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Small-Scale Organic Rankine Cycle Performance Using an Additional Heat Exchanger

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Abstract: The Organic Rankine Cycle (ORC) power generation system is a unique approach to heat recovery which substitutes an organic fluid with a low boiling point for water. To improve its lower thermal efficiency and maximum power generation, an Internal Heat Exchanger (IHE) is proposed after the expansion scroll expander. Using a small-scale scroll expander ORC testing facility as the simulation model, this study analyzes the net thermal efficiency and energy consumption of the ORC system with and without the IHE under conditions of equivalent power output. While the working fluid's outlet temperature in the evaporator was adjusted from 70 to 130 degrees Celsius, the outlet condenser temperature was kept constant at 55, 60, and 65 degrees Celsius. In the numerical simulation of the small-scale ORC, five distinct working fluids, including R245fa, R123, R1233zd, n-Pentane, and R141b were assessed. The results indicated that R245fa had the largest recuperation effect on the working fluid, followed by n-Pentane, R1233zd, R123, and R141b, with a total thermal energy reduction of 3.34 kW, 2.63 kW, 2.06 kW, 1.9 kW, and 0.92 kW, respectively. In conclusion, the installation of IHE in ORC units leads to improved thermal efficiency and maximum power generation.

Keywords: ORC, IHE, thermal efficiency, small-scale, R245fa, R123, R1233zd

1. Introduction

The challenge of today's world is how much capability it is to utilize new renewable energy that produces zero carbon emissions. Net zero emissions are directly correlated to CO_2 levels as well as global warming which is essential for the future resilience of this planet. Most countries around the world are moving towards green economic growth and low carbon emissions by reducing greenhouse gas (GHG) emissions. Energy transition to net zero emission is part of the commitment to support the Sustainable Development Goals (SDGs) and Nationally Determined Contributions (NDCs), one of which includes affordable and clean energy. Nonetheless, renewable energy will continue to play a significant role in the energy mix until 2050, with some considering it as a possible substitute and replacement for fossil fuels. According to statistical analyses, low- to medium-grade waste heat contributes for more than 50% of the total heat released in industry. In many applications, including geothermal energy2,3,4), biomass energy5), ocean thermal6), solar energy6,7), and automobile vehicles8), the Organic Rankine Cycle (ORC) is a well-known alternative technology to recover waste heat from low-medium grade heat sources. Indonesia has geothermal potency of 29 GW9,10) and also needs ORC technology to utilize low enthalpy geo fluid11). It is an effective method for converting heat energy which is fairly free from heat sources into electricity. Furthermore, due to its compact, adaptability, serviceability, and increased performance compared to other waste heat technologies, the ORC has a great potential and is widely used. Recently, the ORC system added components of an internal heat exchanger (IHE) which to reduce heat load by taking the remaining heat of the fluid flow that leaves the turbine expander. Even though ORC uses organic working fluids rather than water, it is fundamentally very similar to the steam Rankine cycle. The performance of the thermodynamic cycle depends on the choice of the right working fluids. Working fluids were taken into consideration based on criteria such as the critical temperature, the heat source, the type of expander, the thermophysical fluid properties, as well as the environment and safety considerations. Moreover, simultaneously choose the designs for each of its parts.

Non-toxic, non-flammable, non-corrosive, low GWP and ODP, non-aggressive, also not very heavy conditions should be fulfilled by working fluids[5,7].

Several researchers have proposed and discussed the thermodynamic performance of an ORC unit with an IHE. According to certain research, the installation of an IHE enhances thermodynamic performance, such as thermal efficiency and energy efficiency[12,13,14,15]. Even the investigation of Guo et al.[15] and Saleh et al[16] is capable of a more significant enhancement with a combination of IHE and superheat. This research demonstrates that IHE is crucial for ORC from a thermodynamics point of view and significantly influences the cycle performances. The IHE component provides for a 1%–3% efficiency improvement across the cycle without a recovery, with little to no change in the specific work. Unfortunately, studies on the total impact of IHE on ORC are scarce. Roy[17] described how recovering at 150 ºC with working fluid R123 & R134a gaining the consistent superheat affected the waste heat recovery system. Muslim[18] also investigated R134a using expander system. As well as Liu[19] through the utilization of brine water in the range of 100 ºC – 150 ºC using R600, R600a, R601, R601a, and hexane. Sharma reviewed many working fluids on different applications and modification various configurations of cycle ORC[6].

An ideal schematic process of the small-scale ORC with IHE is depicted in Fig 1. As a result, the working fluids were chosen with the temperature range in consideration in order to improve thermal efficiency and power output[20,21,22]. Some experimental studies[17,23,24] and reviews[20,21,22,25] regarding various types of working fluids have been investigated to gain thermodynamic performance analysis. Finally, ORC technology is expected to be able to answer the challenges of environmental impacts[26] on geothermal energy and electric generation for low & medium temperatures[27].

In addition to comparing the results of the existing ORC with IHE and ORC without IHE in terms of net thermal efficiency and energy consumption evaporator at equivalent power output conditions, this study aims to evaluate five different working fluids, i.e R245fa, R123, R1233zd, n-Pentane, and R141b. Also, the temperature of evaporation varies from 70°C to 130°C with a 5°C increase, which is referred to as low-grade heat. The goal of our research is to offer further prediction and improvement for small-scale ORC units for low heat recover that use thermal oil as a heat source. The architecture of the small-scale facility ORC, which is suggested in Table 2, served as the model for the Rankine cycle system's approach.

2. System description

Table 1. The characteristics of the organic fluids employed in this case study[20,21]

Fluids	Molecular weight (kg/Kmol)	Normal Boiling point (ºC)	Critical pressure (bar)	Critical temperature (ºC)
R245fa	134.05	14.90	42.5	154.05
R123	152.93	27.8	36.6	183.83
R1233zd	130.5	18.1	35.7	166.5
R141b	116.95	32.05	42.1	204.5
n-pentane	72.15	36	33.7	196.7

Heat transfer fluid (HTF) from around 70 ºC to 130 ºC was conceived and produced as a small-scale ORC with a 2 kW capacity using R245fa as the working fluid. Fig. 1 and 2 depict the schematic layout process diagram of the 2 kW ORC system and ORC testing facility. Induction generator, centrifugal pump, plate heat exchanger (PHE) type evaporator, shell-and-tube type condenser, IHE acting as recuperator, and hermetic type scroll expander are the key parts of this system. A pipe-in-pipe (tube-in-tube) heat exchanger is used in an IHE, where one fluid stream flows within the inner pipe and the other stream flows in the annulus created by the coaxial pipes. The direction of flow fluid in an IHE was a counter-flow configuration in which two kinds of fluids enter from different sides. It is very profitable and efficient to reach temperature differences and obtain the great change in temperature of each fluid. At the intake and outflow of each major component, temperature and pressure sensors were fitted. At the centrifugal pump's outlet, a vortex flowmeter was mounted to measure the rate of working fluid flow, and a power meter was used to gauge the amount of energy produced, which includes the voltage, current, power, and power factor. A pump with a variable frequency was used to regulate the working fluid's flow rate variance. The specification of the main components and their surrounding are described in Table 2.

Modeling the primary component allows for an investigation of the system's performance under a range of different working conditions. The model has taken into account the parameter inputs, such as changes in working fluid temperature at the evaporator and working fluid temperature remaining in the condenser; thermal oil mass flow rate; and ORC pressure. The quantity of data needed for the evaporator and condenser models is reduced since the outlet temperatures of the thermal oil and cooling water are both assumed to be controlling factors. EES software is used to forecast a net thermal efficiency as a function of the evaporator's heat load, the condenser's heat sink, the organic fluid's mass flow rate, the thermal oil's mass flow rate, and other factors. A net thermal efficiency is predicted using EES software as a function of the evaporator's heat load, the condenser's heat sink, the mass flow rates of the organic fluid and thermal oil, the saturation temperature and the organic fluid's intake temperature

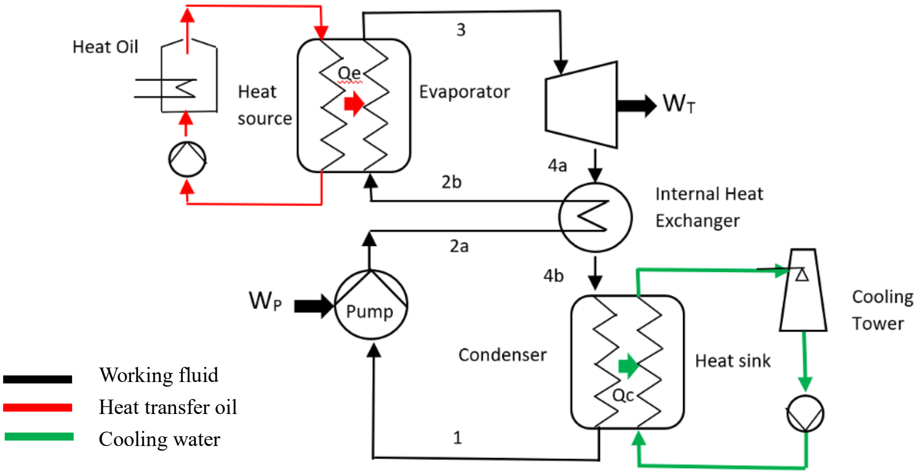

Fig. 1: Schematic process diagram of ORC with IHE

Table 2. specification of testing facility ORC is proposed in this study

Components	Descriptions
ORC type	Scroll expander, capacity 2-3 kW
Working fluid	Refrigerant R245fa
Expander	Hermetic-type scroll expander up to 3 kW
Pump	Rated flow 3 m^3/h, Head 92.5 m, max operating 25 bar/120 C, rate power 1.5 kW, speed 2890-2910 rpm, efficiency motor at full load 84.2%
Evaporator	Plate Heat Exchanger (PHE) type Heat transfer area 9.3 m^2, heat load capacity 30 kW Working pressure 30 bar, plate material 316, solder copper Flow arrangement countercurrent Hot oil transfer inlet 70 °C– 130 °C Capacity heater bar 12 pcs @ 4 kW
Condenser	Shell and tube type Shell volume 12.2 L Tube volume 7.4 L Temperatur inlet 30 °C, outlet 35 °C, Flow rate 11.2 m^3/h, pressure drop 6.7 kPa

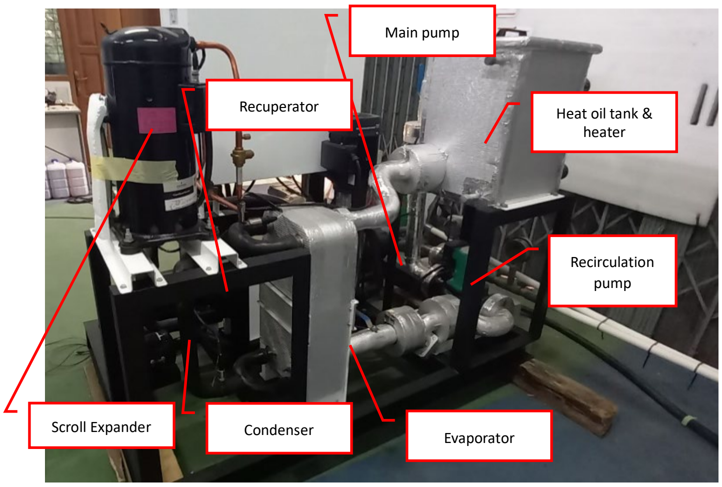

Fig. 2: Small-scale ORC testing facility was proposed

3. Thermodynamic analysis

For ease of analysis, the following assumptions were made: steady-state conditions, no pressure drop in the line system components, an equal intake and output mass flow, and the absence of lubricant in the working fluid. Equation Table 3 describes the specifics of the terms and conditions of the operating model ORC using the program Engineering Equation Solver (EES). REFPROP was used to examine the working fluids' physical characteristics. In simulations for ORC with IHE, a recuperator effectiveness assumption of around 0.7 is considered. The expander and pump are assumed to have isentropic efficiency values of 0.85 and 0.65, respectively. These values are expected to gain higher efficiency in the scroll expander where the higher pressure discharge at the pump and the lower pressure discharge at the scroll expander. Actually, the result in the simulation is usually very optimistic compared with the experimental works. The simulation result gives a predictive number for the improvement of the thermal efficiency performance system both with IHE and without IHE components.

The calculation of the energy equation of the main components that refers process diagram in Fig.1 is summarized as follows:

Table 3. Model ORC parameters and given condition

Parameter	Symbol	Value
Hot source		
Hot fluid		Thermal oil
Hot source inlet temperature	$T_{hf,in}$	[70-140] °C
Hot source outlet temperature	$T_{hf,out}$	independent
The evaporation temperature of organic working fluids	$T_{wf,out}$	[70-130] °C
Terminal temperature difference at the evaporator	TTD_{evap}	10 K
Cold source		
Cold source fluid		Water
Cold source inlet temperature	$T_{cf,in}$	30 °C
Cold source outlet temperature	$T_{cf,out}$	35 °C
Terminal temperature difference at the condensor	$TTD_{,cond}$	5 K
The condensation temperature of organic working fluids	$T_{wf,out}$	[50-60] °C
Cold source mass flow rate	m_{cond}	dependent
Cycle parameters		
Turbine inlet temperature	$T_{turb,in}$	independent
Working fluid mass flow rate	$\dot{m}_{wf}$	dependent
Pump isentropic efficiency	η_{pump}	0.65
Turbine isentropic efficiency	η_{turb}	0.85
The effectiveness of IHE	ε	0.7

No.	Component	Energy balance model with IHE	
1.	Pump	$W_P = \dot{m}_{wf}(h_{2a} - h_1)$	(1)
		$\eta_{is\_pump} = (h_{2s} - h_1)/(h_2 - h_1)$	(2)
2.	Evaporator	$Q_{evap} = \dot{m}_{wf}(h_3 - h_{2b})$	(3)
3.	Expander	$W_T = \dot{m}_{wf}(h_3 - h_{4a})$	(4)
		$\eta_{is\_exp} = (h_3 - h_4)/(h_3 - h_{4s})$	(5)
4.	Condenser	$Q_{cond} = \dot{m}_{wf}(h_{4b} - h_1)$	(6)
5.	IHE (recuperator)	$Q_{IHE} = \dot{m}_{wf}(h_{2a} - h_{2b}) = \dot{m}_{wf}(h_{4a} - h_{4b})$	(7)
		$Q_{IHE} = \dot{m}_{wf} C_p(T_{4a}-T_{4b}) = \dot{m}_{wf} C_p(T_{2b}-T_{2a})$	(8)
		$Q_{IHE} = \varepsilon\left(\dot{m}_{wf}\, C_p(T_{4a} - T_{2a})\right)$	(9)
6.	Thermal Efficiency	$\eta_{th} = \dfrac{W_T}{Q_{evap}}$	(10)
		$\eta_{net} = \dfrac{W_T - c}{Q_{evap}}$	(11)
7.	Specific work	$W = \dfrac{W_T - W_p}{\dot{m}_{wf}}$	(12)

4. Results and discussion

The comparison of the net thermal efficiency of the ORC system for 5 working fluids i.e. R245fa, R123, R1233zd, R141b, and n-pentane has been evaluated in a range of evaporator and condenser temperatures. In this study, these working fluids respectively are employed to simulate in conditions with and without IHE. By consideration, the power output and pressure ratio are constant, all variations of working fluids that applicants of IHE exhibited improvement in thermal efficiency. In addition, energy consumption for heating up of the evaporator has undergone a decline. The detailed number comparison of thermal efficiency and requirements of the total heat in evaporators in terms of various temperature evaporators for R245fa is shown in Table 4. Between IHE and non-IHE, there is a slightly linear difference in the amount of thermal energy used to increase the temperature of the working fluid in the evaporator, ranging from 0.23 kW to 3.34 kW. These numbers are equal to the total heat that recuperates in an IHE as well as the net thermal efficiency increase in the range 0.085% to 0.66%.

According to graphs in Fig. 3-7, for both conditions of with IHE and without IHE, indicate the net thermal efficiency increase along with the rise of evaporator temperature and reduction of the condenser temperature. All of the variations of the best conditions for each working fluid are found at the outlet temperature of the evaporator at 130 °C and the outlet temperature of the condenser at 50 °C.

The results of the comparative net thermal efficiency on the working fluid R245fa, R123, R1233zd, R141b, and n-Pentane in both of with IHE & without IHE are shown in Fig. 3-7, respectively. The comparison results of the thermal efficiency curve are seen significantly in line with the increase in evaporation temperature and the best result is achieved at the evaporation temperature of 130 °C and the condenser temperature of 50 °C. The results of this study have a similar trend pattern as that investigation14) which thermal efficiency is relatively increased in line with temperature evaporation in the range of 350 K – 440 K with a variation of working fluids R123, R141b, and R245ca. Likewise, the results of the comparison of thermal efficiency performance with R141b fluids in both non-IHE & IHE conditions indicated a very significant increase with installed IHE. In addition, the results of this study were also strengthened by the results of an investigation performed by Deethayat et al24) who compared thermal efficiency with zeotropic organic fluid samples where the mixture with a composition of R245fa / R152a in the temperature range of 70 °C – 100 °C on both condition basic ORC & within IHE.

A summary of the variations in the working fluid that undergoes thermal efficiency improvements is shown in Fig. 8 where the best thermal efficiency increase is achieved by n-Pentane and then followed by R123, R245fa, R1233zd, and R141b with the following number as follows: 1.33%, 0.74%, 0.66%, 0.57%, 0.45%, respectively. Meanwhile, the total heat was recuperated through the IHE components in each range of evaporation temperature & working fluid are described in Fig. 6. The most significant IHE regenerative effect on the working fluid was R245fa followed by n-Pentane, R1233zd, R123, and R141b, with the following sequential number of heat was 3.34 kW, 2.63 kW, 2.06 kW, 1.9 kW, and 0.92 kW, respectively. Overall, regenerative IHE plays a significant role in enhancing the ORC system.

Figure 9 illustrates the impact of the amount of heat that may be decreased in the evaporator area for each organic fluid when fitted with IHE under the same electric power output settings. The thermal oil heater will supply less energy to the evaporator as a result of this heat recovery. The amount of total thermal energy that could be lowered in the organic fluids R245fa, n-Pentane, R1233zd, R123, and R141b was 3.34 kW, 2.63 kW, 2.06 kW, 1.9 kW, and 0.92 kW, respectively. The capacity of power generation may be increased through energy savings on electricity use.

A comparison of the test result ORC system with R245fa that uses IHE and without IHE is represented in Table 5. The parameter of hot oil mass flow rate in ORC with IHE is needed less than ORC without ORC due to the effect of recuperator heat in a heat exchanger. According to Fig. 10, the parameter data were shown in the T-s graphic diagram of the saturation condition for the working fluid R245fa.

Table 4. Case study comparative of thermodynamic analysis result for R245fa

Temp. Evaporator, ^{O}C	**70**	**75**	**80**	**85**	**90**	**95**	**100**	**105**	**110**	**115**	**120**	**125**	**130**
$Q_{evap\ w/o\ IHE}$, kW	12.31	14.32	16.61	19.20	22.13	25.45	29.21	33.46	38.27	43.74	49.97	57.13	65.43
$Q_{evap\ w/\ IHE}$, kW	12.08	14.00	16.16	18.61	21.38	24.50	28.02	32.00	36.50	41.63	47.48	54.22	62.09
Q_{rec}, kW	0.23	0.32	0.44	0.59	0.76	0.96	1.19	1.46	1.77	2.11	2.49	2.91	3.34
$Eff._{thermal.\ w/o\ IHE}$, %	4.54	5.49	6.37	7.19	7.95	8.66	9.31	9.92	10.48	10.99	11.46	11.89	12.28
$Eff._{thermal\ w/\ IHE}$, %	4.62	5.61	6.54	7.41	8.23	9.00	9.71	10.37	10.99	11.55	12.07	12.53	12.94
$Eff._{gross\ w/o\ IHE}$, %	4.71	5.71	6.65	7.53	8.35	9.13	9.86	10.54	11.18	11.79	12.35	12.89	13.38
$Eff._{gross\ w/\ IHE}$, %	4.80	5.84	6.83	7.76	8.65	9.48	10.27	11.02	11.72	12.38	13.00	13.58	14.10

Term & condition: T_{wf} at cond. 50 °C and Wexpander, specific work & pressure ratio are constant

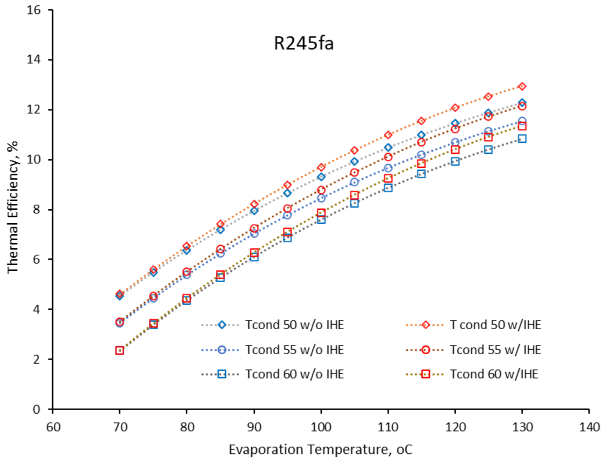

Fig 3: Thermal efficiency comparison for R245fa working fluid as a function of evaporation output temperature

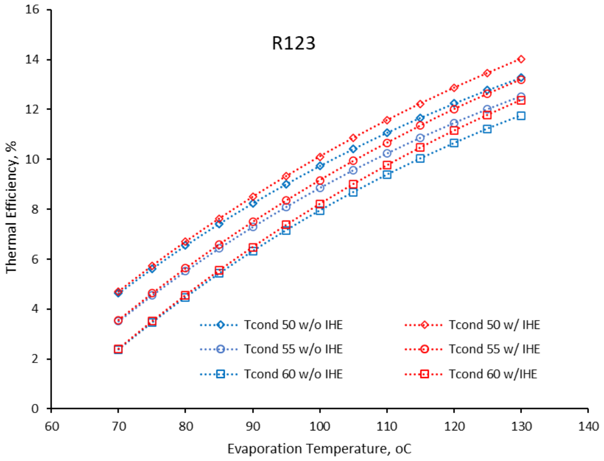

Fig 4: The thermal efficiency for R123 working fluid as a function of evaporation outlet temperature

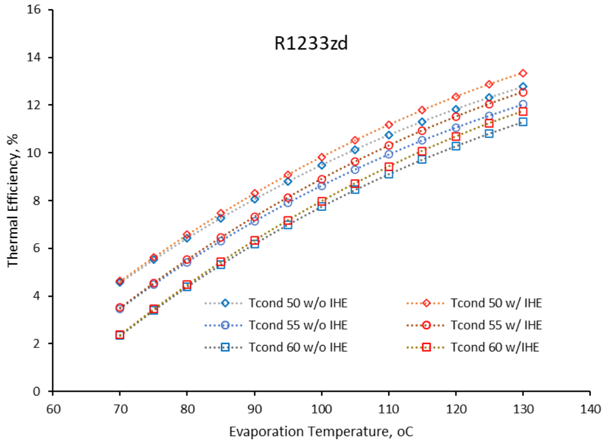

Fig. 5: The working fluid of R1233zd's thermal efficiency as a function of the evaporation temperature outlet

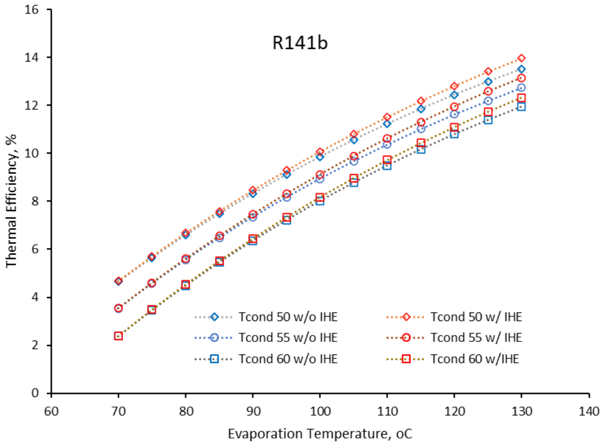

Fig. 6: Thermal efficiency for working fluid of R141b as a function of evaporation temperature outlet

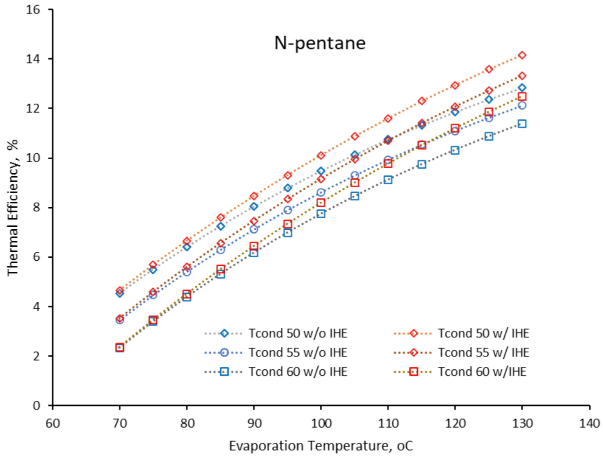

Fig. 7: Thermal efficiency of n-Pentane working fluid as a function of evaporation temperature outlet

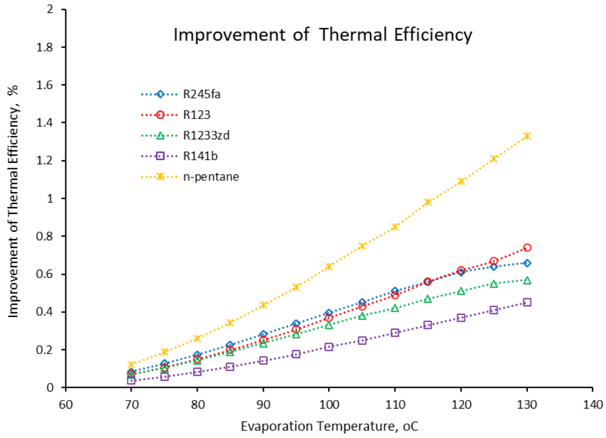

Fig. 8: Improvement of thermal efficiency due to IHE

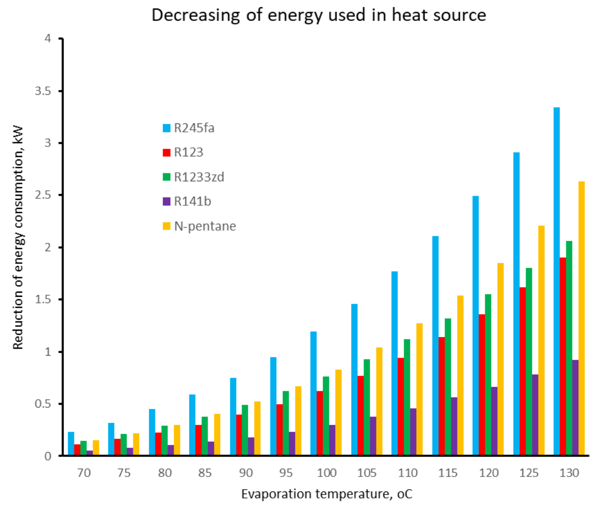

Fig. 9: The amount of recuperation heat in IHE that reduces the energy consumption oil heater enter the evaporator

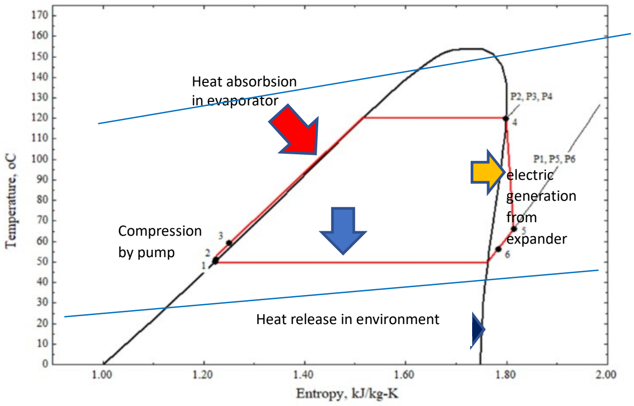

Fig. 10: T-s diagram for operating ORC with R245fa

Table 5. Comparison of test result in case study R245fa with IHE and without IHE

Parameter	**Unit**	**w/ IHE**	**w/o IHE**
Hot oil temperature at evaporator inlet	ºC	130	130
Hot oil temperature at evaporator outlet	ºC	90	80
Water temperature at condenser inlet	ºC	30	30
Water temperature at condenser outlet	ºC	40	40
Hot oil mass flow rate	kg/s	0.423	0.446
Cold water mass flow rate	kg/s	0.99	1.059
R245fa pressure at scroll inlet	bar	19.29	19.29
R245fa temperature at scroll inlet	ºC	120	120
R245fa pressure at scroll outlet	bar	3.432	3.432
R245fa temperature at scroll outlet	ºC	66.03	66.03
R245fa pressure at IHE outlet (low pressure side)	bar	3.432	-
R245fa temperature at IHE outlet (low pressure side)	ºC	55.64	-
R245fa pressure at IHE outlet (high pressure side)	bar	19.29	-
R245fa temperature at IHE outlet (high pressure side)	ºC	58.95	-
R245fa pressure at condenser outlet	bar	3.43	3.43
R245fa temperature at condenser outlet	ºC	50	50
R245fa pressure at pump outlet	bar	19.29	19.29
R245fa temperature at pump outlet	ºC	51.18	51.18

5. Conclusion

In this study, working fluids of R245fa, R123, R1233zd, n-Pentane, and R141b have been used to simulate the ORC system with and without IHE. The temperature of evaporation, which varies from 70 ºC to 130 ºC, and the discharge temperature of a condenser, which is maintained in the range of 50 ºC to 60 ºC, were established as the boundary conditions for the model ORC, respectively. The findings of the thermodynamic study, including the thermal efficiency, tend to be slightly better with IHE application in terms of evaporator temperature rise and condenser temperature decline. Based on the results analysis exhibit an IHE able to smoothly improve the performance of the net thermal efficiency and decrease overall thermal consumption as well as strengthen of the ORC system. R245fa had the greatest recuperation impact on the working fluid, followed by n-Pentane, R1233zd, R123, and R141b. The total thermal energy that can be reduced was 3.34 kW, 2.63 kW, 2.06 kW, 1.9 kW, and 0.92 kW, respectively. This heat recuperation will reduce the amount of energy supplied to the evaporator by the thermal oil heater. Energy savings on electricity consumption itself potentially increase the capacity of power generation. The influence on the net thermal efficiency by using working fluids of R245fa, R123, R1233zd, R141b, and n-Pentane provided improvement of 0.66%, 0.74%, 0.57%, 0.45%, and 1.33%, respectively.

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Nomenclature

$\dot{m}_{wf}$	Mass flow rate working fluid, kg/s
h	Specific enthalpy, J/kg
W_P	Work of pump, W
W_T	Work produced in expander, W

Q_{evap}	Heat input in evaporator, W
Q_{cond}	Heat sink in condenser, W
Q_{IHE}	Heat absorbed in IHE, W
η_{is_pump}	Pump isentropic efficiency
η_{is_exp}	Expander isentropic efficiency
C_p	Heat capacity, J/kg-K
s	Specific entropy, J/kg-K
η_{th}	Thermal efficiency, %
η_{net}	Net thermal efficiency, %
ε	Effectiveness of IHE

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