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The Integration of Supercritical and Reheating Rankine Cycles in Advanced Thermal Energy Systems for Extreme Weather Adaptation#

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ABSTRACT

Extreme high-temperature weather circumstances have also created notable opportunities for harnessing medium and low-temperature energy, particularly solar thermal energy. This study introduces an innovative binary Rankine cycle (BRC) system intending to optimise the available temperature range and enhance the energy conversion capacity. The proposed system comprises two subsystems: a reheating steam Rankine cycle (RSRC) system and a supercritical organic Rankine cycle (SORC) system. The numerical simulation demonstrates that the proposed BRC system exhibits great superiority in energy conversion compared to a single RSRC or SORC system. The proposed BRC system has a significant system efficiency of up to 25.4%, surpassing the individual RSRC (23.23%) or SORC (7.59%) system. This feature makes it highly promising for harnessing medium and low-temperature heat sources and its scale development can potentially mitigate harsh high-temperature weather conditions.

Keywords: reheating steam Rankine cycle, supercritical organic Rankine cycle, binary Rankine cycle, solar thermal energy, energy conversion efficiency

1. INTRODUCTION

The Rankine cycle is a maestro at the energy conversion of large-scale medium and low-temperature heat sources, particularly solar heat energy. The quality of solar thermal energy is improved by the presence of extremely high temperatures weather, which presents a significant potential for this technology [1]. Researchers are pursuing various enquiries on the Rankine cycle [2].

The steam Rankine cycle (SRC) remains a prominent research hotspot in power production technology due to its high thermal conductivity, high latent heat of vaporisation, wide operating temperature range, pure, nontoxic, safety, affordability, and accessibility [3]. [4] proposes a novel dual-pressure SRC to recover multi-stage waste heat from ship engines. The fuel costs are reduced by up to 4%.

The simplicity and efficacy of the organic Rankine cycle (ORC) have intrigued numerous researchers. [5] evaluates a dual-stage ORC and determines the optimal working fluid combination for various geothermal energy temperature ranges. A data-driven robust parametric optimisation method is proposed in [6] to guarantee constant and high performance in the presence of uncertainty.

The complex Rankine cycle technology has also emerged as an innovation in energy conversion. In [7], a supercritical steam Rankine cycle is proposed, and it is confirmed that the Rankine cycle can exceed the thermal efficiency of the S-CO2 Brayton cycle. [8] examines a combined steam–organic Rankine cycle system and determines the optimal working fluids across various temperature conditions.

Nevertheless, there is a dearth of the Rankine cycle on maximal energy conversion in the presence of an extremely high-temperature environment. This work proposes a novel binary Rankine cycle (BRC) system which can expand the effective temperature range and increase the energy conversion capacity. The reheating steam Rankine cycle (RSRC) and the supercritical organic Rankine cycle (SORC) are the two fundamental cycles. To optimise energy conversion, reheating and supercritical technology are initially incorporated into a unified system. System optimisation, thermodynamic property, and off-design operating analysis are examined in this paper.

Section 2 establishes the proposed system. The BRC's mathematical models are formulated and validated in Section 3. Section 4 delves into the numerical outcomes. This endeavour is concluded in Section 5.

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2. SYSTEM DESCRIPTION

Fig. 1 and Fig. 2 depict the structure and T-s diagram of the BRC system, respectively. Solar heat energy is absorbed by the photovoltaic collector and subsequently transferred to the evaporator of the RSRC system [2]. After that, the water is heated to superheated vapour. The energy is converted into electrical energy through two steam turbines. Subsequently, the water vapour transfers energy to the SORC in the heat exchanger and condenses into saturated water. The SORC system can more effectively utilise thermal energy of lower quality, thereby guaranteeing the overall cycle's optimum energy utilisation.

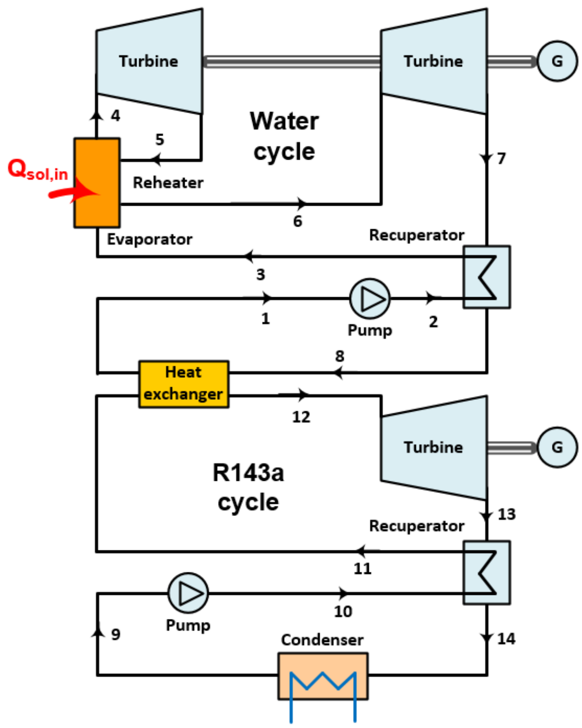

Fig. 1 The proposed binary Rankine cycle

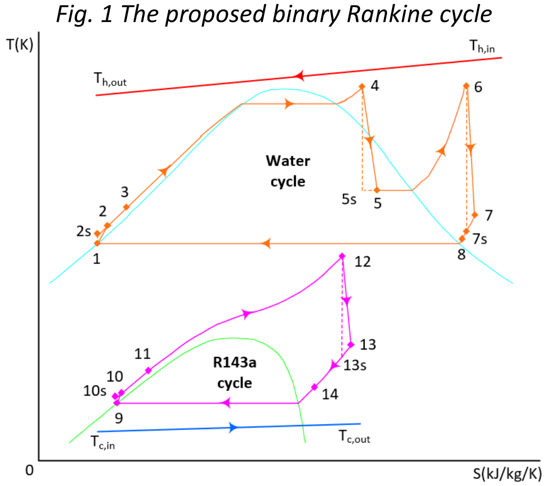

Fig. 2 T-s diagram of the binary Rankine cycle

3. METHODS

This section proposes and validates the mathematical models of the BRC system.

3.1 Mathematic models

The two pumps of the binary Rankine cycle are presumed in the same settings and the pump isentropic efficiency is as follows:

$$\eta_{is,pump} = \frac{h_{2,is} - h_1}{h_2 - h_1} = \frac{h_{10,is} - h_9}{h_{10} - h_9} \tag{1}$$

where h is the enthalpy of the specific state point. Subscript *is* means the isentropic process.

There are five main thermal exchanger equipment: an evaporator, two recuperators, a heat exchanger, and a condenser. The energy exchange efficiencies are identical at 80%. The energy balance is assumed as follows:

$$\begin{aligned} m_W(h_4 - h_3 + h_6 - h_5) &= 0.8Q_{in} \\ h_3 - h_2 &= 0.8(h_7 - h_8) \\ h_{11} - h_{10} &= 0.8(h_{13} - h_{14}) \\ h_{12} - h_{11} &= 0.8(h_8 - h_1) \\ 0.8m_R(h_{14} - h_9) &= Q_{out} \end{aligned} \tag{2}$$

where m_W and m_R stand for the mass flow rates of water and R143a respectively. Q_{in} and Q_{out} represent the heat energy input and output of the BRC, respectively.

In addition, the approach temperature, pinch point, and superheating temperature are all assumed to be 5K and the expression can be formulated as bellow:

$$\begin{aligned} T_4 &= T_{sat} + 5K \\ T_6 &= T_4 \\ T_8 &= T_2 + 5K \\ T_{14} &= T_{10} + 5K \\ T_1 &= T_{12} + 5K \\ T_9 &= T_{amb} + 10K \end{aligned} \tag{3}$$

where T_{sat} is saturated steam temperature of the water cycle. T_{amb} is the ambient temperature and is 10K lower than the condensing temperature for the cooling effect.

The BRC is equipped with three turbines. The isentropic efficiencies are delineated as:

$$\begin{aligned} \eta_{is,tur-W1} &= \frac{h_4 - h_5}{h_4 - h_{5,is}} \\ \eta_{is,tur-W2} &= \frac{h_6 - h_7}{h_6 - h_{7,is}} \\ \eta_{is,tur-R} &= \frac{h_{12} - h_{13}}{h_{12} - h_{13,is}} \end{aligned} \tag{4}$$

The turbine's specific isentropic efficiency is contingent upon the pressure ratio and can be represented as [9]:

$$\eta_{is,tur} = c[0.9403305 + 0.0293295\ln(V_{out}) - 0.026698\frac{V_{out}}{V_{in}}]$$

$$c = \begin{cases} 1 - 0.264\ln(\frac{V_{out}}{V_{in}}) & \frac{V_{out}}{V_{in}} > 7 \\ 1 & \frac{V_{out}}{V_{in}} \leq 7 \end{cases} \quad (5)$$

where V_{in} and V_{out} are the inlet and outlet medium volume of the turbine.

Additionally, the water cycle is controlled by three operating pressures: the high pressure (P_h) of saturated steam, the intermediate pressure (P_m) between the two turbines, and the low pressure (P_l) of the saturated water. They usually conform and can be formulated by the following geometric mean relationship formula:

$$p_m = \sqrt{p_h \cdot p_l} \quad (6)$$

The isentropic efficiency of the pump is 80% and can be determined as:

$$\eta_{is,pump} = \frac{h_{2,is} - h_1}{h_2 - h_1} = \frac{h_{10,is} - h_9}{h_{10} - h_9} \quad (7)$$

The RSRC generates net electricity as follows:

$$P_W = m_W\eta_g\eta_m(h_4 - h_5 + h_6 - h_7) - m_W(h_2 - h_1) / \eta_{motor} \quad (8)$$

where η_g and η_m are the electrical generator efficiency (98%) and mechanical efficiency (99%), respectively. η_{motor} is the motor efficiency (80%).

The produced net electricity of SORC is determined as:

$$P_R = m_R\eta_g\eta_m(h_{12} - h_{13}) - m_R(h_{10} - h_9) / \eta_{motor} \quad (9)$$

The BRC's efficacy is denoted as:

$$\eta_{BRC} = \frac{P_W + P_R}{Q_{in}} \quad (10)$$

3.2 Model Validation

According to [10], we evaluate the two fundamental cycle models (RSRC and SORC) of the presented BRC model. The results have verified the model's reliability and are summarised in Table 1.

Table 1 Model validation.

ORC model	Simple	Reheat
Working fluid	Cyclopentane	Cyclopentane
T_{sat} (°C)	90	130
T_C (°C)	36	36
P_{el} (kW)	10	15
η_{ORC} (%)	10.60	17.27
η_{ORC} (%) in [10]	10.46	16.94
Deviation (%)	1.297	1.919

4. RESULTS AND DISCUSSION

The numerical investigation is conducted using the software Engineering Equation Solver [11]. The BRC's superiority is evaluated by comparing two fundamental models (RSRC and SORC) in section 4.1 and 4.2. The analysis of sensitivity and system performance is discussed in the final section.

4.1 Simulation setting

The two reference models are a RSRC model based on [10] and a SORC model based on [12]. The parameters are established consistent with the presented BRC model in this work. Water is the working fluid of the RSRC for its cleanliness, safety, low cost, easy accessibility, and relatively high critical temperature. R143a is selected as the working fluid in the SORC for its excellent system efficiency performance [12]. Table 2 shows the setting.

Table 2 Parameter setting.

Parameter	Value
Saturation temperature of steam, °C	350
Condensing temperature of steam, °C	125
Superheating temperature of R143a, °C	120
Condensing temperature of R143a, °C	35
Ambient temperature, °C	25
Temperature differences in all heat exchange equipment, K	5
Pump isentropic efficiency, %	80
Mechanical efficiency, %	99
Electrical generator efficiency, %	98
Motor efficiency, %	80
System capacity (net electric generation), kW	10

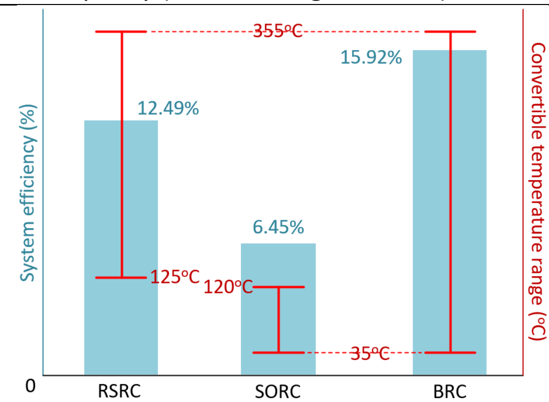

Fig. 3 The net electricity generation efficiency

4.2 System performance

Fig. 3 illustrates the system efficiencies of the three systems. The BRC is the most effective, with a system efficiency of 15.92%. The efficacy of the RSRC system is 12.49%, which is higher than that of the SORC system, which is 6.45%. The RSRC system exhibits superior performance for its competitive medium with higher latent heat. Additionally, RSRC can operate with a higher temperature range. Correspondingly, SORC is capable of converting energy within lower temperature ranges.

Consequently, the BRC system incorporates the benefits of the two systems mentioned above and has a high operational efficiency and a vast convertible temperature range. Table 3 details the performance of the three systems. It is important to note that the BRC system necessitates significantly less energy than the other two systems, with a consumption of only 62.8kW.

Table 3 System performance with 10kW electricity output.

Parameter	RSRC	SORC	BRC
$Q_{in,W}$, kW	**80.07**	-	**62.8**
$Q_{out,W}$, kW	-	-	41.84
m_W, kg/s	0.0242	-	0.01898
$P_{tur,W}$, kW	10.65	-	8.356
$P_{pump,W}$, kW	0.65	-	0.5128
$\eta_{is,tur,W1}$, %	25.94	-	25.94
$\eta_{is,tur,W2}$, %	77.83	-	77.83
$\eta_{ORC,W}$, %	12.49	-	12.49
$Q_{in,R}$, kW	-	**155.2**	33.47
m_R, kg/s	-	0.6855	0.1479
$P_{tur,R}$, kW	-	14.03	3.026
$P_{pump,R}$, kW	-	4.03	0.8686
$\eta_{is,tur,R}$, %	-	72.96	72.96
$\eta_{ORC,R}$, %	-	6.445	6.445
η_{ORC}, %	-	-	15.92

4.3 Off-design analysis

To investigate the system's potential, we designed a series of sensitivity tests on core independent parameters in variable operating conditions scenarios. To convert more thermal energy to electricity, we maximize the system's temperature range. The condensing temperature is set to be 35°C which is 10°C higher than the ambient temperature. The superheating temperature of the R143a cycle ($T_{h,R}$), the superheating pressure of the R143a cycle ($P_{h,R}$), the saturation vapour temperature of the water cycle ($T_{sat,W}$), and the system capacity (net electricity generation, P_{net}) are the four key independent parameters. The system efficiency (η_{ORC}) is employed as the key judging indicator.

1) When $T_{sat,W}$=350°C and P_{net}=10kW, $T_{h,R}$ fluctuates between 80°C to 160°C and $P_{h,R}$ varies from 3.8MPa to 5.4MPa. The value range setting of the organic medium is based on its critical point characteristics. As shown in Fig. 4 (a), 140°C is the most efficient temperature. Fig. 4 (b) amplifies the pressure-impacting results and illustrates the best points under each pressure. 18.53% is the maximum efficacy when $T_{h,R}$=140°C and $P_{h,R}$=5.2MPa.

2) When P_{net}=10kW, $T_{h,R}$=140°C, and $P_{h,R}$=5.2MPa, $T_{sat,W}$ ranges from 150°C to 373°C. The saturation temperature range of water vapour is contingent upon the critical and the condenser temperature. As shown in Fig. 5, the highest efficiency is 25.4% when $T_{sat,W}$=370°C. However, this point seems to be an outlier, despite its genuine validity. A more refined model needs to be constructed to elucidate this phenomenon. Apart from this solution, 18.53% is the optimal efficiency between 346°C to 350°C.

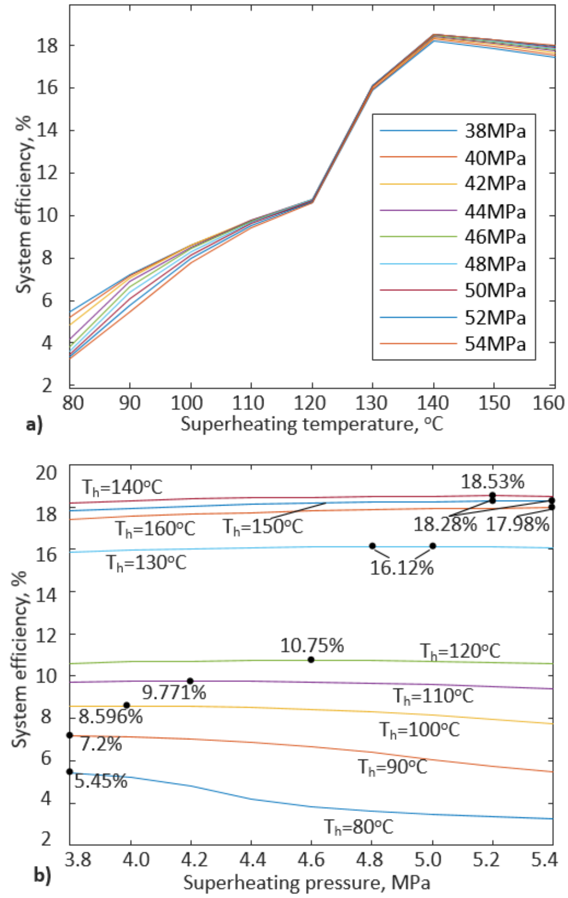

Fig. 4 Variation of system efficiency with various high P and T

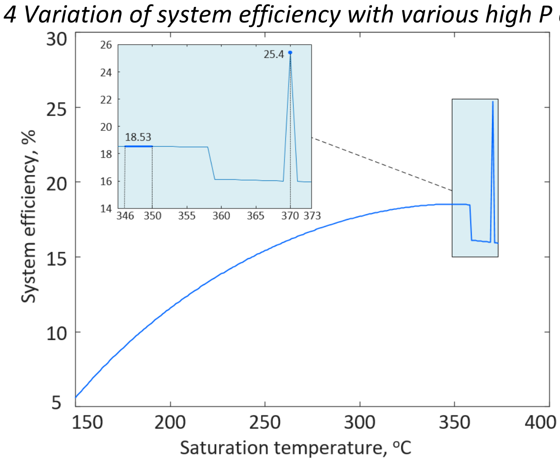

Fig. 5 Variation of system efficiency with various $T_{sat,W}$

3) When $T_{sat,W}$=370°C, $T_{h,R}$=140°C, and $P_{h,R}$=5.2MPa, P_{net} varies from 5MW to 1110MW. All of the critical independent variables are addressed with their most effective value. In Fig. 6, the result shows that the system consistently performs at the highest efficiency. The system efficiency is 25.4%, the water cycle efficiency is

23.23%, and the R143a cycle efficiency is 7.59%. Electricity generation output is proportional to the mass flow rates of the two functional mediums.

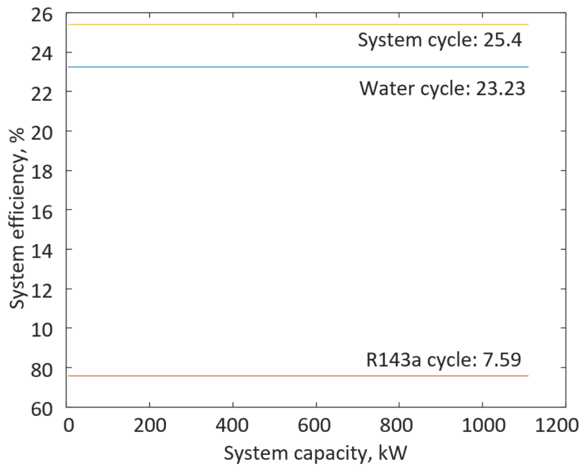

Fig. 6 Variation of system efficiency with capacity

5. CONCLUSIONS AND FUTURE PERSPECTIVES

This work presents a novel binary Rankine cycle model comprising two sub-cycles: a reheating steam Rankine cycle and a supercritical organic Rankine cycle. We evaluate the system under various conditions and determine the optimal parameter setting that maximises system efficacy. The result shows that, when $T_{sat,W}$=370^{o}C, $T_{h,R}$=140^{o}C, and $P_{h,R}$=5.2Mpa, the system efficiency is up to 25.4%. This BRC model is capable of absorbing significantly more solar thermal energy than other models, which can be a significant factor in mitigating extreme high-temperature weather. In our future work, we will put more effort into parametrical modelling the influence of extremely high temperatures on the solar thermal-based Rankine cycle. In addition, the intelligent algorithm will be employed to integrate with the BRC model for multi-objective optimisation and multi-parameter analysis.

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