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Comparative Study of Rankine Cycle Power Generation using Water and Organic Fluids in Saturated and Superheated States

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Abstract

The Rankine cycle is an electricity generation system that uses water or organic fluids as high-grade or low-grade heat sources, respectively. In this paper, we present the results of our study of Rankine-cycle power generation in which we compared water and organic fluids (toluene and n-nonane) as working fluids in saturated and superheated states. We analyzed the energy and exergy of the Rankine cycle in a saturated vapor state at 300 °C and superheated states at 400 °C and 500 °C (the pressure remained the same as that at 300 °C), and assumed a constant heat input for all states. In the energy analysis, we determined the mass flow rate, heat rejection, work input of the pump, work generated by the turbine, net work output, and thermal efficiency. In the exergy analysis, we determined the exergy input, exergy loss, exergy destruction at the pump and the turbine, and the exergetic efficiency. The results show that water, categorized as a wet fluid, obtains a better performance with respect to both analyses in saturated and superheated states than toluene and n-nonane, which are categorized as isentropic and dry fluids, respectively. The water realizes a higher performance in the superheated than in the saturated state, whereas the performances of toluene and n-nonane are poorer in the superheated than in the saturated state.

Abstrak

Studi Perbandingan Pembangkit Daya Sistem Rankine Menggunakan Air dan Fluida Organik dalam Keadaan Jenuh dan Superpanas. Sistem Rankine adalah sistem yang digunakan untuk membangkitkan listrik. Air digunakan sebagai fluida kerja untuk sumber kalor tinggi, sedangkan fluida organik digunakan untuk sumber kalor rendah. Makalah ini membahas studi pembangkit listrik siklus Rankine dengan membandingkan air dan fluida organik (toluene dan n-npnane) sebagai fluida kerja pada tingkat keadaan uap jenuh dan superpanas. Studi ini menganalisis energi dan eksergi siklus Rankine dengan tingkat keadaan uap jenuh pada 300 °C dan superpanas pada 400 °C dan 500 °C (tekanan sama dengan 300 °C) sebagai data awal, dan panas yang masuk diasumsikan konstan untuk semua tingkat keadaan. Laju aliran massa, panas yang hilang, kerja pompa dan kerja turbin, kerja netto, dan efisiensi termal merupakan bagian dari analisis energi. Analisis eksergi dilakukan dengan menghitung eksergi masuk sistem, eksergi yang hilang, eksergi destruksi pada pompa dan turbin, dan efisiensi eksergi. Hasil analisis menunjukkan bahwa air sebagai fluida basah memberikan performa terbaik pada analisis energi dan eksergi pada tingkat keadaan uap jenuh maupun superpanas dibandingkan dengan toluene dan n-nonane yang termasuk kategori fluida isentropik dan kering. Air memberikan performa yang lebih baik pada tingkat keadaan superpanas dibandingkan uap jenuh, dan toluene dan n-nonane menghasilkan performa yang lebih rendah pada tingkat keadaan superpanas dibandingkan uap jenuh.

Keywords: organic Rankine cycle, rankine cycle, steam Rankine cycle, working fluid

1. Introduction

The Rankine cycle is a system commonly used to produce electricity. Based on the operating temperature, the Rankine cycle is divided between the steam (SRC) and organic (ORC) Rankine cycles. The SRC is suitable for producing electricity from a high-grade heat source, whereas the ORC is commonly used with low- to medium-grade heat sources [1–3]. At these grades, the ORC realizes higher performance at lower operational and maintenance costs than the SRC [4–6].

Water is the working fluid commonly used for the SRC at high operating temperatures. Otherwise, organic fluids are used in the ORC to generate electricity from low- and medium-grade heat sources [7]. The choice of organic fluid for ORC systems is critical to ensure high system performance [8]. Hydrocarbons, siloxanes, and refrigerants are generally used as ORC fluids [9]. Based on the slope of their T-s diagrams, fluids are categorized as either wet, dry, or isentropic. Dry and isentropic fluids are suitable low- and medium-grade heat sources for ORC applications [10]. Wet fluids are more suited as high-grade heat sources, and require superheating [11]. As a wet fluid, water is appropriately used in this grade [12].

An operating temperature of 300 °C is relatively low for an SRC, but is categorized as a high temperature for an ORC system. Researchers have studied and compared Rankine cycle systems using an operating temperature of approximately 300 °C with water and various organic fluids. Thurairaja *et al.* [13] evaluated the ORC performances of different fluids and found that water, m-Xylene, and p-Xylene perform better as working fluids for energy extraction at operating temperatures of 200–320 °C. Rad *et al.* [14] studied industrial-waste-heat power generation at temperatures ranging from 120 °C to 300 °C, and compared the performances of water, benzene, and cyclohexane at 300 °C. The authors found water to be the best-performing working fluid.

Many researchers have investigated the utilization of organic fluids as high-grade heat sources. Dumont *et al.* [15] performed energy and exergy analyses on the ORC with the heat source at 300 °C for seven organic fluids. The results revealed that R1233zd, R245fa, and ethanol generated more power than other fluids. Fergani *et al.* [16] applied ORC using the waste heat from the chimneys of a cement plant to generate electricity. They compared three working fluids, including cyclohexane, toluene, and benzene, in a pressure range from 2 bar to 25 bar and a temperature range from 260 °C to 320 °C. The results showed that cyclohexane achieved the highest economic and thermodynamic efficiency. Linnemann *et al.* [17] investigated a power plant with two cascaded ORCs that used waste heat from exhaust gas and a high-temperature ORC that used toluene as a working fluid. Uusitalo *et al.* [18] evaluated siloxanes and hydrocarbons to determine the best fluid for high-temperature ORC applications. Xi *et al.* [19] reported that hydrocarbons are the most suitable working fluids for ORCs because of their high energy efficiency, low cost, and good environmental compatibility. Shi *et al.* [20] also found toluene to be a superior working fluid for high-temperature ORC.

In this paper, we compare the performances of the Rankine cycle system for three fluid categories: wet, isentropic, and dry. The comparison was conducted in three states: the saturated vapor state at 300 °C, and the superheated state at 400 °C and 500 °C (with the same pressure as that at 300 °C). We chose water as a representative wet fluid, and toluene and n-nonane as representative organic isentropic and dry fluids, respectively. As a wet fluid, water is typically used in systems operating at very high temperatures, but in this study, we analyzed its performance at temperatures not as high as usual. In addition, we compared the performance of water with those of the organic fluids. The fluid with the best performance is one in which the operating temperature is lower than that required by water in SRC systems, and higher than that used for organic fluids in ORC systems. The energy and exergy balances are used to obtain the system performance values.

2. Methods

Working principle. The Rankine cycle consists of four main components: a pump, evaporator/boiler, turbine, and condenser. Figure 1 shows a schematic of a basic Rankine cycle, the working principle of which is as follows:

- Process 1-2: the working fluid in liquid phase is pumped to the boiler/evaporator from low pressure to high pressure.
- Process 2-3: the working fluid, which has been heated by the heat source in the boiler/evaporator (fluid has transformed from a liquid to a vapor), flows to the turbine to generate electricity. This process works under constant pressure.
- Process 3-4: the vaporous fluid expands in the turbine to generate electricity. This process causes a decrease in temperature and pressure that causes it to condense.
- Process 4-1: all the fluids are condensed/cooled in the condenser. The fluid returns to the liquid state to be pumped back to the boiler/evaporator.

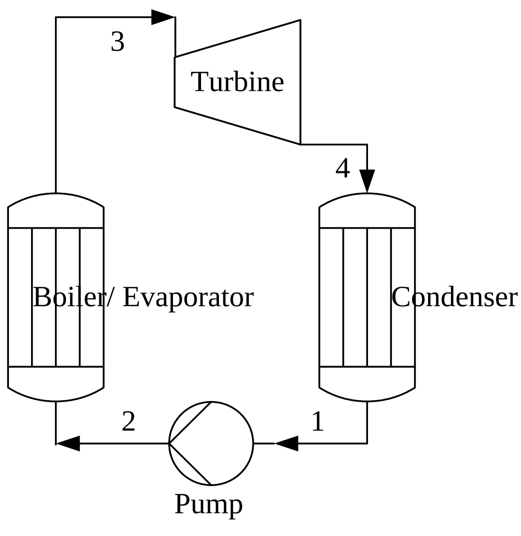

Figure 1. Schematic of Rankine Cycle

Working fluids. In our comparative study of the Rankine cycle, we used water and organic fluids as the working fluids. As organic fluids, we chose hydrocarbons (toluene and n-nonane) because researchers have reported hydrocarbons to be more suitable for use as working fluids in a high-temperature ORC [18–20]. Table 1 shows the properties of water, toluene, and n-nonane.

In the T-s diagram, water, as a wet fluid, has a negative slope with low molecular mass. In contrast, toluene has an infinite slope with a medium molecular mass, and n-nonane (dry fluid) has a positive slope with a high molecular mass [22,23]. As such, we used water as a wet fluid and the hydrocarbon fluids toluene and n-nonane as isentropic and dry fluids, respectively.

Figure 2 shows a T-s diagram for a saturated in state 3, and superheated states in states 3´ and 3´´ (inlet turbine/ outlet evaporator/boiler). Both states were analyzed to determine the performance of each fluid in saturated and superheated states. The pressures in the superheated and saturated states were the same.

Table 1. Properties of the Working Fluids [18,20,21]

Properties	Fluids		
	Water	Toluene	N-nonane
Molecular Weight (g/mol)	18	92.1	128.3
Critical Temperature (°C)	374	319	321
Critical Pressure (bar)	220.06	41.3	22.8
Category	Wet	Isentropic	Dry

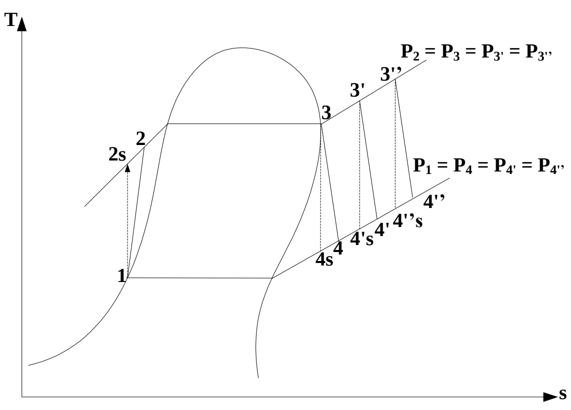

Figure 2. T-s Diagram

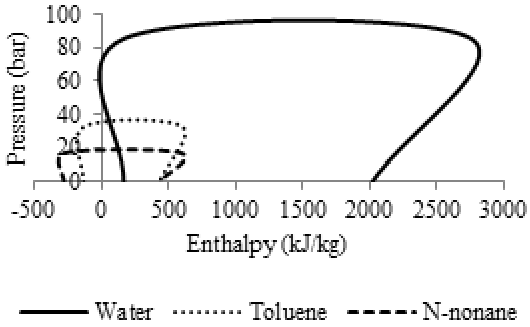

Figure 3. P-h Diagram

Figure 3 shows a P-h diagram for the water and organic fluids (toluene and n-nonane), in which water obtained higher pressure and enthalpy values at the same operating temperature than the toluene and n-nonane. We analyzed and compared the energy and exergy balances of the three fluids with respect to the first and second laws of thermodynamics.

Energy and exergy balances of working fluids. In our energy analysis, we calculated the mass flow rate ($\dot{m}_f$) from the energy balance in the boiler/evaporator. We then determined the heat rejection (Q_{loss}) from the energy balance in the condenser. The work input of the pump (W_p) and work generated by the turbine (W_t) were calculated using the energy balances in the pump and turbine. Last, we determined the net work output (W_{net}) and thermal efficiency (η_{th}). Equations (1) to (6) show the equations for these energy balance parameters from Moran *et al.* [24]:

$$Q_{in} = \dot{m}_f(h_3 - h_2), \quad (1)$$

$$Q_{loss} = \dot{m}_f(h_4 - h_1), \quad (2)$$

$$W_p = \dot{m}_f(h_2 - h_1) = \dot{m}_f(h_{2s} - h_1)/\eta_p, \quad (3)$$

$$W_t = \dot{m}_f(h_3 - h_4) = \dot{m}_f(h_3 - h_{4s}) \times \eta_t, \quad (4)$$

$$W_{net} = W_t - W_p, \quad (5)$$

$$\eta_{th} = \frac{W_{net}}{Q_{in}}, \quad (6)$$

where Q_{in} is the heat input (kW), $\dot{m}_f$ is the mass flow rate (kg/s), Q_{loss} is the heat rejection (kW), W_p is the work input of the pump (kW), W_t is work generated by the turbine (kW), W_{net} is the net work output (kW), η_{th} is the thermal efficiency (%), η_p is the isentropic efficiency of the pump, η_t is the isentropic efficiency of the turbine, h_1 is the enthalpy in state 1 (kJ/kg), h_2 is the enthalpy in state 2 (kJ/kg), h_3 is the enthalpy in state 3 (kJ/kg), h_4 is the enthalpy in state 4, h_{2s} is the enthalpy in state 2s (kJ/kg), and h_{4s} is the enthalpy in state 4s (kJ/kg).

In the exergy analysis, we used the exergy balance in the boiler/evaporator to calculate the exergy input (Ex_{in}), and then calculated the exergy loss (Ex_{loss}) based on the exergy balance in the condenser. The calculation continued by calculating the exergy destroyed in the pump ($\dot{I}_p$) and the turbine ($\dot{I}_t$), based on the respective exergy balances of the pump and turbine. Last, we calculated the exergetic efficiency (η_{ex}) from the ratio of the net work output and exergy input. Equations (7) to (11) show the equations for these exergy calculations, which were taken from Moran *et al.* [24]:

$$Ex_{in} = \dot{m}_f[h_3 - h_2 - T_0(s_3 - s_2)], \quad (7)$$

$$Ex_{loss} = \dot{m}_f[h_4 - h_1 - T_0(s_4 - s_1)], \quad (8)$$

$$\dot{I}_p = \dot{m}_f T_0(s_2 - s_1), \quad (9)$$

$$\dot{I}_t = \dot{m}_f T_0(s_4 - s_3), \quad (10)$$

$$\eta_{ex} = \frac{W_{net}}{Ex_{in}}, \quad (11)$$

where Ex_{in} is the exergy input (kW), Ex_{loss} is the exergy loss (kW), $\dot{I}_p$ is the exergy destroyed at the pump (kW), $\dot{I}_t$ is the exergy destroyed at the turbine (kW), η_{ex} is the exergy efficiency (%), T_0 is the ambient temperature (°C), s_1 is the entropy in state 1 (kJ/kg K), s_2 is the entropy in state 2 (kJ/kg K), s_3 is the entropy in state 3 (kJ/kg K), and s_4 is the entropy in state 4 (kJ/kg K).

In this comparative study, we assumed that the heat input in the evaporator/boiler remains constant for all states, the pump inlet temperature is set for a saturated liquid (and also remains constant for all states), the turbine inlet pressure remains constant for all states, the pump and turbine work adiabatically, and the potential and kinetic energies are neglected. As initial data for the analysis, the heat input (Q_{in}) was assumed to be 1 MW, with the temperature at the inlet pump 40 °C in a saturated liquid. These initial data were the same for all three fluids. The operating temperature is set for a 300-°C saturated vapor state, with the superheated states at 400 °C and 500 °C (and the same pressure values as that at 300 °C). The enthalpy (h) and entropy (s) are determined from the properties of the fluids (water, toluene, and n-nonane) in each state. The η_p and η_t values are assumed to be 75%, and T_0 is assumed to be 30 °C. To evaluate the system performance, all states were analyzed and compared using water, toluene, and n-nonane (organic fluids) as working fluids.

3. Result and Discussion

Energy and exergy balances of working fluids in saturated vapor state (300 °C). Table 2 shows the energy and exergy results for a Rankine cycle with a constant heat input (Q_{in}) in the saturated state (300 °C) for water, toluene, and n-nonane (organic fluids). The results indicate that water obtained a better performance than the organic fluids (toluene and n-nonane) with thermal efficiency (η_{th}) and exergetic efficiency (η_{ex}) values of 27.98% and 29.76%, respectively. The efficiency depends on net work output (W_{net}), heat input (Q_{in}), and exergy input (Ex_{in}). As the Q_{in} value is assumed to be constant for all states, the thermal efficiency value is dependent on the W_{net} value. Furthermore, the W_{net} value depends on the work input of the pump (W_p) and the work generated by the turbine (W_t). The Wp and Wt values depend on the mass flow rate ($\dot{m}_f$) and enthalpy differences in the pump ($h_2 - h_1$) and turbine ($h_3 - h_4$). However, Ex_{in} depends on the $\dot{m}_f$ values and the enthalpy ($h_3 - h_2$) and entropy ($s_3 - s_2$) differences in the boiler/evaporator. Thus, we can conclude that all the parameters shown in Table 2 influence the performance value.

Water obtained a lower mass flow rate ($\dot{m}_f$) than the organic fluids (toluene and n-nonane) because it had the highest enthalpy difference in the evaporator ($h_3 - h_2$) (see Figure 4). The low $h_3 - h_2$ values of toluene and n-nonane results in high mass flow rates $\dot{m}_f$. From Eq. 1, we can see that the lower is the $h_3 - h_2$ difference, the higher is the $\dot{m}_f$ value. In addition, the heat rejection (Q_{loss}) value of water was lower than that of the organic fluids. The Q_{loss} value is influenced by the $\dot{m}_f$ value

Table 2. Energy and Exergy Results for Working Fluids in a Saturated Vapor State (300 °C)

Parameter	Water	Toluene	N-nonane
$\dot{m}_f$ (kg/s)	0.39	1.37	1.15
Q_{loss} (kW)	720.16	771.91	815.21
W_p (kW)	4.49	7.04	3.70
W_t (kW)	284.33	235.14	188.49
W_{net} (kW)	279.84	228.09	184.79
η_{th} (%)	27.98	22.81	18.48
Ex_{in} (kW)	940.20	935.18	934.23
Ex_{loss} (kW)	651.17	701.15	745.34
$\dot{I}_p$ (kW)	0.11	0.17	0.09
$\dot{I}_t$ (kW)	9.08	5.77	4.00
η_{ex} (%)	29.76	24.39	19.78

and enthalpy difference in the condenser ($h_4 - h_1$). Although water obtained the highest $h_4 - h_1$ value (see Figure 4), the difference between the $\dot{m}_f$ values for water and toluene is greater than the difference in their $h_4 - h_1$ values. As the $\dot{m}_f$ value of toluene is 3.5 times higher than that of water, the $h_4 - h_1$ value of water is 3.3 times higher than that of toluene, so water has a lower Q_{loss} value than the organic fluids. This result means that the energy loss in the system with water is less than that when using the organic fluids, which means the water performance was the best of the three fluids.

Due to the large difference between the enthalpy values of the pump ($h_2 - h_1$)(see Figure 4), water obtained a lower pump work input (W_p) value than toluene, which is lower than the high mass flow rate of toluene. The $h_2 - h_1$ value of water is 2.3 times greater than that of toluene, which means water obtained a lower W_p value. However, n-nonane obtained the lowest W_p value because the $h_2 - h_1$ value of water was 3.6 times higher than that of n-nonane, and the $\dot{m}_f$ value of n-nonane was only three times higher than that of water. Thus, the W_p value of n-nonane was lower than those of both water and toluene. In contrast, water generated more work by the turbine (W_t) than the organic fluids because of the high enthalpy difference in the turbine ($h_3 - h_4$). The difference between the $h_3 - h_4$ values for water and the organic fluids is greater than that between the $\dot{m}_f$ values. The $h_3 - h_4$ value of water is 4.3 times that of toluene, and the $\dot{m}_f$ value of toluene is 3.5 times higher than that of water. These results indicate that water obtains a higher W_t value than toluene and n-nonane.

The high W_t and low W_p values of water enabled it to obtain a higher net work output (W_{net}) than toluene and n-nonane. As the heat input (Q_{in}) value for all the fluids was the same, we can conclude that water obtained higher thermal efficiency (η_{th}) than the organic fluids. The higher is the W_{net} value and the lower is the Q_{in} value, the higher is the η_{th} value (see Eq. 6).

In Table 2, we can see that water obtained the highest exergy input (Ex_{in}) because it has the highest $h_3 - h_2$ value. Although water obtained the highest entropy difference in the evaporator $s_3 - s_2$ (see Figure 5), the $s_3 - s_2$ value is very low compared to the $h_3 - h_2$ value, which means water obtained a slightly higher Ex_{in} value than the organic fluids. In addition, the exergy loss (Ex_{loss}) value of water was lower than those of the organic fluids because it has the lowest $\dot{m}_f$ value. Although water has the highest $h_4 - h_1$ and $s_4 - s_1$ values (entropy difference in the condenser), the differences in the $h_4 - h_1$ and $s_4 - s_1$ values between water and organic fluids are smaller than the differences in the $\dot{m}_f$ values. Thus, water has a lower Ex_{loss} value than toluene and n-nonane.

The exergy destroyed at the pump when using water ($\dot{I}_p$) was lower than that for toluene because of its low $\dot{m}_f$ value. Although Figure 5 shows that the entropy difference in the pump ($s_2 - s_1$) for water was 2.2 times that of toluene, its value is still lower than the higher $\dot{m}_f$ value of toluene. Thus, water obtained a lower $\dot{I}_p$ value than toluene. In addition, n-nonane obtained the lowest $\dot{I}_p$ value because it had the lowest $s_2 - s_1$. The $s_2 - s_1$ value of water was 3.6 times that of n-nonane, which means n-nonane obtained a lower $\dot{I}_p$ value than water. However, the exergy destroyed at the turbine ($\dot{I}_t$) for water was higher than that destroyed for the organic fluids because of the high entropy difference in the turbine ($s_4 - s_3$), as shown in Figure 5. The $s_4 - s_3$ value of water is 5.5 times higher than that of toluene, so the $\dot{I}_t$ value is also significantly higher than those of the organic fluids. These results indicate that water obtains a higher total exergy destruction (I_{tot}) than the organic fluids (toluene and n-nonane).

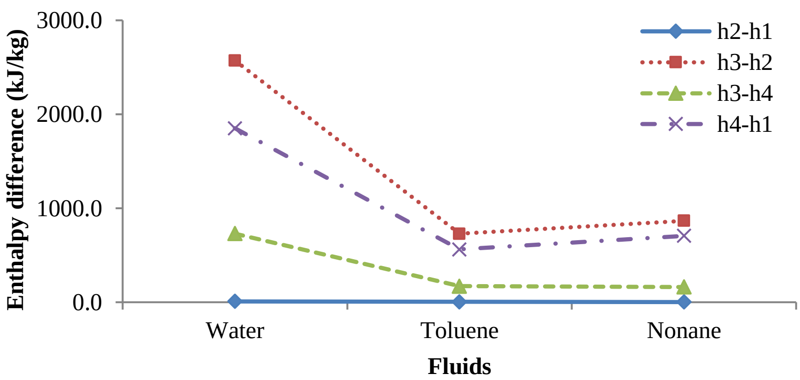

Figure 4. Enthalpy Differences of the Working Fluids in a Saturated Vapor State (300 °C)

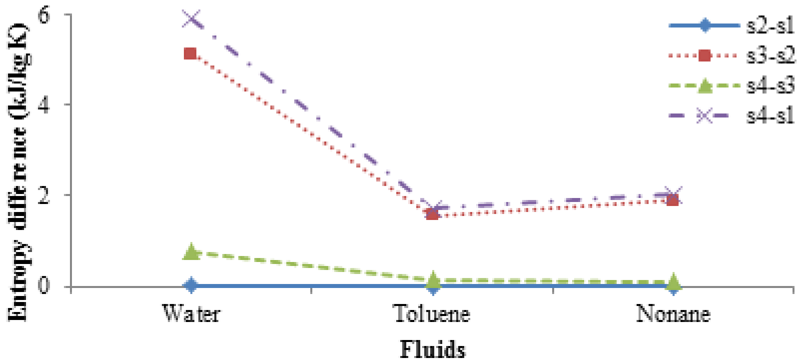

Figure 5. Entropy Difference of Working Fluids in Saturated Vapor State (300 °C)

Table 3. Energy Results of Working Fluids in Superheated States

Parameter	Fluids	400 °C	500 °C
$\dot{m}_f$ (kg/s)	Water	0.34	0.31
	Toluene	1.00	0.80
	N-nonane	0.83	0.65
Q_{loss} (kW)	Water	708.75	697.81
	Toluene	777.53	787.44
	N-nonane	830.52	843.29
W_p (kW)	Water	3.91	3.59
	Toluene	5.12	4.09
	N-nonane	2.68	2.10
W_t (kW)	Water	295.16	305.78
	Toluene	227.59	216.64
	N-nonane	172.16	158.80
W_{net} (kW)	Water	291.25	302.19
	Toluene	222.47	212.56
	N-nonane	169.48	156.71
η_{th} (%)	Water	29.12	30.22
	Toluene	22.25	21.26
	N-nonane	16.95	15.67

Table 4. Enthalpy Differences of Working Fluids in Superheated States

Parameter	Fluids	400 °C	500 °C
$h_3 - h_2$ (kJ/kg)	Water	2948.34	3213.34
	Toluene	1002.55	1257.51
	N-nonane	1200.44	1531.81
$h_3 - h_4$ (kJ/kg)	Water	870.23	982.58
	Toluene	228.17	272.43
	N-nonane	206.66	243.26
$h_4 - h_1$ (kJ/kg)	Water	2089.65	2242.30
	Toluene	779.52	990.22
	N-nonane	996.99	1291.77

Table 5. Exergy Results of Working Fluids in Superheated States

Parameter	Fluids	400 °C	500 °C
Ex_{in} (kW)	Water	941.62	943.00
	Toluene	939.63	943.45
	N-nonane	939.05	943.25
Ex_{loss} (kW)	Water	640.85	630.96
	Toluene	712.72	727.33
	N-nonane	766.54	784.15
$\dot{I}_p$ (kW)	Water	0.09	0.09
	Toluene	0.12	0.10
	N-nonane	0.06	0.05
$\dot{I}_t$ (kW)	Water	9.42	9.76
	Toluene	4.32	3.47
	N-nonane	2.97	2.34
η_{ex} (%)	Water	30.93	32.05
	Toluene	23.68	22.53
	N-nonane	18.05	16.61

The exergy efficiency (η_{ex}) value is influenced by the net work output (W_{net}) and exergy input (Ex_{in}) values. Here, water obtained a higher η_{ex} value than the organic fluids because it had the highest W_{net} value. Although water obtained a higher Ex_{in} value, the W_{net} value of water is 1.2 times higher than that of toluene, whereas the Ex_{in} value of water is only one times higher than that of toluene. The higher is the W_{net} value, the higher is the η_{ex} value obtained.

Energy and exergy balances of working fluids in superheated states (400 °C and 500 °C). Tables 3 and 5 show the respective energy and exergy results for water and the organic fluids in superheated states (400 °C and 500 °C, at the same pressure as for 300 °C). Tables 4 and 6 show the respective enthalpy and entropy differences of all the fluids in superheated states (400 °C and 500 °C).

Table 6. Entropy Differences of Working Fluids in Superheated States

Parameter	Fluids	400 °C	500 °C
$s_3 - s_2$ (kJ/kgK)	Water	5.74	6.11
	Toluene	2.02	2.37
	N-nonane	2.44	2.90
$s_4 - s_3$ (kJ/kg K)	Water	0.93	1.05
	Toluene	0.1445	0.1453
	N-nonane	0.1188	0.1196
$s_4 - s_1$ (kJ/kg K)	Water	6.67	7.16
	Toluene	2.16595	2.51975
	N-nonane	2.56007	3.01967

As shown in Table 3, the water and organic fluids obtain lower $\dot{m}_f$ values in a superheated than in a saturated state because they have higher $h_3 - h_2$ values (see Table 4). Furthermore, water obtained a lower $\dot{m}_f$ value than the organic fluids because it has a higher $h_3 - h_2$ value.

A lower $\dot{m}_f$ value and a higher $h_4 - h_1$ value (see Tables 3 and 4) in a superheated rather than a saturated state for water resulted in a lower Q_{loss} value. This result was caused by a decrease in the $\dot{m}_f$ value greater than the increment of the $h_4 - h_1$ value. In contrast, the use of toluene and n-nonane as organic fluids yielded a higher Q_{loss} value in the superheated state because the increment of the $h_4 - h_1$ value was greater than the decrease in the $\dot{m}_f$ value.

The W_p values obtained for water and the organic fluids in superheated states are lower than those obtained when in a saturated state. A constant $h_2 - h_1$ value (from Table 4) and a lower $\dot{m}_f$ value (see Table 3) yields a lower W_p value. Furthermore, the W_t value obtained in a superheated state for water is higher than that obtained in a saturated state (see Table 3), because it has a higher $h_3 - h_4$ value (see Table 4). The increment of the $h_3 - h_4$ value is larger than the decrease in the $\dot{m}_f$ value. Thus, water obtains a higher W_t value in a superheated than in a saturated state. Organic fluids obtain a lower W_t value when in a superheated than in a saturated state because the increment of the $h_3 - h_4$ value is smaller than the decrease in the $\dot{m}_f$ value, which means organic fluids obtain a poorer result when in a superheated than in a saturated state.

As shown in Table 3, the W_{net} value for water is higher because it has a lower W_p value and a higher W_t value. In contrast, toluene and n-nonane obtain a lower W_{net} value because they have lower W_t and W_p values, which means they obtain a low W_{net} value in a superheated state. Water obtains a higher W_{net} value in a superheated state than in a saturated state, which means water obtains a higher η_{th} value. In addition, because toluene and n-nonane as organic fluids obtain a lower W_{net} value in a superheated state than in a saturated state, they obtain a lower η_{th} value.

In Table 5, we can see that all the fluids obtained a higher exergy input (Ex_{in}) in a superheated than in a saturated state. A smaller $s_3 - s_2$ increment (see Table 6) than that of the $h_3 - h_2$ value obtained a higher Ex_{in} value. However, water obtained a lower Ex_{in} value when superheated at 500 °C than the organic fluids. This result is because the increment of the $h_3 - h_2$ value is smaller from water in superheated states of 400 °C and 500 °C than the increment of the $h_3 - h_2$ value of the organic fluids. Furthermore, the organic fluids obtained a lower $s_3 - s_2$ value than water, which means they obtained a higher Ex_{in} value than water superheated to 500 °C.

Water obtained a lower exergy loss (Ex_{loss}) value when in a superheated state than in a saturated state, whereas the organic fluids obtained a higher value. The $h_2 - h_1$ and $s_2 - s_1$ increments of water are smaller than the decrease in the $\dot{m}_f$ value, which means water obtained a lower Ex_{loss} value when in a superheated state than in a saturated state. In contrast, the increments of the $h_2 - h_1$ and $s_2 - s_1$ values for toluene and n-nonane are larger than the decrease in their $\dot{m}_f$ values, which means toluene and n-nonane obtained a higher Ex_{loss} value when in a superheated than in a saturated state. Water also obtained a lower Ex_{loss} value than the organic fluids because it had a lower $\dot{m}_f$ value than the organic fluids. Although water had higher $h_2 - h_1$ and $s_2 - s_1$ values, the increment of the $h_2 - h_1$ and $s_2 - s_1$ values is smaller than the decreases in the $\dot{m}_f$ values. This situation means that the $\dot{m}_f$ value has a stronger influence on the Ex_{loss} value, so water obtained a lower Ex_{loss} value than toluene and n-nonane.

The exergy destroyed at the pump ($\dot{I}_p$) for all the fluids decreased in the superheated state. As there are no data specific to the inlet and outlet of the pump, the $\dot{I}_p$ value depends on the $\dot{m}_f$ value. As shown in Table 2, the $\dot{m}_f$ value for all the fluids decreased, which decreased the $\dot{I}_p$ value for all the fluids. In addition, water obtained higher exergy destruction in the turbine ($\dot{I}_t$) in the superheated state because it had a higher $s_4 - s_3$ value (see Table 5). The increment in the $s_4 - s_3$ value is larger than the decrease in the $\dot{m}_f$ value, which means water obtained a higher $\dot{I}_t$ value in the superheated than in the saturated state. In contrast, the organic fluids obtained a lower $\dot{I}_t$ value in the superheated than in the saturated state, despite their higher $s_4 - s_3$ values. The increment in the $s_4 - s_3$ values of toluene and n-nonane is lower than the decrease in their $\dot{m}_f$ values, which means they obtained a lower $\dot{I}_t$ value in the superheated than in the saturated state.

A higher net work output (W_{net}) yielded a higher exergetic efficiency (η_{ex}) for water in the superheated than in the saturated state, although it had a higher exergy input (Ex_{in}). The increment of the Ex_{in}value for water is not significant, which resulted in a higher η_{ex} value. Otherwise, the organic fluids obtained a lower η_{ex} value due to their a lower W_{net} and higher Ex_{in} values, which means they obtained lower η_{ex} values in the superheated than in thesaturated state.

The results of our analysis of the saturated (300 °C) and superheated (400 °C and 500 °C) states for the three fluids reveal that water performed better than the organic fluids toluene and n-nonane. These results accord with those of previous studies. i.e., that water is a wet fluid suitable for use at high operating temperatures [12]. As a wet fluid, water also obtains a higher performance in the superheated than in the saturated state, whereas the isentropic fluid toluene and the dry fluid n-nonane obtain a lower performance. In the analysis by Liu *et al.* [11], wet fluids were found to require superheating to ensure better performance. Furthermore, toluene and n-nonane, as isentropic and dry fluids, respectively, were found to obtain better results in the saturated than in the superheated state, as also reported by Pezzuolo *et al.* [25], because most organic isentropic and dry fluids do not require superheating to produce electricity in the ORC system.

Regarding the organic fluids, we found toluene to obtain better performance than n-nonane in both the saturated or superheated states. The higher mass flow rate and higher enthalpy difference in the turbine with toluene accounts for its better performance than n-nonane. However, as noted in the introduction, many researchers use toluene in high-temperature ORC systems because it has been proven to perform well.

4. Conclusions

In our comparative study of Rankine-cycle power generation, the results revealed that the utilization of water is more appropriate than organic fluids for a Rankine cycle when using high-grade heat, whether in the saturated or superheated state. Water obtained a higher performance than the two organic fluids in both the saturated and superheated states, but it obtained a higher performance in the superheated than in the saturated state. The performances of toluene and n-nonane were poorer in the superheated than in the saturated state. Our comparison of these organic fluids showed that toluene performed better than n-nonane in both the saturated and superheated states. In the future, analysis of more organic fluids at high operating temperatures is necessary to identify which fluids are more appropriate for use in the ORC when using high-grade heat sources. In addition, an economic analysis will be important to realize economic savings among the water and organic fluid options.

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