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# How to quantitatively describe the role of the pure working fluids in subcritical organic Rankine cycle: A limitation on efficiency

Weicong Xu, Shuai Deng, Li Zhao*, Wen Su, Ying Zhang, Shuangjun Li, Minglu Ma

*Key Laboratory of Efficient Utilization of Low and Medium Grade Energy (Tianjin University), Ministry of Education of China, Tianjin 300072, China*

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ABSTRACT

As one of the most promising methods to convert medium- and low-temperature heat into power, organic Rankine cycle (ORC) has been widely studied. Working fluid, which plays the most important role in ORC, is the root of the huge gap on energy-efficiency between the actual cycle and ideal cycle. This paper presents the limiting thermal efficiency and limiting thermodynamics perfection of simple organic Rankine cycle (S-ORC) and regenerative organic Rankine cycle (R-ORC) in subcritical region to quantitatively describe the role of the pure working fluids. The expressions of limiting thermal efficiency and limiting thermodynamics perfection of S-ORC and R-ORC are derived respectively. 20 working fluids are employed in S-ORC and 10 working fluids are employed in R-ORC to demonstrate the effects of working fluids and operating conditions on limiting thermal efficiency and limiting thermodynamics perfection. The limiting thermal efficiency of S-ORC increases with the increase of the slope of working fluid saturated liquid line and latent heat of vaporization. The limiting thermal efficiency of R-ORC increases with the increase of the slope of working fluid saturated liquid line and latent heat of vaporization and the decrease of the slope of working fluid saturated gas line and specific heat capacity of superheat gas at constant pressure. According to the results of limiting thermal efficiency, the maps for S-ORC and R-ORC which might guide the selection of working fluids for different operating temperature are provided as well.

## 1. Introduction

ORC, as an effective technology of medium- and low-grade heat utilization, has been widely employed to utilize solar energy, geothermal energy, waste heat and so on [1–4]. Over the past 15 years, more than 2000 articles about ORC have been published [5], which mainly focused on the selection of working fluids, design and optimization of cycle structures, research and development of key components and so on [6–8]. To improve the efficiency of ORC approaching the efficiency of Carnot cycle is the ultimate promise of all these researches. However, in practical applications, the efficiency of ORC is much lower than theoretical efficiency. According to the statistical results of the experimental data, the thermodynamics perfections (which is equal to the ratio of thermal efficiency to the efficiency of Carnot cycle under the same heat source and heat sink temperature.) of ORC are generally less than 50% [9]. The existence of irreversible loss in each thermodynamic process is the main reason of the great difference between actual cycle and ideal cycle, as shown in Fig. 1.

Actually, all irreversible losses in actual S-ORC could be summed up in four processes: evaporation process, expansion process, condensation process and compression process. But the factors that affect irreversible losses in each process are different. For example, irreversible losses in compression process and expansion process are mainly affected by the thermos-physical properties of working fluid and the performance of the working fluid pump and expander. Irreversible losses in evaporation process and condensation process are mainly affected by thermos-physical properties of working fluid, heat exchanger parameters, heat source parameters and heat sink parameters. However, the thermos-physical properties of working fluid would affect irreversible losses in all four processes. The thermodynamic parameters, transport parameters and other factors of working fluid directly affect the efficiency, safety, stability and economy of ORC [10,11]. Therefore, the study on working fluid is the key step to improve the efficiency of ORC.

As the “blood” of ORC, the studies on working fluid are the research hotspots at present, such as working fluids selection or design, thermos-physical properties research, thermo-economic analysis and so on. Based on the traditional enumerative method used in the selection of working fluids, more and more scholars focus on exploring the quantitative relationship between thermos-physical properties parameters of working fluids and thermodynamic processes or cycles. Zheng et al.

* Corresponding author.
*E-mail address:* jons@tju.edu.cn (L. Zhao).

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## Nomenclature

*Symbols*

| | |
|---|---|
| $A$ | area |
| $C$ | cycle |
| $c$ | specific heat capacity (kJ·kg$^{-1}$·K$^{-1}$) |
| $dS$ | entropy change (kJ·kg$^{-1}$·K$^{-1}$) |
| $f$ | objective function |
| $h$ | specific enthalpy (kJ·kg$^{-1}$) |
| $M$ | Molar mass (g·mol$^{-1}$) |
| $P$ | pressure (MPa) |
| $Q$ | heat transferred (kJ) |
| $R$ | degree of reaction |
| $r$ | latent heat of vaporization (kJ·kg$^{-1}$) |
| $S$ | entropy (kJ·K$^{-1}$) |
| $SP$ | size parameter (m) |
| $s$ | specific entropy (kJ·kg$^{-1}$·K$^{-1}$) |
| $T$ | temperature (K) |
| $VR$ | volumetric flow ratio |
| $W$ | work (kJ) |
| $wf$ | working fluid |
| $X$ | other factors |
| $\Phi$ | flow coefficient |
| $\psi$ | loading coefficient |
| $\alpha_V$ | volume expansion coefficient (K$^{-1}$) |
| $\beta$ | the slope of working fluid saturated liquid line in *T-s* diagram |
| $\alpha$ | the slope of working fluid saturated gas line in *T-s* diagram |
| $\sigma$ | zeotropic working fluids selection parameters |
| $\Delta s$ | specific entropy difference (kJ·kg$^{-1}$·K$^{-1}$) |

*Subscripts and superscripts*

| | |
|---|---|
| b | boiling point |
| Carnot | Carnot cycle |
| c | critical point |
| com | compression process |
| con | condensation process |
| eva | evaporation process |
| exp | expansion process |
| H | high temperature |
| hse | heat source |
| L | low temperature |
| LTE | limiting thermal efficiency |
| LTP | limiting thermodynamics perfection |
| net | net output |
| P | pressure |
| R | regenerative temperature |
| re | regenerative process |
| TE | thermal efficiency |
| TP | thermodynamics perfection |
| tt | total of turbine |
| wf | working fluid |

*Greek symbols*

| | |
|---|---|
| $\eta$ | efficiency |
| $\rho$ | density (kg/m$^3$) |

*Abbreviations*

| | |
|---|---|
| L-ORC | limiting organic Rankine cycle |
| LR-ORC | limiting regenerative organic Rankine cycle |
| LS-ORC | limiting simple organic Rankine cycle |
| ORC | organic Rankine cycle |
| S-ORC | simple organic Rankine cycle |

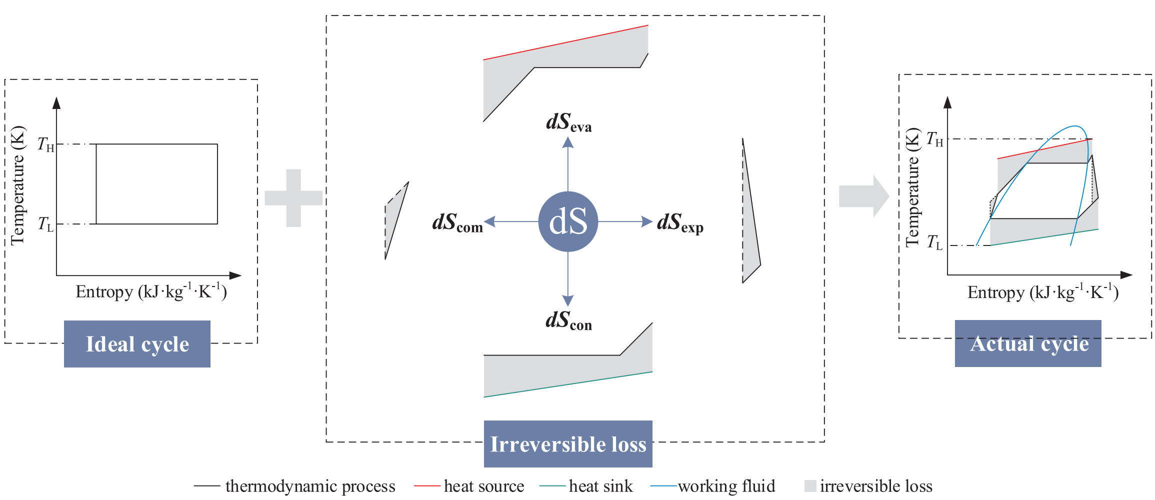


**Fig. 1.** Schematic diagram of the gap between actual cycle and ideal cycle.

[12] proposed the selection parameter $\sigma$ of zeotropic working fluids, which reflecting the nonlinearity of the working fluids. With the decrease of $\sigma$, the irreversible losses in heat transfer process decrease. Therefore, this parameter could be used as a criterion for the selection of zeotropic working fluids in heat transfer process. Focusing on the compression process in ORC system, the influence of thermos-physical properties parameters of working fluids on isentropic efficiency of compression process is studied by Xu et al. [13]. A combinatorial parameter $\alpha_V/\rho c_p$ was proposed as the criterion of working fluids selection in compression process. Lio et al. [14] studied the expansion process in ORC and found that the overall efficiency of the expander is closely related to the thermos-physical properties of the working fluids in addition to its structural parameters. The expression of the overall efficiency of the expander was derived as $\eta_{tt} = f(\Phi, \psi, R, SP, VR, wf)$.

In addition to thermodynamic process, many scholars have also studied the selection criterion of working fluids for the whole cycle.