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Investigation on the fluid selection and evaporation parametric optimization for sub- and supercritical organic Rankine cycle

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ABSTRACT

ORC (Organic Rankine cycle) is a promising technology for recovery of low-grade heat. In the previous studies, different conclusions for working fluid selection criterion can be found and relatively few work for supercritical ORC has been made. Therefore, this paper investigates the net power output of ORC utilizing waste flue gas with various evaporation parameters and 12 working fluids in both subcritical and supercritical condition. The results indicate that the variation of the net power output with evaporation pressure is related to the heat source temperature, and the maximum net power output appears at supercritical condition rather than subcritical condition if the heat source temperature is about 25–40 °C higher than the working fluid's critical temperature. Besides, the parametric optimization is performed, and the most suitable working fluids for various flue gas inlet temperature of 150–250 °C have been found. It can be found that the most suitable working fluids have a critical temperature about 40–65 °C lower than flue gas inlet temperature, and the optimum condition is always supercritical. For subcritical ORC, it is better to adopt the working fluids with low evaporation latent heat and high liquid specific heat to pursue a high net power output.

1. Introduction

As the development of industrialization, the shortage of traditional energy and pollution of environment have become a more and more severe challenge to the whole world, leading to the growing attention in renewable energy development and energy saving devices. The ORC (Organic Rankine Cycle) () is one of the most promising technologies for recovery of low-grade waste heat and utilization of medium-to-low temperature thermal energy. Therefore, it has become a hot topic and attracted more and more attentions in recent years.

The studies mainly focus on the selection of working fluids and system optimization to achieve better system performance, including thermal efficiency, net power output, exergy efficiency, electricity production cost, and so on. The suitable working fluid should be safe, non-toxic, economic, and environmental friendly basically. However, with respect to the effects of thermodynamic properties of working fluids on the system performance, different, even contradictory, conclusions could be found in the literature. Chen et al. [1] proposed a theoretical formula to analyze the work output per unit mass of working fluid and it indicated that the working fluids with high latent heat of evaporation and low specific heat at liquid state could achieve high work output. Wang et al. [2] stated that at the same evaporation and condensation temperature, higher thermal efficiency can be obtained when using working fluids with lower critical temperature, higher latent heat, and lower liquid specific heat. He et al. [3] noted that the ORC coupling with waste heat and geothermal energy should pursue maximum net power output, and the working fluids with low latent heat and high liquid specific heat should be adopted, while the ORC coupling with solar energy should pursue maximum thermal efficiency, and the working fluids with high latent heat and low liquid specific heat should be adopted. He et al. [4] pointed out that the working fluids with a critical temperature close to heat source temperature exhibited high net power output, while Liu et al. [5] found that working fluids with a low critical temperature exhibited low thermal efficiency. Bao et al. [6] made a review on the selection of working fluids and concluded that suitable but not large evaporation latent heat would result in better system performance of ORC for waste heat or geothermal plants. Obviously, the criteria for working fluid selection about critical temperature, latent heat, and specific heat are inconsistent for various studies. That's because the

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heat sources and optimization objectives are different in the literatures, which means that no single working fluid is optimal for all the ORCs. Some recommended working fluids are shown in Table 1.

With respect to parametric optimization, most of the investigations focus on subcritical ORC, especially on the effects of evaporation temperature (pressure) on the system performance. Wang et al. [7] presented a multi-objective optimization model by simulated annealing algorithm, and indicated that there was an optimal evaporation temperature to maximize the objective function. Quoilin et al. [8] conducted both the thermodynamic and economic optimization of a small scale ORC. They found that an optimal evaporation temperature far lower than the heat source temperature exits to maximize the output power and minimize the investment cost. Many studies also proved that there was an optimal evaporation temperature lower than critical temperature to obtain the greatest system performance [9–11]. However, Liu et al. [12] studied the effect of the critical temperature on the second law efficiency under different waste heat temperatures, and found that the net power output increased monotonously with the rise of evaporation temperature when the waste heat temperature is 18 ± 5 K higher than the working fluids' critical temperature. Thus it can be seen that the variation of system performance with evaporation temperature is relevant to the heat source and critical temperature of working fluids. Li et al. [13] analyzed the variation of net power output with water temperature and correlated with the critical temperature, and defined an “applicable water temperature ($T_{\mathrm{w\_app}}$)”. With water temperature higher than $T_{\mathrm{w\_app}}$, the net power output would increase smoothly along the evaporation temperature up to near-critical temperature. Pan et al. [14] studied the system performance in subcritical and supercritical cycles and found a sudden rise of net power output in near-critical condition.

Until now, few efforts in near-critical condition, and even fewer works for supercritical ORC have been made, given that the heat transfer mechanisms about supercritical evaporation process are still less known, but supercritical ORC is still promising because of the higher average temperature in evaporation and the better matching in temperature for heat source and working fluid. Schuster et al. [15] compared various working fluids in subcritical and supercritical parameters and an improvement about 8% in efficiency was observed in supercritical parameters. However, supercritical ORC is not always better than subcritical ORC in thermal performance. Guo et al. [16] indicated that supercritical ORC would match well with the heat source only if the difference of inlet and outlet temperature of heat source was large. Pan et al. [14] stated that the maximum net power output appeared in near-critical condition rather than supercritical. Larsen et al. [17] presented working fluids selection and parametric optimization in subcritical and supercritical cycle and found that supercritical was not beneficial when the heat source temperature was lower than 240 °C. Therefore, supercritical ORC is preferable for certain conditions and a comparison of subcritical and supercritical ORC should be conducted to obtain the suitable conditions for each cycle. In regard to working fluid selection for supercritical ORC, the CO_2 transcritical Rankine cycle has been studied a lot due to the favorable characteristics of CO_2 [18], such as stability, low critical temperature, environmental protection, low cost, and abundance in nature. However, Xu et al. [19] pointed out that the low critical temperature working fluid had a bad temperature match in evaporator, leading to lower ORC thermal performance. Le et al. [20] and Guo et al. [21] both compared some organic fluids with CO_2 in supercritical cycle and found that CO_2 always led to the worst system performance. Therefore, suitable organic fluids instead of CO_2 should be used in supercritical cycles.

In general, in the previous literature, the criterion for working fluid selection may be different in various researches, and few efforts in near-critical and supercritical ORC including parametric optimization and working fluid selection have been made. Therefore, in the present study, a thermodynamic model of ORC is built and the evaporation parameters are optimized to obtain the maximum net power output at various heat source temperatures with 12 working fluids. The effects of the evaporation parameters and properties of working fluids on the system performance are investigated in both subcritical and supercritical condition, and thus the suitable condition for supercritical ORC is summarized. Besides, some conclusions are summarized for working fluid selection after the calculation of 12 working fluids.

Table 1
Recommended working fluids in literature.

Ref.	Heat source temperature	Optimization objective	Working fluids	Type of ORC
[4]	150 °C	Net power output, evaporation pressure, heat absorption	R114,R245fa,R123,R601a,R141b	Subcritical
[7]	100–180 °C >180 °C	Heat recovery efficiency, heat exchanger area per unit power output	R123 R141b	Subcritical
[9]	80–140 °C 150–170 °C >180 °C	Net power output	R227ea R236fa R236ea	Subcritical
[10]	150–200 °C	Electricity production cost	R123, n-pentane, R11 and R141b	Subcritical
[11]	100/150 °C	Exergy construction Heat exchanger area per unit power output	Novec649, RE347mcc, R365mfc Benzene, R141b,Hexane	Subcritical
[13]	95 °C 120 °C 150 °C 170 °C	Net power output	R125,R143a,R32 R1270,R1234yf,R290,R134a R1234ze,R152a,RC218,R236fa R236fa,R600,R236ea	Subcritical
[22]	327 °C	Thermal efficiency	Alkylbenzenes	Regenerative subcritical
[23]	90–150 °C	Exergy efficiency	R600a,butane,R245fa,R245ca,R123	Subcritical
[24]	327 °C	Thermal efficiency	R245fa,R245ca	Regenerative subcritical
[25]	90 °C	Thermal efficiency, exergy construction, volume flow rate	R134a	Subcritical
[26]	280/350 °C	Heat capacity flow rate, thermal efficiency, volume flow rate	Cyclopentane	Regenerative subcritical
[19]	150 °C	Thermal efficiency, exergy efficiency	R134a,R236fa	Supercritical
[20]	150 °C	Thermal efficiency	R32 R152a	Supercritical Regenerative supercritical
[21]	90 °C >100 °C	Thermal efficiency, net power output, volume flow rate, heat exchanger area	R125 R32,R143a	Supercritical
[27]	125–200 °C	Thermal efficiency	R134a	Supercritical
[28]	220 °C	Net power output, exergy efficiency, expander size parameter	R152a, R143a	Supercritical