THERMODYNAMIC, ECONOMIC AND ENVIRONMENTAL MULTI-OBJECTIVE OPTIMIZATION OF ORC UNDER VARYING WEIGHT

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ABSTRACT

Organic Rankine cycle (ORC) is an effective, simple and environmental friendly technology to make use of waste heat or renewable energy such as solar energy, geothermal energy and biomass. With the research on ORC develops, the multi-objective optimization (MOO) recently attracts increasingly attention, in which thermodynamic, economic and environmental performance are optimized simultaneously in ORC system. Since results of MOO are various trade-off solutions, multi-criteria decision making (MCDM) method is widely applied in selecting the optimal one. However, present studies optimize ORC system under a special fixed objective weight and pay little attention to decision making process as well as different weight scenarios. This study firstly analyses the effects of objective weight on the system parameters design and working fluid selection quantitatively using MOO and MCDM method. R1234yf, R290 and R134a are selected as three working fluids with hot water as heat source (373.15 K, 1 kg/s). Results show that R1234yf is the optimum fluid when weight of carbon dioxide emission reduction (*CER*) is over 0.3 while R134a is optimal when weight of *CER* is under 0.3. In addition, the annual leakage rate has important effects on optimal working fluid and should be strictly limited. In terms of system parameters, evaporation temperature and superheat degree are the most sensitive parameters to weight scenarios, while pinch point temperature difference and heat sink outlet temperature are least sensitive since they maintain constant under all weight scenarios. It is revealed that, under the optimal path, design evaporation temperature must be improved if decision makers move toward exergy efficiency.

1. INTRODUCTION

As energy crisis and environmental pollution become increasingly serious, reducing the fossil energy consumption has been the key topic in world energy structure transformation. In this process, renewable energy utilization and waste heat recovery are two valid strategies by directly reducing fossil energy consumption or improving energy utilization efficiency. ORC has been proven a promising technology for power generation from low and medium grade heat sources including both renewables such as solar (Yang, et al., 2019) , geothermal and waste heat such as engine gas (Tian, et al., 2017).

System optimization is an ongoing research for ORC to achieve the highest performance by designing key system parameters and selecting optimum working fluid. With the research develops, optimization method gradually turns from single-objective optimization to multi-objective optimization. Thermodynamic, economic and environmental performance are key indicators to evaluate the ORC system (Li, et al., 2018). Recently there are mainly two ways to comprehensively optimize an ORC system such as (1) transform multiple objectives into single objective based on linear weighting method. (2) optimize several objectives simultaneously using multi-objective optimization algorithm (Gotelip Correa Veloso, et al., 2018). Although more complicated, the second method has more flexibility with a series of trade-off solutions in once calculation and is thus taken into consideration in this study.

Since the optimum solutions are more than one, suitable method should be introduced to select the single one for engineering application. Multi-criteria decision making method is widely used in selecting the optimum value from the Pareto frontier. Fergani, et al. (2016) carried an exergy, exergoeconomic and exergoenvironmental analysis on ORC using Multi-objective Particle Swarm Optimizer (MOPSO) algorithm with a fuzzy technique. Yang, et al. (2015) analyzed the ORC performance for recovering diesel engine exhaust waste heat using Multi-objective Genetic algorithm (MOGA). Yi, et al. (2018) proposed a multi-objective optimization for a liquid separation condensation-based ORC system using epsilon-constrained method. The author used a MCDM method called LINMAP (linear programming technique for multidimensional analysis of preference) to select the optimal solution.

However, most researchers optimize the ORC system under a specially fixed weight of objective and pay little attention to the effects of objective weight on parameter design and fluid selection. In fact, weight scenario directly affects the final optimal solution in decision-making progress and thus affects the system parameters design and working fluid selection, which should consider both the subjective and objective factors. Though important, it is always a puzzling problem to determine the weight of the objective, which however is not the focus here. Instead, this study is interested in exploring the influence of varying weights on the working fluid selection and system parameter design to offer more suggestions in decision making progress and improve the robustness of ORC system.

This study aims at exploring the effect of different weight scenarios on system optimization. Three indexes as levelized energy cost (*LEC*), exergy efficiency, and carbon dioxide emission reduction (*CER*) are selected to evaluate a subcritical ORC system utilizing hot water (373.15 K, 1 kg/s). R1234yf, R290, and R134a are selected as typical working fluids in ORC system and are compared using Non-dominated Sorting Genetic Algorithm II (NSGA-II) algorithm. A multi-criteria decision making method called LINMAP is applied in selecting the optimal solution from the Pareto frontier when weights of three objectives vary from 0 to 1 increasing by 0.05. Optimal working fluid selection and system parameters design are analyzed and the influence of varying weight is firstly explored.

2. SYSTEM MODEL

A basic ORC system consists of an evaporator, an expander, a condenser and a pump. The schematic diagram and *T-s* diagram of an ORC system using dry fluid and wet fluid are shown in Fig 1, Fig 2 and Fig 3. R134a, R290 and R1234yf are selected as three typical working fluids in this study since they belong to hydrocarbons, hydrofluorocarbons and hydrofluorolefins respectively , which are the most common and efficient fluids in ORC. Moreover, these fluids have the suitable critical temperature near heat source and have been proven more efficient (Zhai, et al., 2014). Superheat degree is introduced to avoid two-phase flow in turbine in Fig 2 and Fig 3. A closed loop heat source is introduced and some basic assumptions of ORC system are listed in Table 1.

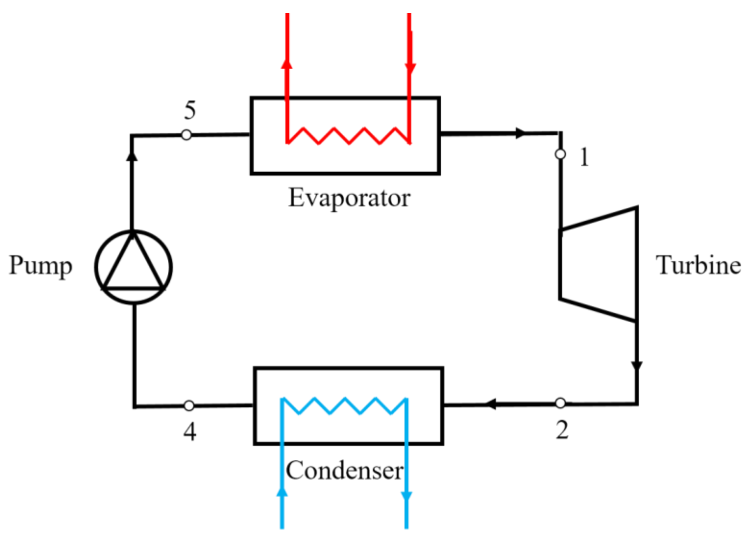

Figure 1: Schematic diagram of ORC system

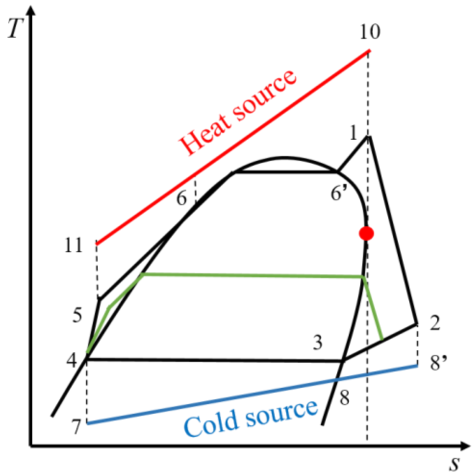

Figure 2: *T-s* diagram of ORC system using dry working fluid

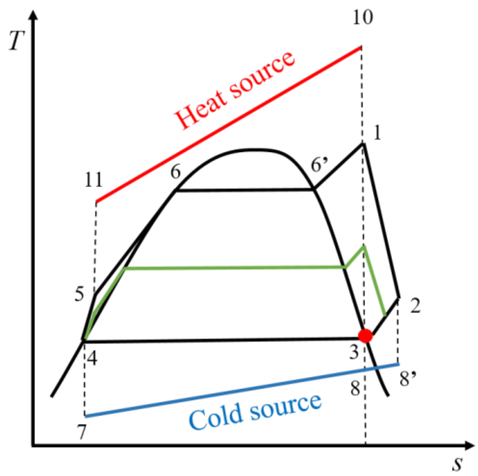

Figure 3: *T-s* diagram of ORC system using wet working fluid

Table 1: Key assumption of ORC system

Item	Symbol	Unit	Value
Hot water temperature	T_{10}	K	373.15
Cold water temperature	T_7	K	293.15
Ambient temperature	T_0	K	293.15
Turbine efficiency	η_t	/	0.85
Pump efficiency	η_p	/	0.65
Heat mass flow rate	m_H	$kg \cdot s^{-1}$	1
Annual operating time	t_{op}	hour	7000
Life cycle period	L_c	year	20

2.1 Thermodynamic model

To simplify the ORC system model, several assumptions are made in this study. (1) ORC system is under steady state. (2) the efficiency of turbine and pump is fixed. (3) flow loss and pressure drop are neglected. The energy flow and exergy loss model of each component are shown in Table 2, where m_H, m_w and m_f is mass flow rate of heat source, heat sink and working fluid respectively.

Table2: Thermodynamic analysis of ORC components

Component	Energy flow	Exergy Loss
Evaporator	$Q_1 = m_H \cdot (h_{10} - h_{11}) = m_f \cdot (h_1 - h_5)$	$I_{eva} = m_H \cdot (h_{10} - h_{11} - T_0 \cdot (s_{10} - s_{11})) - m_f \cdot (h_1 - h_5 - T_0 \cdot (s_1 - s_5))$
Turbine	$W_{tur} = m_f \cdot (h_1 - h_2) = m_f \cdot (h_1 - h_{2s}) \cdot \eta_t$	$I_{tur} = m_f \cdot T_0 \cdot (s_2 - s_1)$
Pump	$W_{pum} = m_f \cdot (h_5 - h_4) = m_f \cdot (h_{5s} - h_4) / \eta_p$	$I_{pum} = m_f \cdot T_0 \cdot (s_5 - s_4)$
Condenser	$Q_2 = m_W \cdot (h_{8'} - h_7) = m_f \cdot (h_2 - h_4)$	$I_{con} = m_f \cdot (h_2 - h_4 - T_0 \cdot (s_2 - s_4))$

Net output power of ORC system is W_{net}

$$W_{net} = W_{tur} - W_{pum} \tag{1}$$

Exergy efficiency is η_{II}

$$\eta_{II} = \frac{W_{net}}{m_H \cdot (h_{10} - h_{11} - T_0 \cdot (s_{10} - s_{11}))} \tag{2}$$

2.2 Economic model

In this study, an axial turbine, a centrifugal pump and two fixed shell-and-tube heat exchangers are applied and the material is mainly carbon steel except the copper tube in heat exchanger. Considering the contingency cost, total investment cost (C_{tot}) is 1.18 times the equipment cost from Lecompte, et al. (2015).

$$C_{tot} = 1.18 \frac{CEPCI_{2017}}{CEPCI_{2001}} \cdot \sum C_p \cdot (B_1 + B_2 \cdot F_M \cdot F_P) \tag{3}$$

Where C_p is the basic cost and F_B is the material and pressure correction factor.

$$\lg C_p = K_1 + K_2 \cdot \lg S_x + K_3 \cdot (\lg S_x)^2 \tag{4}$$

$$\lg F_P = C_1 + C_2 \cdot \lg P + C_3 \cdot (\lg P)^2 \tag{5}$$

Where S_x denontes the power of turbine/pump or the area of heat exchanger, P denotes the pressure in component. K_j and C_j are all constant.

$$LEC = \frac{COM + C_{tot} \cdot \frac{r \cdot (1+r)^{L_c}}{(1+r)^{L_c} - 1}}{W_{net} \cdot t_{op}} \tag{6}$$

Annual operation and maintenance cost (*COM*) is 1.5% of the C_{tot} and r is the interest (5%). t_{op} is annual running hour of ORC system and the levelized electricity cost (*LEC*) is used to represent the system economic performance.

2.3 Environmental model

The environmental performance of ORC system is calculated using the Life Cycle Climate Performance (LCCP) method provided by the International Institute of Refrigeration (IIR). Direct and indirect emissions generated over the lifetime of the ORC system are comprehensively considered in carbon total emission (*CTE*).

$$\text{Direct Emissions} = C \times GWP \times (Lc \times ALR + EOL) \tag{7}$$

$$\begin{aligned}\text{Indirect Emissions} = {} & Lc \times AEC \times EM + MM \times M + RM \times Mr + \\ & RFM \times C + Lc \times ALR \times RFM \times C + C \times RFD \times (1 - EOL)\end{aligned} \tag{8}$$

$$CER = W_{net} \times ECF \times Lc - CTE \tag{9}$$

Where C denotes the charging mass of working fluid based on turbine output (5.57 kg/kW) from Zhang, et al. (2019), L_c is life cycle period of equipment (20 years), *ALR* is annual leakage rate (1% of Refrigerant Charge), *EOL* is the end of life Refrigerant leakage (15% of Charge), *AEC* is the annual energy consumption (kWh), *MM* is the CO_2 emission produced of material (kg CO_2/kg), *M* is the mass of components, *RM* is the CO_2 emission produced of recycled material, *Mr* is the mass of recycled material. The steel mass of the turbine and pump is 31.22 kg/kW and 14 kg/kW based on power respectively. *RFM* is refrigerant manufacturing emissions, *RED* is CO_2 emission produced of refrigerant disposal. Carbon emission reduction is calculated in comparison with the emission of coal-fired power plants (*ECF*, 0.877 kg/kWh) from Liu, et al. (2013). More detailed calculation process can be found in International Institute of Refrigeration.

Table 3: Properties and manufacturing emissions of working fluids from IIR

Working fluid	T_{crit} /K	P_{crit} /Mpa	ODP	GWP /100yr	Mnaufacturing emissions /kg $CO_2 \cdot kg^{-1}$	Disposal emissions /kg $CO_2 \cdot kg^{-1}$
R134a	374.3	4.06	0	1430	5	1.55
R290	369.9	4.25	0	20	0.67	0.05
R1234yf	367.9	3.38	0	4	13.7	2.04

2.4 Optimization and decision making

Multi-objective optimization is recently popular in ORC system design, which is essentially different from single-objective optimization for the absence of single optimal solution. Thus decision making process becomes vital in selecting the optimal one. MCDM has been proven a reliable method in selecting the unique one from trade-off solutions. LINMAP is a simple and intuitive MCDM method, which aims to find the optimal solution closest to the ideal solution. Therefore, NSGA-II is applied in generating more than one solution and then LINMAP is used to select the optimum value in this study. The process of LINMAP is:

1. Non-dimensionalization

These three evaluation indicators are different in unit and magnitude, so they have to be non-dimensionalized. Euclidian non-dimensionalization is applied in LINMAP, which is defined as:

$$f_{ij}^{n} = \frac{f_{ij}}{\sqrt[2]{\sum_{i=1}^{D} (f_{ij})^2}} \tag{10}$$

2. Construct the weighted normalized decision matrix

$$V_{ij} = W_j f_{ij}^{n} \tag{11}$$

$$W_1 + W_2 + W_3 = 1 \tag{12}$$

Where V_{ij} denotes the weighted normalized matrix, W_j denotes the weight coefficient of the jth criteria and f_{ij}^{n} is the normalized matrix.

In this study, W_1 denotes the weight of *LEC*, W_2 denotes the weight of exergy efficiency and W_3 denotes the weight of *CER.*

3. Calculate the ideal solution

$$A^{*} = \left\{V_1^{*}, ..., V_n^{*}\right\} = \left\{(\max V_{ij} \,\middle|\, j \in J), (\min V_{ij} \,\middle|\, j \in J^{"})\right\} \tag{13}$$

Where J denotes the maximizing criteria (power, profit, etc.) and $J^{"}$ denotes the minimizing criteria (loss, cost, etc.).

4. Calculate distance from the ideal solution

$$\mathrm{d}_{i+} = S_i^{*} = \sqrt{\sum_{j=1}^{N} (V_{ij} - V_j^{*})^2}, \; for \;\; i = 1, 2, ..., m \tag{14}$$

The solution with the smallest distance from the ideal solution is optimal.

As mentioned above, objective weight plays an important role in making decision considering subjective and objective factors. Working fluid selection and system parameters are also studied in various weight scenarios to improve the system robustness. As many as 230 scenarios are taken into consideration in this study with W_1 and W_2 increasing respectively from 0 to 1 by 0.05.

3. RESULTS AND DISCUSSION

Fig 4 and Fig 5 show the optimization results of ORC system using three working fluids, it is clear that R134a has the highest exergy efficiency while R1234yf has the highest carbon emission reduction. Fig 4 reveals that R134a is optimal when only exergy efficiency and *LEC* are considered as the two evaluation indicators. However, the inclusion of *CER* deeply changes the selection of working fluids, which is shown in Fig 5. To identify the optimal working fluid quantitatively, a multi-criteria decision making method called LINMAP is applied in selecting the final solution from the Pareto frontier with the weight of *CER* and *LEC* increasing by 0.05. An equal scenario is shown in Fig 6, where the three weights are all equal (W_1=W_2=W_3). Ideal solution in Fig 6 represents the best theoretical solution, which has the highest *CER*, exergy efficiency and the lowest *LEC* among all trade-off solutions of R134a, R290 and R1234yf. The optimal solution is closest to the ideal solution and is located on the Pareto frontier of R1234yf, which indicates that R1234yf is optimum in this equal weight scenario.

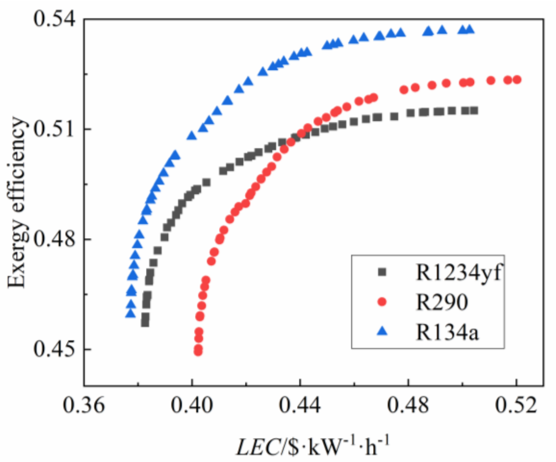

Figure 4: Optimization results of exergy efficiency and *LEC*

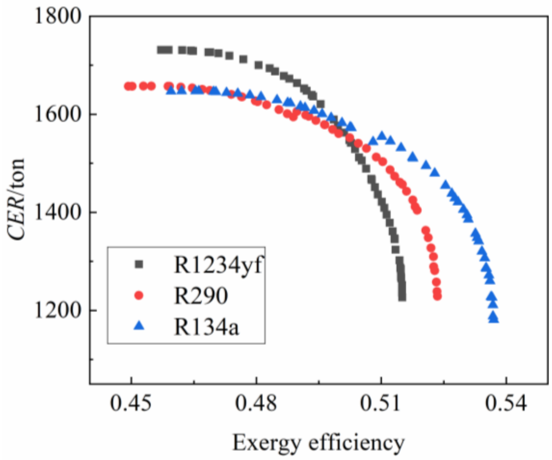

Figure 5: Optimization results of *CER* and exergy efficiency

Optimum working fluid selection of all 230 scenarios are shown in Fig 7 as a function of W_1, W_2 and W_3. It is shown that the optimum fluid selection mainly depends on the weight of *CER* (W_3) and is much less correlated with *LEC* (W_1) or exergy efficiency (W_2). The optimum fluid is R1234yf when W_3 is above approximately 0.3 while R134a is optimal when W_3 is below 0.3. These results are interesting since R134a can still be optimal in some scenarios even though taking environmental performance into consideration (W_3<0.3), which is incredible if making decision only in equal scenario (W_1= W_2= W_3). Therefore, these results highlight the importance of taking different system evaluation indicators (especially environmental performance) into consideration by using MOO and MCDM method instead of only focusing on single weight scenario.

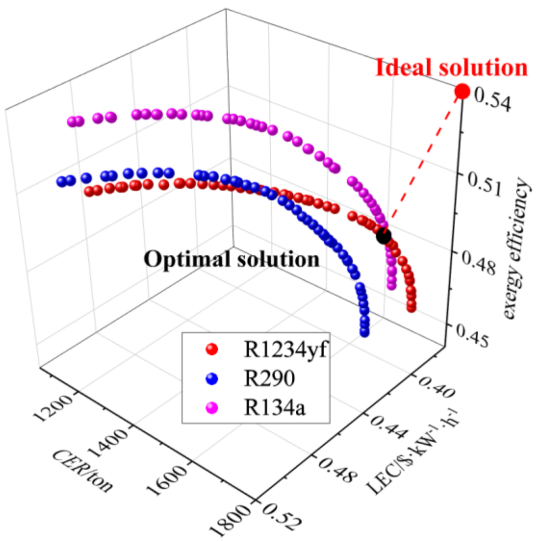

Figure 6: Optimal solution selected by LINMAP (W_1= W_2= W_3)

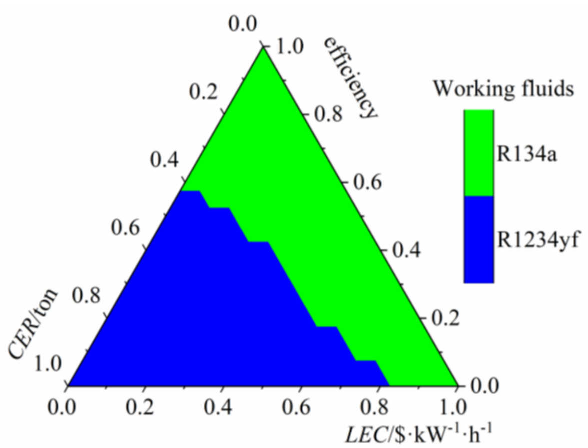

Figure 7: Optimal working fluid in all weight scenarios

In terms of system parameters, the change of weight scenario plays an important role in system design. Optimal pinch point temperature difference in evaporator and condenser as well as the heat sink outlet temperature keep constant when weight changes, which are 5 K, 5 K and 298 K respectively. On the contrary, evaporation temperature and superheat degree are much more sensitive to varying weight. Fig 8 reveals the relationship between evaporation temperature and weight, which indicates that the evaporation temperature is highly related with W_2, since T_1 grows up gradually with increasing W_2 and the contour is almost parallel to horizontal line. Therefore, design evaporation temperature must be improved if the decision maker moves toward exergy efficiency under the optimal path. In the same way, the evaporation temperature should be lower if the weight of *LEC* and *CER* is higher according to Fig 8. Optimal superheat degree value is shown in Fig 9, which indicates that the superheat degree is highly related with working fluid selection in Fig 7. Optimal superheat degree is below 2 K if W_3 surpasses 0.4, when R1234yf is the optimal working fluid. When the optimum working fluid is R134a in Fig 7, optimal superheat degree value mainly depends on W_2. In this case, optimal superheat degree is about 4 K if W_2 is below 0.5. When W_2 is above 0.5, superheat degree increases firstly to 18 K and then decreases to 10 K.

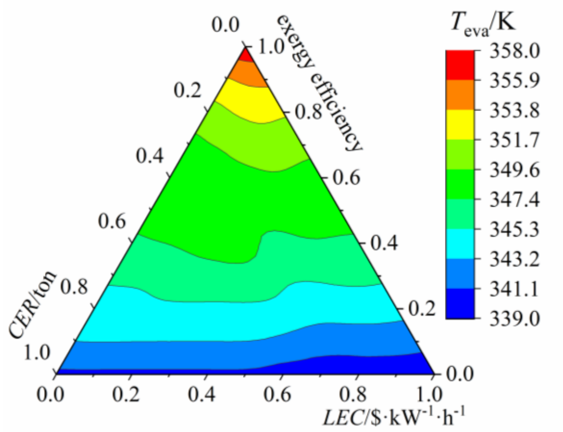

Figure 8: Optimum evaporation temperature in all weight scenarios

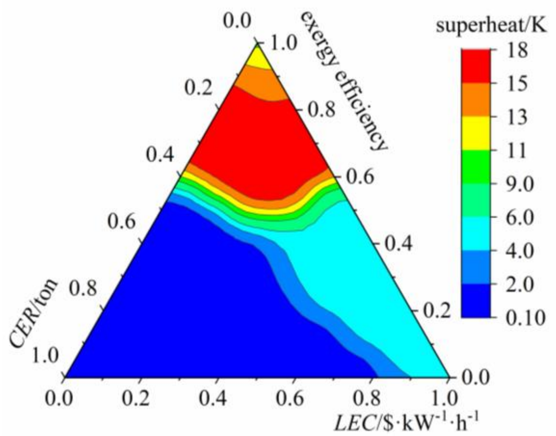

Figure 9: Optimum superheat degree in all weight scenarios

A sensitivity analysis is carried out to explore the effects of different annual leakage rates, and optimal working fluids are listed in Fig 10 and Fig 11. As the annual leakage rate increases, the proportion of R134a gradually decreases. When the annual leakage rate is 3%, only R134a and R1234yf are considered to be the optimum in different weight scenarios. However, when annual leakage rate is 5%, R290 is optimal in several special weight scenarios such as W_3=0.25 and W_2=0.75. In addition, with different annual leakage rates, *CER* is always the key evaluation index that affects the working fluid selection as in Fig 7, which highlights the importance of considering system environmental performance as well as the annual leakage rate limitation.

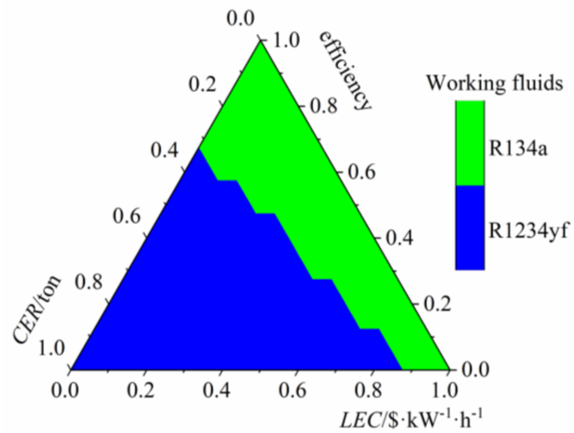

Figure 10: Optimal working fluid when annual leakage rate is 3%

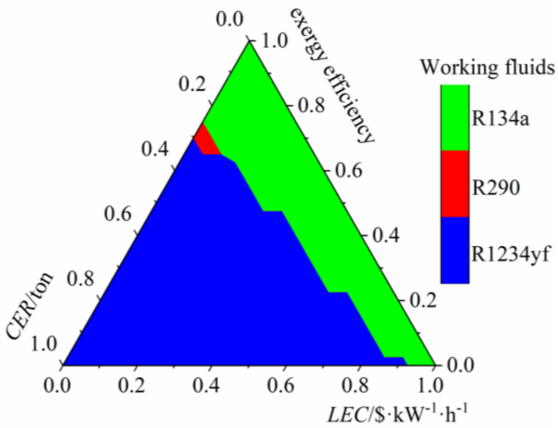

Figure 11: Optimal working fluid when annual leakage rate is 5%

4. CONCLUSION

Multi-objective optimization and multi-criteria decision-making method are applied in this study to firstly explore the effects of different objective weight scenarios on working fluid selection and parameter design in ORC system. Three indexes as levelized energy cost, exergy efficiency, and carbon dioxide emission reduction are selected as system evaluation indicators with a heat source of 373.15 K. Five system parameters as evaporation temperature, pinch point temperature difference in evaporator/condenser, superheat degree and heat sink outlet temperature are optimized.

Results show that the change of weight deeply affects the working fluid selection and system parameter design. R134a exhibits the best thermodynamic performance but the worst environmental performance.

R134a is the optimum fluid when weight of *CER* is below 0.3 while R1234yf is optimal when weight of *CER* is above 0.3. In addition, annual leakage rate has important effects on optimal working fluid and should be strictly limited. In terms of system parameter design, evaporation temperature and superheat degree are sensitive parameters, while the pinch point temperature difference and heat sink outlet temperature are less sensitive to the weight of *CER* and *LEC* since they are constant in all weight scenarios. It is also found that, under the optimal path, design evaporation temperature must be improved if decision makers moves toward exergy efficiency, while superheat degree increases firstly to 18 K and then decreases. This study firstly analyses the effects of evaluation indicator weight on the system parameters design and working fluid selection quantitatively using MOO and MCDM method. Which facilitates the comprehensive optimization of ORC system considering different scenarios in decision making progress.

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NOMENCLATURE

h	enthalpy	(J/kg)
m	mass flow rate	(kg/s)

Subscript

con	condenser	eva	evaporator
net	net power	pum	pump

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