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Study on thermodynamic performances of ORC system configurations and working fluids in two areas

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Abstract
Optimal ORC system configuration, best working fluid and optimal evaporation temperature are determined and the optimum area is selected through comparative analysis of different 8 ORC systems using 8 working fluids in two areas. Multi-objective function combined with the network output and exergy efficiency is proposed to evaluate the overall thermodynamic performances of ORC. The area with lower temperatures of geothermal and cooling water is the thermodynamic optimum one.

Keywords: Organic Rankine cycle, optimization, working fluid, evaporation temperature, thermodynamic performance

Introduction

1. Purpose of this study

The selection of the working fluid, cycle configuration and operation parameters most suitable for given temperature of heat source is the key process to improve the performance of ORC [1]. For these reasons many researchers have reviewed the optimal combination of ORC configurations, working fluid and cycle parameters under the conditions of heat source above 100℃ [2] and below 100℃ [3] as well. However, it is difficult to identify the optimal ORC configuration, working fluid and cycle parameters for particular areas from the above reported data since the best working fluid and cycle parameters vary with the temperatures of heat and cooling source and the system configuration.

The purpose of this work is to perform comparative study of thermodynamic performances and optimization of ORC system configurations based on the network output and exergy efficiency in areas where geothermal and cooling water temperatures are different each other.

2. Description of ORC system configurations and working fluids

2.1 Description of ORC system configurations

Fig. 1. The schematic diagrams of ORC system configurations: a) Basic ORC (system1); b) ORC with preheater (system 2); c) ORC with IHX (system3); d) ORC with superheater (system 4); e) ORC with preheater and IHX (system 5); f) ORC with superheater and preheater (system 6); g) ORC with superheater and IHX (system 7); h) ORC with superheater, preheater and IHX (system 8).

2.2 Selection of working fluids

In this study, 8 working fluids (R123, R134a, R152a, R600, R600a, R290, R717, R245fa) with low ODP and GWP are selected.

Thermodynamic and environmental properties of the selected working fluids are listed in Table 1.

3.2 Performance indices of ORC system

The network output and exergy efficiency are selected as the performance indices for thermodynamic optimization of ORC systems. The network output and exergy efficiency of ORC system are defined by Eq. (1) and Eq. (2), respectively [5].

$$W_{\text{net}} = W_{\text{tur}} - W_{\text{wf.p}} - W_{\text{gw.p}} - W_{\text{cw.p}} \quad (1)$$

$$\eta_{\text{ex}} = \frac{W_{\text{net}}}{E_{\text{gw.in}}} \quad (2)$$

- **where W_{tur}:** output of turbine, kW
- **$W_{wf.p}$:** consumption power of working fluid pump, kW
- **$W_{gw.p}$:** consumption power of geothermal water pump, kW
- **$W_{cw.p}$:** consumption power of cooling water pump, kW
- $E_{gw.\text{in}}$ **:** exergy of geothermal water at inlet of ORC system, kW
- Exergy of geothermal water at inlet of ORC system is defined as

$$E_{\text{gw.in}} = m_{\text{gw}} \left[(h_{\text{gw.in}} - h_0) - T_0 (s_{gw.in} - s_0) \right] \quad (3)$$

Exergy of geothermal water at outlet of ORC system is defined as

$$E_{gw.out} = m_{\text{gw}} \left[(h_{gw.out} - h_0) - T_0 (s_{gw.out} - s_0) \right] \quad (4)$$

- **where m_{gw}:** flow rate of geothermal water, kg/s
- **$h_{gw.in}$, $h_{gw.out}$:** specific enthalpies of geothermal water at inlet and outlet, kJ/kg
- **h_0:** specific enthalpy of the ambient, kJ/kg
- **T_0:** temperature of the ambient, K
- **$s_{gw.in}$, $s_{gw.out}$:** specific entropies of geothermal water at inlet and outlet, kJ/(kg·K)
- **s_0:** specific entropy of the ambient, kJ/(kg·K)

3.3 Mathematical model to evaluate the overall thermodynamic performance

The mathematical model to evaluate overall thermodynamic performance of ORC is defined as

$$\text{Min:} \quad F(X) = \frac{1 - \eta_{ex}}{W_{net}} \quad (5)$$

where, $F(X)$ is the objective function. This objective function is based on the network output and exergy efficiency. The smaller $F(X)$ is, the higher the overall thermodynamic performance of ORC is.

4. Results and discussion

The optimal results for each ORC system configuration in two areas are listed in Table 3.

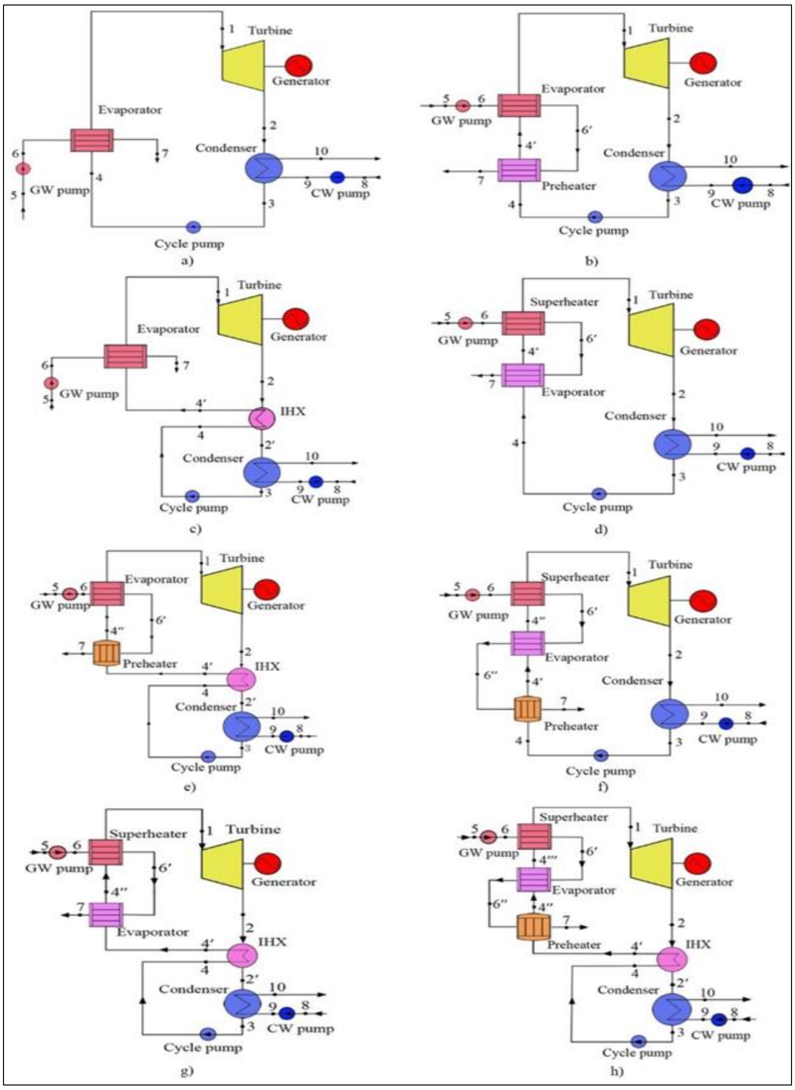

Fig 1: shows the schematic diagrams of ORC system configurations considered in this study.

Table 1: Thermodynamic and environmental properties of the selected working fluids [4]

Working fluids	Normal boiling temperature(℃)	Critical temperature(℃)	Critical pressure(MPa)	ASHRAE34 safety group	ODP	GWP (100year)	Type
R123	27.8	182.8	3.66	B1	0.012	120	dry
R134a	-26.1	101	40.59	A1	0	1300	wet
R152a	-14.02	113.2	45.17	A2	0	140	wet
R290	-42.1	96.68	4.247	A3	0	~20	wet
R600	-0.5	152	3.80	A3	0	20	dry
R600a	-11.6	134.7	3.63	A3	0	20	dry
R717	-33.3	132.3	11.33	B2	0	<1	wet
R245fa	14.9	154.0	3.651	B1	0	1050	dry

3. Given data and mathematical models

3.1 Given data: Given data for two areas considered in this study are listed in Table. 2.

Table 2: Given data for two areas

Term	Area A	Area B
Geothermal water temperature(℃)	80	70
Geothermal water mass flow rate(kg/s)	20	20
Cooling water temperature(℃)	20	10
Ambient temperature(℃)	20	10
Ambient pressure(MPa)	0.1	0.1

As shown in Table 2, temperatures of geothermal water, cooling water and the ambient are different each other, but the available thermal energies are the same in two areas.

Table 3: Optimal results for each ORC system configuration in two areas

System	Area A					Area B				
	Best working fluid	$t_{ev.opt}$,℃	W_{net}, kW	η_{ex}, %	F(X)	Best working fluid	$t_{ev.opt}$,℃	W_{net}, kW	η_{ex}, %	F(X)
System 1	R717	54	69.26	15.17	0.012248	R717	44	71.52	15.21	0.011855
System 2	R245fa	55	80.98	17.74	0.010158	R245fa	45	82.76	17.61	0.009955
System 3	R717	54	69.26	15.17	0.012248	R717	44	71.52	15.21	0.011855
System 4	R717	54	69.52	15.23	0.012194	R717	44	71.75	15.27	0.011809
System 5	R245fa	55	81.16	17.78	0.010131	R245fa	45	82.86	17.62	0.009942
System 6	R245fa	55	80.36	17.6	0.010254	R245fa	45	82.25	17.50	0.010030
System 7	R123	54	70.85	15.52	0.011924	R123	44	72.59	15.44	0.011649
System 8	R245fa	55	81.05	17.75	0.010148	R245fa	45	82.87	17.63	0.009940

As shown in Table 3, in terms of network output and overall thermodynamic performance, all the ORC system configurations are better while in terms of exergy efficiency some ORC system configurations are better in Area B than in Area A.

Table 4 shows the optimization data in terms of network output, exergy efficiency and overall thermodynamic performance for Area A and Area B.

Table 4: Optimization data for Area A and Area B

Performance index	Area A	Area B
Optimal ORC system configuration	System 5	System 8
Best working fluid	R245fa	R245fa
Optimal evaporation temperature(℃)	55	45
Network output of ORC system(kW)	81.26	82.87
Exergy efficiency of ORC system (%)	17.78	17.63
F(X)	0.010131	0.009940

As shown in Table 4, in terms of network output, optimal ORC system is the system 8 for Area B and in terms of exergy efficiency it is the system 5 for Area A.

And in terms of overall thermodynamic performance it is the system 8 for Area B and the best working fluid is R245fa.

5. Conclusion: Considering the analysis of the above discussion, we reached the following conclusion.

Even though the exergy efficiency is lower relatively in the area with lower temperatures of geothermal and cooling water, the network output is greater and the overall thermodynamic performance is more powerful. Hence, the area where geothermal and cooling water temperatures are low relatively is the optimal one in terms of overall thermodynamic performance of ORC.

Declaration of Competing Interests

The authors have no financial conflict for this paper.

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