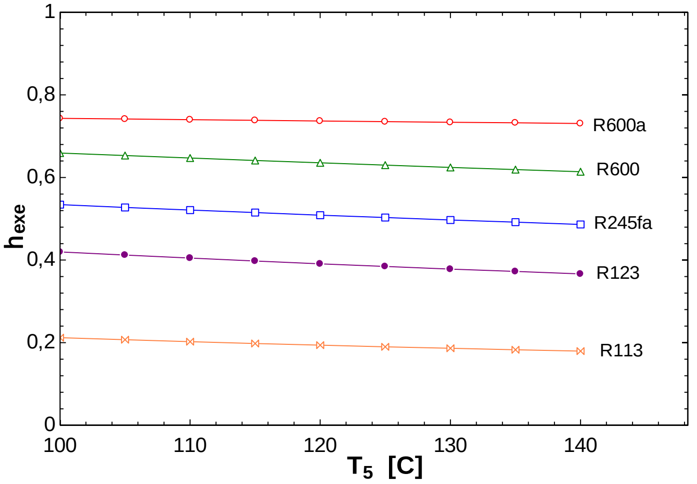

Figure 12: Comparison of the exergy efficiency

As compared the outlet temperature of hot fluid for the working fluids, when the inlet temperature of hot fluid increases in the analysis of ORC, the outlet temperature of hot fluid decreases significantly for all of the working fluids as shown in Figure 11. Otherwise the lowest values of the outlet temperature of working fluid are calculated for the R600a working fluid. In other words, the R600a organic fluid benefits more from the heat of the waste hot fluid to use in the evaporator.

According to Figure 12, the exergy efficiency reduces with the growth of the outlet temperature of hot fluid. When the equation (21) and Figure 12 are commented, it can be shown that the effect of the inlet heat in evaporator on the exergy efficiency is greater than the effect of the increment of the net power on the exergy efficiency. In addition, the highest exergy efficiency is calculated as be 72,81% at the inlet temperature of 100 ^{o}C for the R600a.

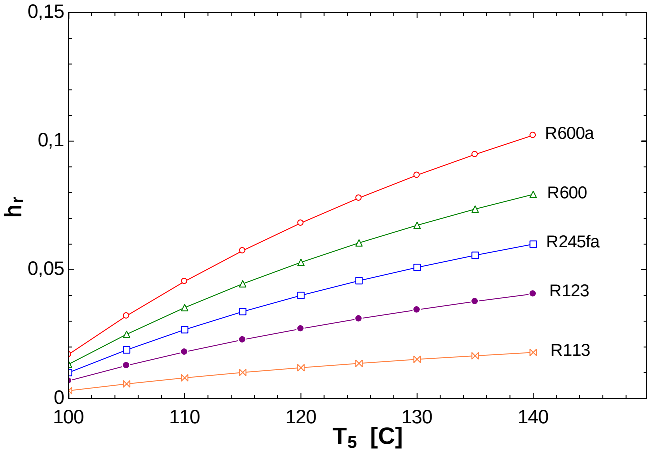

Figure 13: Comparison of the total heat-recovery efficiency

The total heat-recovery efficiency which increases with the growth of the outlet temperature of hot fluid, is calculated in its the maximum value for R600a working fluid as shown in Figure 13. As Equation (22) and Figure13 are commented together, it can be said that the increase of the inlet temperature of the hot fluid is effective on the total-heat recovery efficiency because of the stability of the thermal efficiency.

CONCLUSION

The selection of working fluids according to appropriate evaporation temperature and the inlet temperature of the hot fluid have a significant influence on the performance of an ORC. The working fluid of an ORC determines thermal efficiency, safety, stability, environmental impact and economic profitability of the system. So, in this paper, an ORC with the subcritical and saturated expansion is analysed based on thermodynamic theory. The results obtained from the calculations are compared for five types of working fluids which are R600a, R600, R245fa, R123 and R113. According to analysis, the best performance parameters are calculated for the R600a working fluid considering the thermal efficiency, exergy efficiency, net power and lower total irreversibility at the evaluations of both the increment of the evaporation temperature and the increment of the inlet temperature of waste hot fluid.

NOMENCLATURE

ORC	organic Rankine cycle	Subscripts	
h	specific enthalpy, kj/kg	c	condenser
s	specific entropy, kJ/kgK	e	evaporator
$\dot{m}$	mass flow rate, kg/s	exe	exergetic
$\dot{E}$	Energy, kW	hf	hot fluid
$\dot{Ex}$	Exergy, kW	net	net
$\dot{Q}$	Heat rate, kW	p	pump
$\dot{W}$	Power, kW	pp	pinch point
$\dot{I}$	Irreversibility, kW	o	ambient
T	Temperature, K	s	isentropic case
T_L	The low temperature of cold source, K	t	turbine
		e	evaporator
ΔT	Temperature differential, K	wf	working fluid
η	Efficiency	th	thermal

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