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OPTIMIZATION AND SELECTION OF HYDROCARBONS (HCS) FOR ORGANIC RANKINE CYCLES BASED ON MULTIPLE EVALUATION INDEXES

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ABSTRACT

Hydrocarbons (HCs) are eco-friendly and low-cost, and present an attractive prospect to be widely used in organic Rankine cycle (ORC) systems. However, the existing studies are scattered, and most of optimizations and selections only focus on a single performance index. This study carried out an optimization and selection of hydrocarbons for the subcritical ORCs based on multiple evaluation indexes. The heat source was 100-200°C, and five common hydrocarbons were selected as the working fluids. The selection guidelines of optimal working fluids were provided for various evaluation indexes. Results show that R290, R600a, and R600 achieve the largest net power output for heat sources of 100-150°C, 160-180°C, and 190-200°C, respectively. The system efficiency of R601 is the largest. R290, R600a, and R600 obtain the lowest specific investment cost for heat sources of 100-140°C, 150-160°C, and 170-200°C, respectively. Compared with R245fa, hydrocarbons can achieve larger system efficiency and lower specific investment cost, and the net power output is also larger for heat sources not exceed 180°C.

Keywords: organic Rankine cycle (ORC), hydrocarbon (HC), low grade energy, multi-objective optimization, working fluid selection

NONMENCLATURE

Abbreviations	
ORC	Organic Rankine Cycle
ODP	Ozone Depletion Potential
GWP	Global Warming Potential
PPTD	Pinch Point Temperature Difference
SIC	Specific Investment Cost
Symbols	
W_{net}	Net power output
η_{sys}	System efficiency
Q_{sys}	Heat absorption capacity
PEC_{total}	Total investment cost

1. INTRODUCTION

Organic Rankine cycle (ORC) is a widespread power system utilizing the low-grade thermal energy [1, 2]. The working fluid is an important basis for the system design, and crucially affects the system performance [3]. However, numerous common working fluids, such as hydrochloroflurocarbons (HCFCs) and hydroflurocarbons (HFCs), are being phased out as the international environmental agreements come into force. The wide use of hydrofluoroolefins (HFOs) is also limited by the high price. Thus, seeking the eco-friendly and low-cost organic fluids is urgently demanded. Hydrocarbons (HCs) are eco-friendly (ODP is 0, and GWP is lower than 20) and low-cost; and thus attract more attention in recent years [4]. However, the existing studies on the ORC system using hydrocarbons are scattered and unsystematic, and most of optimizations and selections only focus on a single performance index, such as the system efficiency, net power output or power generation cost. Moreover, most of existing studies are only based on a specific heat source temperature. These deficiencies bring serious obstructions for the widespread application of hydrocarbons in ORC systems.

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This study carried out an optimization and selection of hydrocarbons for the subcritical ORCs based on multiple evaluation indexes. The heat source is 100-200°C with no specific limits on the outlet temperature [5], which is abundant and widely existed in the renewable energy and waste heat resources [1, 5]. The propane (R290), isobutane (R600a), butane (R600), isopentane (R601a), and pentane (R601) were selected as the working fluids due to their suitable critical temperatures to the studied heat source temperatures. In this study, the evaporation pressure, evaporator outlet temperature (superheat degree), and pinch point temperature differences (PPTDs) in the cycle heat transfer processes were optimized. The maximum net power output, maximum system efficiency and minimum specific investment cost (*SIC*) were selected as the evaluation indexes. For heat sources of 100-200°C, the selection guidelines of optimal working fluids were given for various evaluation indexes. The widely-used working fluid, R245fa, was selected as the compared object to assess the application potential of hydrocarbons in ORC systems.

2. METHODS

2.1 Descriptions of ORC system

Schematics of the subcritical ORC system are illustrated in Fig. 1. The ORC system consists of shell-and-tube heat exchangers, axial-flow turbine and centrifugal feed pump. The introductions on the flow paths can refer to Li et al. [3]. The critical parameters and environmental indicators of working fluids are presented in Table 1.

2.2 Analysis model

The heat source fluid is the hot water and its mass flow rate is 5 kg·s^{-1}. The inlet temperature of cooling water is 20°C, and the temperature rise during the condensation process is 5°C. The efficiencies of turbine and pump are 0.8 and 0.75, respectively.

The ORC system is assumed as in a steady state. The heat loss in all components, and the pressure drop in heat exchangers and pipes are assumed to be neglected. The selectable ranges of evaporation pressure and evaporator outlet temperature are the same as those in the study of Li et al. [3]. The selectable ranges of PPTDs are 5-15°C.

The net power output of ORC system is defined as

$$W_{\mathrm{net}} = W_{\mathrm{T}} - W_{\mathrm{P}} - W_{\mathrm{cool}} , \tag{1}$$

where W_{T} is the power output by turbine, and W_{P} and W_{cool} are powers consumed by pump and cooling system, respectively. This index is usually selected as the optimized objective for the open type heat sources [5].

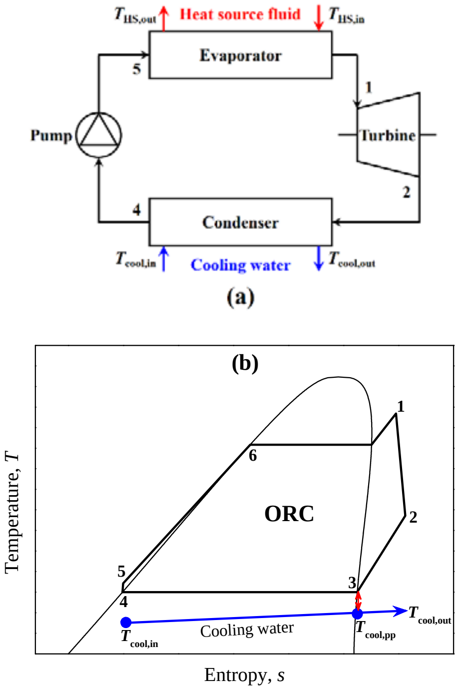

Fig 1 Schematics of the subcritical ORC system: (a). System; (b). Cycle processes

Table 1 Critical parameters and environmental indicators of working fluids

Fluid	Critical pressure /Mpa	Critical temperature /°C	ODP	GWP
R290	4.25	96.74	0	<20
R600a	3.63	134.66	0	<20
R600	3.80	151.98	0	<20
R601a	3.38	187.20	0	<20
R601	3.37	196.55	0	<20
R245fa	3.65	154.01	0	1030

The system efficiency is defined as

$$\eta_{\mathrm{sys}} = W_{\mathrm{net}} / Q_{\mathrm{sys}} , \tag{2}$$

where Q_{sys} is the heat absorption capacity of system. This index is usually selected as the optimized objective for the closed type heat sources [5].

The *SIC* of ORC system is defined as

$$SIC = PEC_{\mathrm{total}} / W_{\mathrm{net}} , \tag{3}$$

where PEC_{total} is the total investment cost of system.

The material of heat exchange tubes is the stainless steel, and the working fluid flows in the tubes to better avoid the leakage. The internal and external diameters of heat exchange tube are 20 mm and 24 mm, respectively. The velocities of hot water and cooling water are 1 m·s^{-1}, and the inlet velocities of working fluid are 1 m·s^{-1} and 8 m·s^{-1} at the inlets of evaporator and condenser, respectively.

For the ORC system, the detailed calculations of thermodynamic performance can refer to Ref. [6]. The calculation methods of the equipment purchased costs and thermo-economic performance can refer to Li et al. [7]. The detailed optimization methods can refer to Ref. [6]. The thermophysical properties of fluids are from the REFPROP 9.1 software. The optimization tool is the MATLAB software.

3. RESULTS AND DISCUSSION

Fig. 2 presents the maximum net power outputs of various working fluids. The net power output increases with increasing the heat source inlet temperature; while, the detailed variation rules are affected by the critical temperature of working fluid. For the working fluid with a high critical temperature, such as R601a and R601, the net power output increases with a high increment as the heat source inlet temperature increases. While, for the working fluid with a low critical temperature, such as R290 and R601a, the increment in net power output initially increases and then nearly remains constant. The reasons for these phenomena have been explained in Ref. [6]. In addition, with increasing the heat source inlet temperature, the variations of optimal evaporation pressure and evaporator outlet temperature are similar as those in the study of Li et al. [6]. The optimal PPTDs are generally their lower limits; while, the optimal PPTD in the heat absorption process will be larger than the lower limit when the heat source inlet temperature is much higher than the critical temperature of working fluid, due to the effects of the variation in PPTD location during the heat absorption process. The R290, R600a, and R600 achieve the largest net power output for heat source inlet temperatures of 100-150°C, 160-180°C, and 190-200°C, respectively. The largest net power output of hydrocarbons is 56.7-487.8 kW when the heat source inlet temperature is 100-200°C. Compared to R245fa, the net power outputs of hydrocarbons can increase by 1.0%-14.2% for heat source inlet temperatures not exceed 180°C. When the heat source inlet temperature exceeds 180°C, the net power output of R245fa is larger than those of hydrocarbons; while, the net power output of R600 is only 0.6%-1.4% lower than that of R245fa. In summary, the hydrocarbons present an attractive prospect to be widely used in ORC systems driven by open type heat sources.

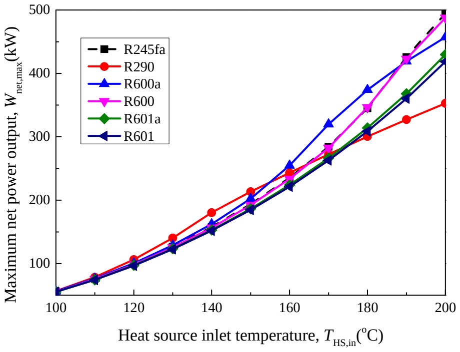

Fig 2 Maximum net power outputs of various working fluids

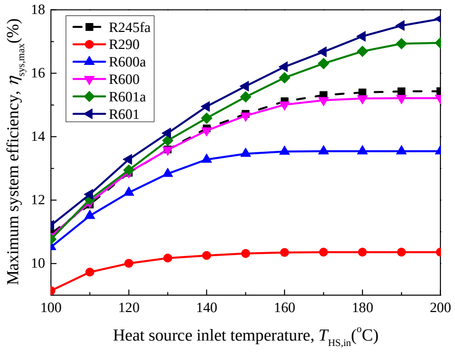

Fig 3 Maximum system efficiencies of various working fluids

The maximum system efficiencies of various working fluids are shown in Fig. 3. With increasing the heat source inlet temperature, the system efficiency increases whereas the increment decreases. The R601 obtains the largest system efficiency for heat source inlet temperatures of 100-200°C, and the R290 obtains the lowest system efficiency. Given a heat source inlet temperature, the maximum system efficiency generally increases with increasing the critical temperature of working fluid. This phenomenon is ascribed that the optimal evaporation pressure of working fluid will be lower when its critical temperature is higher for a given heat source inlet temperature. Thus, the latent heat of working fluid during evaporation process is larger, and that is beneficial to increase the heat source outlet temperature, and thereby obtain a higher system efficiency. The optimal evaporation pressure and evaporator outlet temperature are generally equal to their upper limits, and others are extremely closed to the upper limits. With increasing the heat source inlet temperature, the variations of PPTDs are similar as those obtaining the maximum net power output. Furthermore, the system efficiency of R601 can increase by 2.4%-14.8% compared with R245fa, and the increment increases with increasing the heat source inlet temperature. Hence, the R601 is the optimal option for ORC systems driven by closed type heat sources.

The minimum *SIC*s of various working fluids are presented in Fig. 4. With increasing the heat source inlet temperature, the *SIC* of working fluid generally decreases with a low decrement. The minimum *SIC* of hydrocarbons decreases from 4.37×10^4 \$/kW to 1.19×10^4 \$/kW as the heat source inlet temperature increases from 100°C to 200°C. The R290, R600a, and R600 obtain the lowest *SIC* for heat source inlet temperatures of 100-140°C, 150-160°C, and 170-200°C, respectively. Compared to R245fa, the *SIC* of hydrocarbons can decrease by 1.1%-7.0%, and the decrement increases as the heat source inlet temperature decreases. Hence, the thermo-economic performance of hydrocarbons is better than that of R245fa, and this superiority will be more attractive when the heat source inlet temperature is lower.

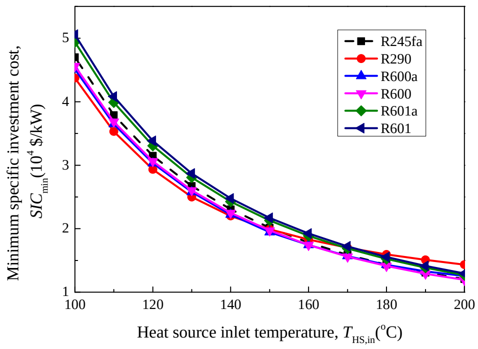

Fig 4 Minimum *SIC*s of various working fluids

In addition, the optimal PPTD in the heat release process is generally larger than the lower limit, and that will be larger when the critical temperature of working fluid is higher. The variations of optimal PPTD in the heat absorption process are similar as those obtaining the maximum net power output. The condenser purchased cost is generally the largest compared to other components, and its ratio to the total equipment purchased cost is 32.9%-50.5% for hydrocarbons. While, for the R600a and R600, the turbine purchased cost is the largest when the heat source inlet temperature exceeds 170°C and 180°C, respectively.

4. CONCLUSIONS

This study carried out an optimization and selection of hydrocarbons for the subcritical ORCs based on multiple evaluation indexes. The heat source was 100-200°C, and five common hydrocarbons were selected as the working fluids. The selection guidelines of optimal working fluids were provided for various evaluation indexes. Main conclusions are summarized as follows:

- R290, R600a, and R600 achieve the largest net power output for heat source inlet temperatures of 100-150°C, 160-180°C, and 190-200°C, respectively.
- The system efficiency of R601 is the largest for heat source inlet temperatures of 100-200°C.
- R290, R600a, and R600 obtain the lowest *SIC* for heat source inlet temperatures of 100-140°C, 150-160°C, and 170-200°C, respectively.
- Compared with R245fa, the hydrocarbons can achieve larger system efficiency and lower *SIC*, and the net power output is also larger for heat source inlet temperatures not exceed 180°C.

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