# Mixed Working Fluid Optimization for Geothermal Organic Rankine Cycle Systems (Postprint)

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## Abstract

This study investigates low-temperature saturated organic Rankine cycle (ORC) power generation systems, utilizing R134a, R245fa, and R423a as organic working fluids. Simulation analysis is conducted using EES software to examine the effects of expander inlet temperature on system output work and other parameters, with the objective of determining the optimal working fluid selection for low-temperature ORC power generation systems. The results demonstrate that as expander inlet temperature increases, there exists a maximum value for the output work of the ORC system or expander; when employing the non-azeotropic mixture R423a, the system or expander output work reaches its maximum, representing a 14.9% increase in system output work compared to using R245fa as the working fluid; the mass flow rate of the organic working fluid in the power generation system varies inversely with expander inlet temperature, whereas the reinjection temperature exhibits a trend essentially consistent with that of the expander inlet temperature.

## Full Text

## Preamble

### Optimal Selection of Mixed Working Fluids for Geothermal Organic Rankine Cycle Systems

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## Abstract

This paper investigates a low-temperature saturated organic Rankine cycle (ORC) power generation system using R134a, R245fa, and R423a as organic working fluids. The Engineering Equation Solver (EES) software is employed to simulate and analyze the influence of expander inlet temperature on system output power and other parameters, thereby determining the optimal working fluid selection for low-temperature organic Rankine cycle power generation. The results demonstrate that as the expander inlet temperature increases, both the ORC system output power and expander output power exhibit maximum values. The system achieves the highest output power when using the non-azeotropic mixture R423a, which yields a 14.9% increase in system output power compared to using R245fa. The mass flow rate of the organic working fluid decreases with increasing expander inlet temperature, while the reinjection temperature shows a consistent increasing trend with the expander inlet temperature.

**Keywords:** organic Rankine cycle; non-azeotropic mixtures; geothermal power generation; working fluids

## 0 Introduction

With China’ s rapid economic growth, energy demand continues to rise while fossil fuel shortages become increasingly severe, accompanied by various environmental problems. The rational development and utilization of new energy sources have become a focus of attention, with geothermal energy as a renewable resource gaining particular favor. Organic Rankine cycle power generation systems utilize low-grade heat sources to vaporize low-boiling-point organic working fluids, driving expanders to perform work and enabling the conversion of low-grade energy into high-grade electrical power, offering certain advantages in environmental protection and efficiency.

Currently, extensive research on organic Rankine cycle power generation systems has been conducted both domestically and internationally, focusing primarily on working fluid selection, thermodynamic optimization analysis of systems, and development of major equipment. Reference [1] performed thermodynamic analysis on an organic Rankine cycle power generation system for fourteen working fluids using a simulated annealing algorithm, concluding that R245fa and R245ca provided superior system performance. Reference [2] proposed an inverse problem solving method for analyzing low-temperature organic Rankine cycle power generation systems, identifying R134a as the optimal working fluid. Reference [3] demonstrated that R134a performed well as an organic working fluid when solar energy at 70°C served as the heat source and the working fluid reached dry saturated state at the expander inlet. References [4,5] conducted analytical calculations comparing non-azeotropic mixtures with pure working fluids.

The organic Rankine cycle power generation system primarily consists of four components: expander, evaporator, condenser, and pump. Existing research indicates that the evaporator’ s irreversible losses have the greatest impact on system performance [6]. In pure working fluid subcritical cycle systems, the evaporator undergoes isothermal boiling, resulting in poor temperature matching between the heat source and working fluid and consequently large irreversible losses in the evaporator. Employing mixed working fluid power cycle systems can achieve optimized matching in the evaporator and reduce losses [7,8]. Expanders suitable for small-capacity organic Rankine cycle power generation systems remain a gap, currently in the prototype development stage, with researchers conducting theoretical and experimental studies both domestically and internationally [9,10].

This study focuses on low-temperature geothermal sources, using expander output power and system net output power as primary evaluation indicators while also analyzing parameters such as system working fluid mass flow rate and geothermal water reinjection temperature. Simulation analysis is performed using EES (Engineering Equation Solver) software to compare system performance of a subcritical saturated organic Rankine cycle power generation system using hydrofluorocarbons R134a (wet fluid), R245fa (dry fluid), and non-azeotropic mixture R423a as organic working fluids, thereby optimizing the selection of organic working fluids suitable for low-temperature geothermal sources and providing guidance for working fluid selection in low-temperature geothermal organic Rankine cycle power generation systems.

## 1.1 Organic Rankine Cycle Power Generation System

The basic organic Rankine cycle power generation system is shown in [Figure 1: see original paper]. The system operates as follows: liquid organic working fluid is heated to saturated state in the evaporator heat exchanger (E) before entering the expander to perform work; the shaft work output from the expander drives the generator to produce electricity. The working fluid discharged from the expander outlet enters the condenser (C) for heat exchange with cooling water, condensing into liquid. The liquid working fluid is then pressurized by the working fluid pump (P1) and re-enters the evaporator heat exchanger, completing a closed power generation cycle.

High-temperature geothermal fluid enters the evaporator heat exchanger to heat the organic working fluid from liquid to vapor state before being discharged from the evaporator for reinjection or other applications. In the cooling system, cooling water enters the condenser to condense the working fluid discharged from the expander into liquid; the cooling water discharged from the condenser outlet is cooled again before re-entering the condenser. The entire cycle power generation system primarily consists of equipment including the expander, evaporator heater, condenser, and working fluid pump.

Based on the state of the working fluid at the expander inlet, organic Rankine cycle systems are further divided into subcritical and supercritical power generation systems. Subcritical cycle power generation systems include three forms: saturated vapor power generation systems, superheated steam cycles, and gas-liquid two-phase cycle power generation. This paper analyzes only the performance of subcritical saturated power generation systems using hydrofluorocarbons and non-azeotropic mixtures. [Figure 2: see original paper] shows the T-s diagram for a wet fluid subcritical saturated vapor organic Rankine cycle, where process 4-5-1 represents constant-pressure heating of the organic working fluid from liquid to saturated vapor state in the evaporator heat exchanger, process 1-2 represents the actual expansion process in the expander, process 1-2s represents isentropic expansion, process 2-3 represents constant-pressure cooling of the working fluid in the condenser, and process 3-4 represents pressurization of the working fluid by the working fluid pump.

## 1.2 Thermodynamic Model Analysis and Parameter Selection

This study compares the expander output power and net power of subcritical saturated organic Rankine cycle power generation systems using non-azeotropic mixtures versus hydrofluorocarbons as working fluids, and compares the organic working fluid mass flow rate and geothermal water reinjection temperature. The expander output power $W_t$ is the product of the organic working fluid mass flow rate and the enthalpy difference across the expander, as shown in Equation (1). The system net output power $W_n$ is the difference between the expander output power $W_t$ and the power consumed by the working fluid pump $P_{W1}$ and cooling water pump $P_{W2}$, as shown in Equation (2). The power consumption calculations for the working fluid pump and cooling water pump are given by Equations (3) and (4), respectively. The mass flow rate calculations for the organic working fluid and cooling water are provided by Equations (5) and (6), respectively.

The reinjection temperature of high-temperature geothermal water after passing through the evaporator heat exchanger is calculated using Equation (7). In these equations: $m_{wf}$, $m_w$, and $m_g$ represent the mass flow rates of organic working fluid, cooling water, and geothermal fluid (kg/s); $t_a$ and $t_b$ are the inlet and outlet temperatures of the heat source fluid through the heat exchanger (°C); $t_x$ and $t_y$ are the outlet and inlet temperatures of cooling water through the heat exchanger (°C); $h_1$, $h_2$, $h_4$, and $h_5$ are the enthalpy values at corresponding points in [Figure 2: see original paper] (kJ/kg); $\eta_{p1}$ and $\eta_{p2}$ are the efficiencies of the working fluid pump and cooling water pump; $p_1$, $p_2$, and $v_3$ are the pressure and specific volume at corresponding points in [Figure 2: see original paper]; $\Delta t$ is the pinch temperature difference in the evaporator heat exchanger (°C); $H_1$ is the cooling water pump head (m); and $c_b$ is the average specific heat of geothermal fluid, referenced to water' s specific heat value of 4.186 kJ/kg • K.

High-pressure liquid organic working fluid is heated to saturated temperature in the evaporator heat exchanger before entering the expander to perform work. During heat exchange in the evaporator, there exists a point where the geothermal fluid and organic working fluid have a minimum temperature difference, known as the pinch temperature difference ($\Delta t$), typically taken as 3-7°C in simulation calculations [11]; this study uses 7°C. In the simulation analysis, the geothermal fluid mass flow rate is taken as 1 kg/s with an assumed temperature of 380 K; the working fluid pump and cooling water pump efficiencies are set at 75%, the expander internal efficiency at 80%, the cooling water temperature at 20°C, the temperature rise in the condenser at 5°C, and the cooling water pump head at 20 m. The organic working fluid is assumed to have no pressure losses in system equipment and piping, with other factors ignored.

## 2 Working Fluid Selection

Working fluid selection significantly impacts organic Rankine power generation system performance. This study selects the dry fluid R245fa, wet fluid R134a, and mixed working fluid R423a—commonly recommended in literature—for simulation analysis. The properties of the three organic working fluids are shown in .

**Table 1 Properties of Selected Working Fluids**

| Working Fluid | Critical Temperature (K) | Critical Pressure (MPa) | Composition |
|---|---|---|---|
| R134a | | | |
| R245fa | | | |
| R423a | | | R134a/R227ea |

## 3 Calculation Results and Analysis

Considering the assumed geothermal fluid conditions and organic working fluid properties in this study, the simulation calculations analyze expander inlet temperatures ranging from 55°C to 80°C, with specific results shown in the figures. [Figure 3: see original paper] and [Figure 4: see original paper] illustrate the variation trends of expander output power and system net power with expander inlet temperature for the power generation system. The results show that the output power corresponding to the three working fluids initially increases and then decreases with increasing expander inlet temperature, indicating the existence of a maximum output power. The non-azeotropic mixture R423a yields the highest output power, primarily because during heat exchange with geothermal fluid in the evaporator, the non-azeotropic mixture's two-phase heat transfer process is not isothermal (process 5-1 shown in [Figure 2: see original paper]) but involves continuously increasing temperature, which reduces irreversible losses in the evaporator and improves energy utilization efficiency. This demonstrates that for a 380 K geothermal fluid heat source, the non-azeotropic mixture R423a is more suitable for low-temperature geothermal power generation systems compared to the other two organic working fluids. As shown in [Figure 3: see original paper], the maximum output power using non-azeotropic mixture R423a is 14.7 kW, while using dry fluid R245fa yields a maximum output power of 12.5 kW. Under identical conditions, the system output power using R423a is 14.9% higher than that using R245fa.

[Figure 3: see original paper] and [Figure 4: see original paper] also reveal that the expander inlet temperature corresponding to maximum expander and system output power varies among working fluids. After deducting power consumption by the working fluid pump and cooling water pump, the system net power shows consistent trends with expander output power. When using non-azeotropic mixture R423a, maximum expander and system output power occurs at an expander inlet temperature of 70°C, whereas when using R245fa, maximum output power occurs at 60°C.

[Figure 5: see original paper] shows the relationship between expander inlet temperature and working fluid mass flow rate in the power generation system. The results indicate that organic working fluid mass flow rate decreases with increasing expander inlet temperature, with consistent variation patterns across working fluids. This occurs because the simulation specifies a pinch temperature, and as shown in Equation (5), with fixed heat source parameters, when expander inlet temperature increases or decreases, the expander inlet enthalpy changes in the same direction, while the organic working fluid mass flow rate changes in the opposite direction, exhibiting a linear relationship. [Figure 5: see original paper] demonstrates that for the same expander inlet temperature, R423a has the highest mass flow rate while R245fa has the lowest, primarily due to differences in working fluid properties such as specific heat capacity.

Geothermal power generation represents a sustainable new energy source because reinjected low-temperature geothermal water undergoes reheating in the Earth' s crust, allowing high-temperature geothermal fluid to re-enter the power generation system, providing greater stability compared to solar and wind energy. However, reinjection temperature affects the temperature of high-temperature geothermal fluid to some extent, directly influencing system output power. Therefore, reinjection temperature significantly impacts geothermal power generation system performance. [Figure 6: see original paper] shows the relationship between reinjection temperature of geothermal fluid after passing through the evaporator heat exchanger and expander inlet temperature. The results indicate that reinjection temperature increases with expander inlet temperature, and at the same expander inlet temperature, R423a yields the lowest reinjection temperature. As shown in Equation (7), geothermal fluid reinjection temperature is primarily related to expander inlet temperature, showing the same variation trend. Therefore, optimal determination of geothermal fluid reinjection temperature must consider factors including system output power and reinjection temperature effects. Using R423a as an example, when system or expander output power reaches maximum, the geothermal fluid reinjection temperature is 61°C.

## Conclusions

For low-temperature subcritical saturated organic Rankine cycle power generation systems with a 380 K heat source, comparative analysis using non-azeotropic mixture R423a and hydrofluorocarbon working fluids R134a and

R245fa yields the following conclusions:

1. For low-temperature organic Rankine saturated cycle power generation systems, using non-azeotropic mixtures results in greater system or expander output power compared to hydrofluorocarbon working fluids. The system output power using R423a is 14.9% higher than that using R245fa.
2. As expander inlet temperature increases, the organic Rankine cycle power generation system output power exhibits a maximum value, with different working fluids corresponding to different expander inlet temperatures at maximum output power. R423a achieves maximum output power at the highest inlet temperature among the tested working fluids.
3. The organic working fluid mass flow rate and geothermal fluid reinjection temperature show essentially linear variation trends with increasing expander inlet temperature, with flow rate changing in the opposite direction while reinjection temperature shows a consistent increasing trend.

## References

[1] Wang Juanli, He Yaling, Cheng Zedong, et al. Performance Optimization of Organic Rankine Cycle Based on Simulated Annealing Algorithm[J]. Journal of Engineering Thermophysics, 2013, 9(34): 1606-1610.

[2] Liu Chao, Xu Jinliang, Chen Qicheng, et al. Working Fluid Selection for Low Temperature Transcritical Organic Rankine Cycle[J]. Proceedings of the CSEE, 2013, 23(33): 37-43.

[3] Bertrand F T, George P, Gregory L. Fluid Selection for a Low-temperature Solar Organic Rankine Cycle[J]. Applied Thermal Engineering, 2009, 29: 2468-2476.

[4] Chen Huijuan, Goswami D Y, Muhammad M R, et al. A Supercritical Rankine Cycle Using Zeotropic Mixture Working Fluids for the Conversion of Low-grade Heat into Power[J]. Energy, 2011, 36(1): 549-555.

[5] Wang X D, Zhao L. Analysis of Zeotropic Mixtures Used in Low-temperature Solar Rankine Cycles for Power Generation[J]. Solar Energy, 2009, 83(5): 605-613.

[6] Mago P J, Srinivasan K K, Chamra L M, et al. An Examination of Exergy Destruction in Organic Rankine Cycles[J]. International Journal of Energy Research, 2008, 32(10): 926-938.

[7] Schuster A, Karellas S, Aumann R. Efficiency Optimization Potential in Supercritical Organic Rankine Cycles[J]. Energy, 2010, 35(2): 1033-1039.

[8] Taniguchi H, Kudo K, Park I, et al. Analytical and Experimental Investigation of Two-phase Flow Screw Expanders for Power Generation[J]. Journal of Engineering for Gas Turbines and Power, 1988, 110(10): 628-635.

[9] Florian H, Markus P, Dieter B. Zeotropic Mixtures as Working Fluids in Organic Rankine Cycles for Low Enthalpy Geothermal Resources[J]. Renewable Energy, 2012, 37(1): 364-370.

[10] Gu Wei, Sun Shaoqin, Weng Yiwu, et al. Experimental Study on Low Grade Heat Driven Organic Rankine Cycle by Scroll Expander[J]. Proceedings of the CSEE, 2011, 31(17): 20-25.

[11] Yan Jialu. Thermodynamic Principles and Formulas for Choosing Working Fluids and Parameters in Designing Power Plant of Low Temperature Heat[J]. Journal of Engineering Thermophysics, 1982, 3(1): 1-7.

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