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Performance optimization of organic Rankine cycle systems for waste-heat recovery: Phase change heat exchanger sizing based on infinitesimal method

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ABSTRACT

Phase change heat exchanger (PCHE) is an essential component of the integrated energy system (cooling, heating and power) modeling and optimization, where the heat transfer performance directly affects the overall performance and the equipment investment accounts for a significant proportion. This work proposes a new collaborative optimization method for coupling micro-phase change heat exchanger (MPCHE) sizing and organic Rankine cycle (ORC) systems performance to recover different grades low-temperature waste heat considering the heat transfer characteristics with fuzzy heat transfer zones, complex flow patterns and chaotic motion law. Firstly, considering the dynamic changes of thermophysical property of fluids, a new design method of the infinitesimal phase-change heat exchanger based on phase transition rate infinitesimal (PCHE-PTI) is proposed, and a thermo-hydraulic model close to the real heat transfer law is established. Then, the traditional-three-stage phase change heat exchanger design method (PCHE-TTS) and the micro-segmentation phase change heat exchanger design based on the number of baffle and tube pass (PCHE-MBT) are coupled to ORC system respectively. Finally, the reinforcement learning neural network algorithm (RLNNA) is used to solve the three mixed integer nonlinear programming models to achieve the optimal thermal-economic. The results show that the new method proposed can accurately describe the actual phase change heat transfer behavior and can also obtain an electricity production cost that is 5% lower than the traditional method and 8% lower than the original design. Furthermore, the coupling optimization process of MPCHE-ORC-Fluid is successfully realized by considering Fluid selection, and the most cost-effective optimization configuration is obtained, thereby improving the accuracy and reliability of design optimization.

Keywords: Organic Rankine cycle, micro-segment heat transfer, low grade waste heat, neural network algorithm with reinforcement learning, thermo-economic analysis

NONMENCLATURE

Abbreviations	
ORC	Organic Rankine cycle
PCHE	Phase change heat exchanger
RLNNA	Reinforcement learning neural network algorithm
STHE	Shell-and-tube heat exchanger
EPC	Electricity production cost
Symbols	
A	heat transfer surface area, m^2
B_c	baffle cut ratio
c_p	specific heat capacity (J/kg·K)
C_{tot}	initial investment cost ($)
D, d	diameter (m)
h	enthalpy(J/kg); heat transfer coefficient(W/m^{2}K)
hr	full-load operation duration (8000 hours)
m	mass flow rate (kg/s)
n, N	number; lifetime (20 years)
P	pressure (Pa)
Q	heat capacity (W)
W	power (W)
s	specific entropy (J/kg·K)
T	temperature (K)
ρ	density (kg/m^3)
λ	thermal conductivity (W/m·K)
μ	viscosity (Pa·s)

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η	efficiency
Subscripts and superscripts	
bc	baffle spacing
c	condenser; cold fluid side; baffle cut
cond	condensation
crit	critical
e	evaporator; entrance and exit
evap	evaporation
g	low-temperature exhaust gas
h	hot fluid side
i,in	inlet; inside; the interest rate (5%); equipment
l	leakage; liquid
net	net
o,out	outlet; outside
p	pump
s	isentropic; shell; heat transfer microsegment
t	tube; expander; total
wf	working fluid

1. INTRODUCTION

The low-grade (<493.15 K) waste heat accounts for approximately 60 % [1], and only 30 % of the waste heat is re-used [2]. ORC power generation system using these ultra-low-temperature or renewable energy is found to be a most suitable technique and promising low-temperature waste heat recovery technology, which has a broad market scale and prospect that has been maintaining a trend targeting towards carbon neutrality [3]. Also, heat exchangers are amongst of the key components that affect the performance of ORC systems since they can recover energy from low-grade heat source to electricity [4].

Recently, Lu [5] reviewed the design and optimization of organic Rankine cycles based on heat transfer enhancement and novel heat exchanger. Zhang [6] analyzed the performance variation of the ORC under four flow-boiling correlations and four flow-condensing correlations. Zhang [7] evaluated and compared the heat economy of sub-critical ORC in four sub-critical ORC type configurations within a fixed pressure drop. Choi [8] optimized the recovery of cold energy by combining an ORC with a liquefied natural gas regasification plant under a limited total conductance of heat exchangers, regardless of specific heat exchanger size design. Bull [9] evaluated the work output and thermal efficiency of ORC systems with plate and STHE under several operating pressures and concluded that PHE is better than STHE in overall heat transfer coefficient and area, but the investment is larger. However, as none of the above explicitly consider the coupling between the pressure drop and the performance assessments of an ORC system and working-fluid selection exercises that fail to may yield suboptimal results and can overestimate the capabilities of such systems relative to practical experience. Therefore, Li [10] focuses on the interaction of the heat exchanger pressure drop and the thermo-economic performance of ORC systems in engine waste-heat recovery applications. In our previous publications, a multi-temperature partition and multi-configuration integrated organic Rankine cycle system model [11] was proposed to improve low temperature heat utilization and a comprehensive comparison with basic organic Rankine cycle, recuperative organic Rankine cycle and regenerative organic Rankine cycle is conducted to assess thermal and economic performance with ten working fluids. Though the proposed model has been validated for waste heat recovery from refinery diesel heat source, the ORC system does not involve coupling optimization of phase conversion thermal equipment.

In view of the heat transfer characteristics of phase change heat exchangers with complex zones and flow patterns and chaotic motion law, this study aims to propose an improved collaborative optimization method the coupling between the PCHE and the performance of an associated ORC system. The main work is as follows: 1) considering the dynamic changes of thermophysical properties of fluids in ORC system; 2) establishing a thermal-hydraulic model of micro-segment phase change heat transfer based on phase transition rate infinitesimal; 3) applying the neural network algorithm with reinforcement learning to solve this model to achieve the optimal cost-effective thermal-economic configuration. Then, the proposed approach can accurately describe the actual phase change heat transfer behavior, thus improving the reliability and accuracy of system design and analysis compared with PCHE-TTS and PCHE-MBT design method.

2. MODELLING METHODOLOGY

2.1 ORC thermodynamic model

Fig. 1 shows the three co-design methods coupling MPCHE sizing and ORC system. Energy analysis of ORC is as follows:

$$W_P = m_{wf} \cdot (h_4 - h_3) = m_{wf} \cdot (h_{4s} - h_3)/\eta_p \quad (1)$$

$$Q_{evap} = m_{wf} \cdot (h_1 - h_4) = m_g \cdot c_{p,g} \cdot (T_{g,i} - T_{g,o}) \quad (2)$$

$$W_t = m_{wf} \cdot (h_1 - h_2) = m_{wf} \cdot (h_1 - h_{2s}) \cdot \eta_t \quad (3)$$

$$Q_{cond} = m_{wf} \cdot (h_2 - h_3) = m_{cw} \cdot c_{p,cw} \cdot (T_{cw,o} - T_{cw,i}) \quad (4)$$

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

The pressures at each state considering the pressure drop are listed as below:

$$P_3 = P_{cond} \quad (6)$$

$$P_4 = P_5 + \Delta P_{wf,preh} \quad (7)$$

$$P_5 = P_6 + \Delta P_{wf,evap} \quad (8)$$

$$P_6 = P_{evap} \quad (9)$$

$$P_2 = P_{2s} + \Delta P_{wf,desup} \quad (10)$$

$$P_{2s} = P_3 + \Delta P_{wf,cond} \quad (11)$$

The Cooper nucleate pool-boiling method is adopted in the evaporation zone [14]:

$$h_i = 1.5 \cdot 55(P_r)^{[0.12-0.2\cdot log(R_p)]}[-log(P_r)]^{-0.55} q^{0.67} M_r^{-0.5} \quad (15)$$

The Dobson correlation [15] is used for the condensation process:

when $G \geq 500\, kg/m^2 s$:

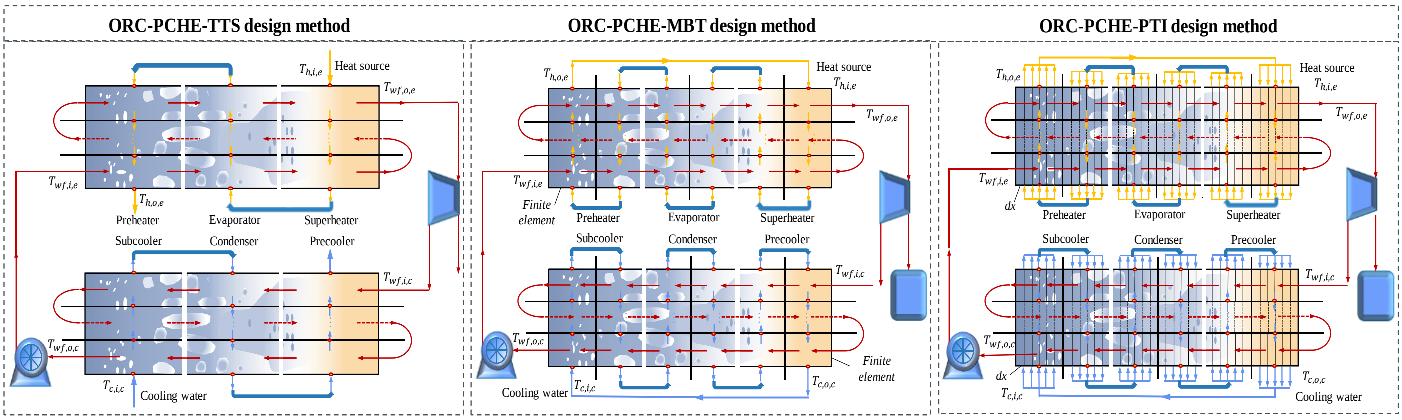


Fig. 1. Three co-design methods coupling MPCHE sizing and ORC system

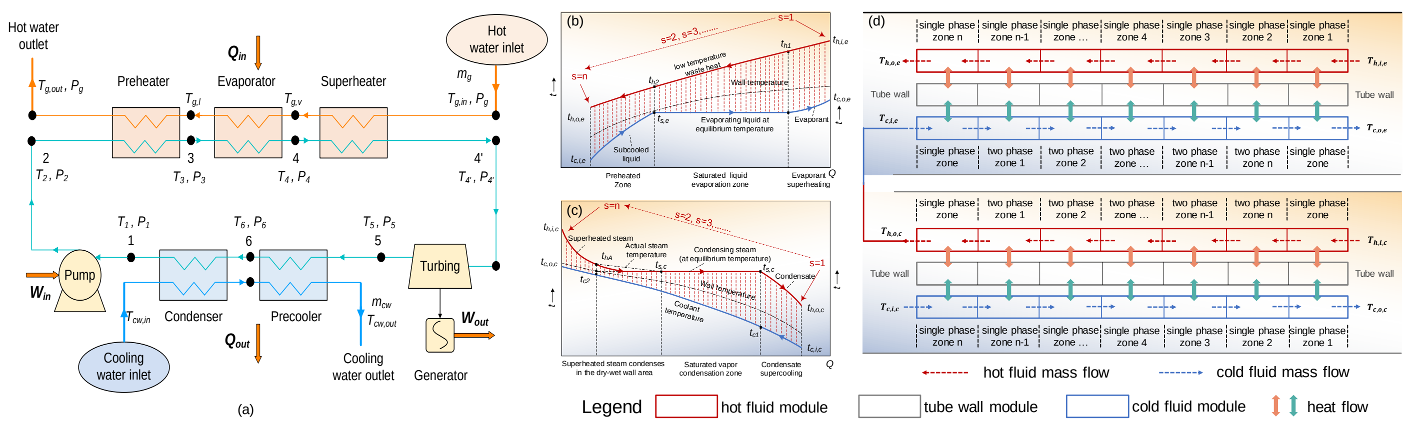


Fig. 2. (a) The schematic diagram of the ORC system; (b) and (c) T-Q schematic diagram; (d) A improved design method for PCHE

$$h_t = 0.023 \cdot \frac{\lambda_i}{d_i} \cdot Re_l^{0.8} Pr_l^{0.4} \cdot \left(1 + \frac{2.22}{X_{tt}^{0.89}}\right) \quad (16)$$

when $G < 500 kg/m^2 s$:

$$h_t = \frac{\lambda_i}{d_i}\left[\frac{0.23\cdot Re_{vo}^{0.12}}{1+1.11\cdot X_{tt}^{0.58}}\left(\frac{Ga\cdot Pr_l}{Ja_l}\right)^{1/4} + \frac{arccos(2\cdot \gamma -1)}{\pi} Nu_f\right] \quad (17)$$

where $Re_l, Pr_l, X_{tt}, Re_{vo}, Ga, Ja_l, \gamma, Nu_f$ are calculated from [15]:

The total pressure drop at the tube side is composed of pressure drop Δp_n at the nozzle inlet and outlet, pressure drop Δp_{tb} at the tube bundle, pressure drop loss Δp_{ce} at the tube outlet due to sudden contraction and expansion, and pressure drop Δp_r related to steering loss, which are calculated from [13]:

$$\Delta p_i = \Delta p_n + \Delta p_{tb} + \Delta p_{c,e} + \Delta p_r \quad (18)$$

2.2 Micro-segment phase change heat exchanger

Fig. 2 shows a detailed improved design method for Micro-PCHE of the ORC system. The shell-side of evaporator and condenser is low-temperature waste gas and cooling water without phase transition process. Bell-Delaware method [12] is used to calculate the heat transfer coefficient and pressure drop of the shell side.

$$h_o = h_{id}\, J_c\, J_l\, J_b\, J_s\, J_r \quad (12)$$

$$\Delta p_o = \Delta p_{cr} + \Delta p_w + \Delta p_{io} \quad (13)$$

The Dittus-Boelter correlation [13] is used in the single-phase zone (preheating, superheating, cooling and subcooling) on the tube-side of the evaporator and condenser, where n=0.4 for heating and n=0.3 for cooling.

$$h_i = 0.023\, \lambda_i/d_i\, {Re_i}^{0.8} {P_{ri}}^{n} (\mu_i/\mu_{wi})^{0.14} \quad (14)$$

2.3 Economic model

Investment cost of ORC system is composed of equipment cost, system operation cost and management cost, which can be calculated as:

$$C_{tot} = \sum C_{BM,i} \tag{19}$$

$$C_{BM} = C_p^0(B_1 + B_2 F_M F_P) \tag{20}$$

$$\log C_p^0 = K_1 + K_2 \log(X) + K_3(\log(X))^2 \tag{21}$$

Where i refers to the various equipment; X is the technical parameter of the equipment (the heat exchange area for PCHE, W for the expander and P for the pump). K_1, K_2, K_3, B_1 and B_2 are fitting cost coefficients for different equipment. The values are given in [16].

2.4 *Objective function, variables and constraints*

Optimization is carried out by using EPC as objective function. The evaporative temperature of ORC system and the temperature difference of PCHE are taken as operating variables, and the tube diameter, shell diameter, tube length, baffle spacing, baffle cut, tube pitch ratio and tube passes number of PCHE are taken as design variables, which are collaboratively optimized.

$$EPC = (C_{tot}\frac{i(1+i)^N}{(1+i)^N - 1} + 0.015 \cdot C_{tot})/hr/W_{net} \tag{22}$$

The minimum exhaust gas temperature in the evaporator is set to be 355.15 K to avoid any corrosion.

$$T_{g,out} \geq 355.15\ K \tag{23}$$

The inlet and outlet temperature constraints of each infinitesimal segment are as follows:

$$T_{h,i,k}^1 = T_{h,i,k}, (k = e\ or\ c) \tag{24}$$

$$T_{h,o,k}^n = T_{h,o,k}, (k = e\ or\ c) \tag{25}$$

$$T_{h,o,k}^i = T_{h,i,k}^{i+1}, (i = 1,2,\cdots,n; k = e\ or\ c) \tag{26}$$

$$T_{c,i,k}^1 = T_{c,i,k}, (k = e\ or\ c) \tag{27}$$

$$T_{c,o,k}^n = T_{c,o,k}, (k = e\ or\ c) \tag{28}$$

$$T_{c,o,k}^i = T_{c,i,k}^{i+1}, (i = 1,2,\cdots,n; k = e\ or\ c) \tag{29}$$

Pressure drop allowance:

$$\Delta p_s \leq 30\ kPa \tag{30}$$

$$\Delta p_t \leq 20\ kPa \tag{31}$$

Some geometric constraints within the TEMA standard heat exchanger are as follows:

$$0.2D_s \leq L_{bc} \leq 1.0D_s \tag{32}$$

$$3D_s \leq L \leq 15D_s \tag{33}$$

$$0.18D_s \leq L_c \leq 0.4D_s \tag{34}$$

$$0.2D_s \leq L_{bio} \leq 1.0D_s \tag{35}$$

An ORC model is developed in MATLAB, with fluid properties obtained from REFPROP 9.1. The Micro-PCHE-ORC model is developed in MATLAB, with fluid properties obtained from REFPROP 9.1, and Fig. 3 shows that the reinforcement learning neural network algorithm for solving coupled ORC-PCHE systems.

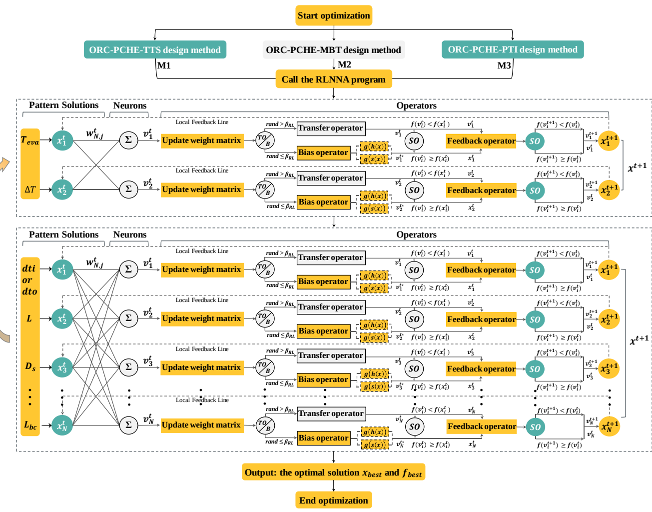
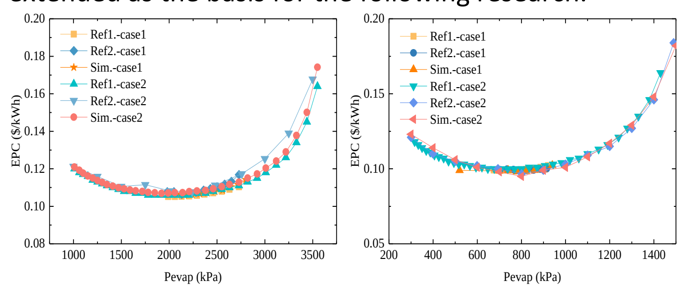


Fig. 3. Neural network algorithm with reinforcement learning for solving coupled ORC-PCHE systems

3. RESULTS AND DISCUSSION

3.1 *Model validation*

The PCHE-ORC model based on conventional approaches is validated against Ref. [7,10]. Two different cases are considered for both R600 and R601. Case 1 refers to $T_{h,out} \geq 355.15\ K$ and case 2 refers to the scenario where there is no limitation for $T_{h,out}$. It can be clearly seen in Fig. 4 that this basic model is in good agreement with the reference EPC values and can be extended as the basis for the following research.



(a) R600 (b) R601

Fig. 4. Model validation against data from Ref. [7,10]

3.2 *Optimization result*

Fig. 5 presents the variation of EPC with the pinch point temperature in the evaporator (ΔT_e) at $T_e = 102$℃ of R600 and $T_e = 102$℃ of R601. It can be seen that with the increase of ΔT_e, EPC first decreases and then increases. Therefore, there is an optimal ΔT_e corresponding to the minimum EPC, the same as the optimal result for the condenser pinch point temperature difference (ΔT_c). The reason for this is, on the one hand, that as ΔT_e increases, the average heat transfer temperature difference increases, the heat transfer area decreases, and the capital cost decreases; on the other hand, for a given T_e, the heat transfer decreases due to an increase in ΔT_e, which leads to a decrease in power output. Firstly, in the lower ΔT_e range, the reduction of C_{tot} has a greater effect on the EPC than the reduction of power output. Therefore, EPC decreases with ΔT_e. As ΔT_e increases further, the decrease in power output becomes the dominant factor due to the rapid decrease in heat input, leading to an increase in EPC. In this study, due to the use of room temperature water as coolant, ΔT_c is limited to a small range of 5-10°C, and the optimum result is almost 8°C. In addition, the results show that the optimization results of ORC-PCHE-PTI design method are better than the other two methods. When the pinch point temperature in the lower range, the difference between the three design methods is small, but as the temperature difference increases, the deviation between the three design methods is also increasing, and the EPC of ORC-PCHE-PTI is generally about 2%~5% lower than that of the other two methods.

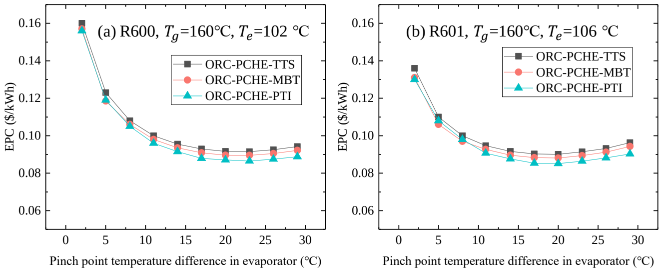


Fig. 5. Variation of EPC with ΔT_e for three design method ((a) and (b))

3.3 Working fluid selection

As shown in Fig. 6 and Fig. 7, the minimum EPC, and the corresponding W_{net} for different design methods at $T_{\mathrm{h}} = 160$°C are presented. The EPC for ORC-PCHE-TTS design method using different working fluids is the largest, followed by ORC-PCHE-MBT and ORC-PCHE-PTI. The EPC of ORC-PCHE-PTI ranging from 0.0849 to 0.0934 $/kWh are apparently lower than that of ORC-PCHE-TTS and ORC-PCHE-MBT ranging from 0.0865 to 0.0958 $/kWh for different working fluids, and the reduction can be as much as 6%.

Similarly, as shown in Fig. 7, the first two design methods have little difference in the influence of W_{net} using different working fluids, and the ORC-PCHE-MBT method is slightly higher than the other two. Among them, there are more differences in R601, R152a, R600, R245fa and R601a. The W_{net} of ORC-PCHE-PTI ranging from 81.22 to 93.37 kW are apparently higher than that of ORC-PCHE-TTS and ORC-PCHE-MBT ranging from 79.5 to 91.1 $/kWh for different working fluids, and the results show that ORC-PCHE-MBT can obtain the W_{net} that is 4.16% higher than the traditional method and 5.78% lower than the original design, respectively. So, the heat exchanger configuration design and working fluid have a significant influence on the economic performance of ORC systems.

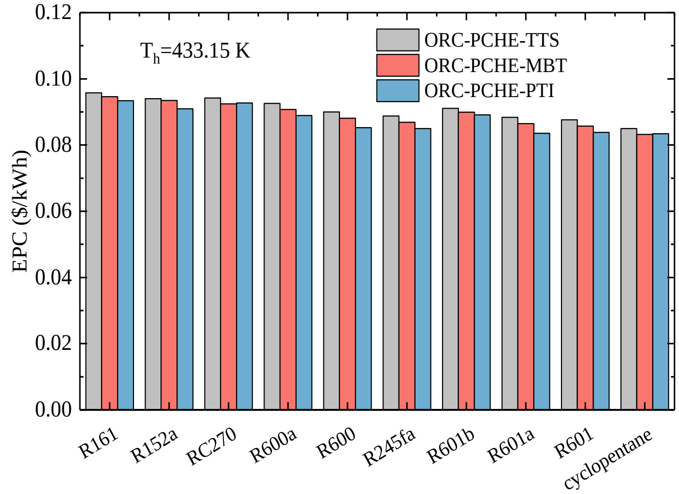


Fig. 6. The minimum EPC of different working fluid for different design methods

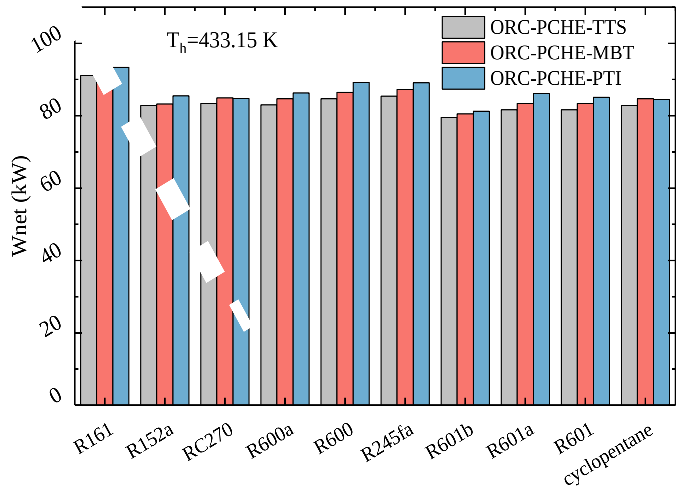


Fig. 7. The W_{net} of different working fluids for different design methods at the minimum EPC

3.4 Low-temperature waste heat source

Fig. 8 and Fig. 9 show that the minimum EPC of different working fluids at different heat source temperatures using different design methods. The minimum EPC are greatly affected by T_{h}. However, the difference of minimum EPC between two heat source temperatures will become much smaller with the increase of T_{h}. Taking R600 as example, the minimum EPC of ORC-PCHE-PTI method has a reduction rate of 26.56%, 20.33%, 15.91% and 8.82%, respectively. Also, at a low heat source temperature of 120 °C, the ORC-PCHE-PTI method for each working fluid achieves an EPC reduction of up to 8% compared to the other two methods. However, as the heat source temperature increases, the reduction level shows a decreasing trend, reaching a reduction ratio of around 2% at a high heat source temperature of 200 °C. Clearly, the results indicate that R601 has excellent EPC performance at heat source temperatures below 180 °C.

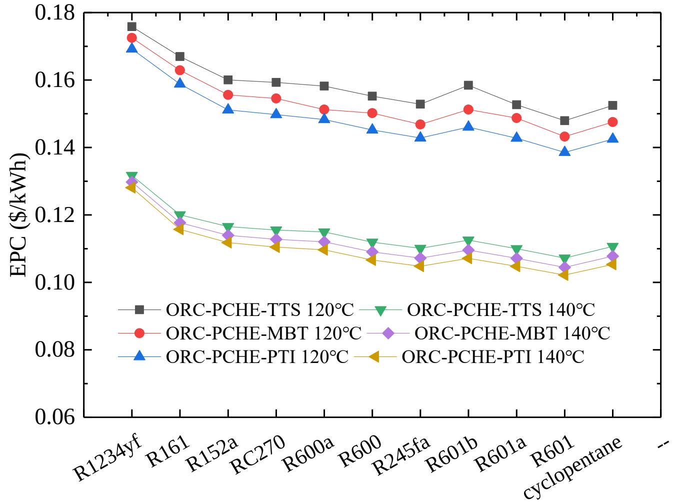


Fig. 8. The minimum EPC of different working fluids at low heat source temperatures

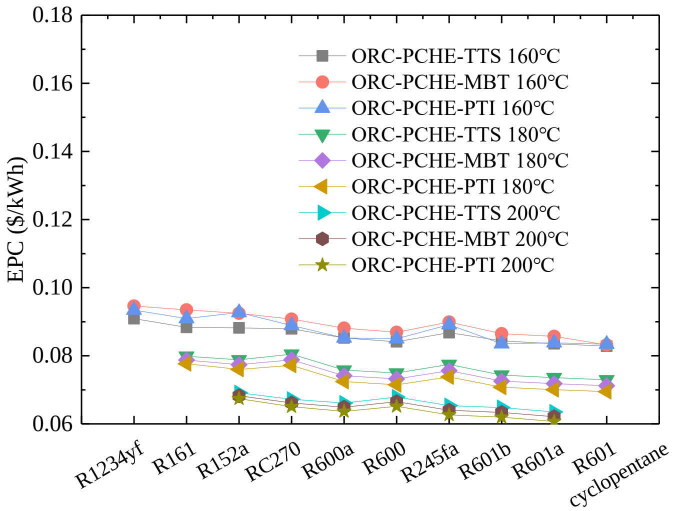


Fig. 9. The minimum EPC of different working fluids at high heat source temperatures

4. CONCLUSIONS

This study proposed an improved collaborative optimization method the coupling the phase change heat exchanger and the performance of an associated ORC system based on the heat transfer characteristics of phase change heat exchangers with complex zones and flow patterns and chaotic motion law. Then, the reinforcement learning neural network algorithm method was used to optimize and obtain the optimal EPC. The results show that the new design method can accurately describe the actual phase change heat transfer behavior and can also obtain the net work output that is 4.16% higher than the traditional method and 5.78% lower than the original design, respectively. So, the electricity production cost is also reduced by 5% and 8% lower than PCHE-TTS and PCHE-MBT method respectively. The most cost-effective optimization configuration is obtained, thereby improving the accuracy and reliability of design optimization.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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