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Performance analysis of organic Rankine cycle based on location of heat transfer pinch point in evaporator

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HIGHLIGHTS

- Model seeking the location of heat transfer pinch point in evaporator of ORC is established.
- The matching coefficient between heat source and working fluid can be revealed based on pinch point.
- Performances of subcritical and supercritical ORCs are investigated using trough solar collector as heat source.
- The optimal initial pressure and maximum work output are obtained with and without IHX in cycles.

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ABSTRACT

The location of heat transfer pinch point in evaporator is the base of determining operating parameters of organic Rankine cycle (ORC). The physical mathematical model seeking the location of pinch point is established, by which, the temperature variations both of heat source and working fluid with UA can be obtained. Taking heat source with inlet temperature of 160 °C as example, the matching potentials between heat source and working fluid are revealed for subcritical and supercritical cycles with the determined temperature difference of pinch point. Thermal efficiency, exergy efficiency, work output per unit area and maximum work outputs are compared and analyzed based on the locations of heat transfer pinch point either. The results indicate that supercritical ORC has a better performance in thermal efficiency, exergy efficiency and work output while outlet temperature of heat source is low. Otherwise, subcritical performs better. Small heat transfer coefficient results in low value of work output per unit area for supercritical ORC. Introduction of IHX may reduce the optimal evaporating pressure, which has a great influence on heat source outlet temperature and superheat degree. The analysis may benefit the selection of operating parameters and control strategy of ORC.

1. Introduction

There are abundant heat sources with low or intermediate temperature, including that of solar energy, biomass and geothermal, as well as industrial waste heat [1–3]. A large number of solutions have been proposed to generate electricity by recycling waste heat, such as Organic Rankine cycle, Stirling cycle, Kalina cycle, et al. Among these ways, Organic Rankine Cycle (ORC) is preferred to be developed because of its high efficiency, reliability, flexibility and low requirement for maintenance [4,5]. Recently, some new techniques, buoyancy organic Rankine cycle [6] and pumpless Rankine-type cycle [7,8], for examples, have also been put forward for ORC.

Numerous studies have been carried on selecting a working fluid matching well with heat source, which is one of the most important steps in building organic Rankine cycle [9–11]. However, no single pure fluid has been identified as optimal for the ORC, which is mainly due to the strong interdependence between the optimal working fluid, the working conditions and the cycle architecture [12,13]. Different inlet and outlet temperature of heat source together with diverse working fluids make a variety of combinations. Matching rules therein will contribute to the selection of appropriate working fluid for a given heat source. It was also found that using zeotropic mixtures as working fluids have some advantages. First, the temperature glide at phase change could provide a good match of temperature profiles in the evaporator and condenser. Second, equipment costs could be reduced using

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Nomenclature

A	area, m^2
c_p	specific heat capacity at constant pressure, J kg^{-1} K^{-1}
d	diameter, m
E	exergy, W
h	enthalpy, J kg^{-1}
I	exergy loss, W
m	mass flow rate, kg s^{-1}
Nu	Nusselt number
P	pressure, Pa
Pr	Prandtl number
Q	heat, W
r	latent heat, kJ kg^{-1}
s	entropy, J kg^{-1} K^{-1}
T	temperature, °C
U	mean overall heat transfer coefficient, W m^{-2} K^{-1}
v	volume flow rate, m^3 s^{-1}
V	specific volume, m^3 kg^{-1}
w	power, W
x	vapor mass quality
X_{tt}	Lockhart–Martinelli number

Greek symbols

α	heat transfer coefficient, W m^{-2} K^{-1}
ε	effectiveness of the heat exchanger
η	efficiency
λ	thermal conductivity, W m^{-1} K^{-1}
μ	matching coefficient
ρ	density, kg m^{-3}

Subscripts

cr	critical state
con	condenser
exg	exergy
ev	evaporator
f	working fluid
i	section
in	inner diameter
is	isentropic
IHX	internal heat exchanger
l	liquid
net	net output
o	outer diameter
out	output of the cycle
p	pump
pc	pseudo-critical
pinch	pinch point
r	recycled heat
s	heat source
sh	shell
t	in theory
the	thermal
tu	tube
tur	turbine
v	vapor
w	wall
ww	wet wall region
0	ambient

mixtures for their smaller volume flow rates [14–16]. Third, using mixtures could find a balance point between flammability and environmental friendliness [17,18].

Research about heat exchangers in ORC includes the measurement of heat transfer coefficient and design of new types of the heat exchanger. There are numerous researches regarding the phase change process for organic working fluid for heat transfer coefficient of subcritical pressure [19–21]. However, few researches can be reviewed for supercritical pressure, for the reason that heat transfer mechanisms about supercritical cycle around the critical point is still less known [22].

Pinch point has the minimum temperature difference in evaporator. Determination of the location of pinch point makes notable impact on the optimum pressure selection of the ORC system, and benefits the optimal design. Several researches introduced the methods of determining pinch point for subcritical ORC [23–25]. For supercritical ORC, there is no isothermal boiling section in the evaporator. A few paper have been published stating that the location of pinch point may exist in the heating process in supercritical condition [26,27], but few researches present specific method for pinch point determination.

In the present study, mathematical and thermodynamic models are built and solved in Matlab together with REFPROP. A new method is introduced for finding pinch point in evaporator of ORC for pure working fluids under both subcritical and supercritical pressures. In further, operating parameter selections were discussed for the two types of ORC combining a typical practical case. Some conclusions are drawn for the selection of cycle styles, working fluids and operating parameters for low grade heat sources utilization.

2. System description and thermodynamic modeling

The organic Rankine cycle applies the same principle as that of the steam Rankine cycle, but uses organic working fluids with low boiling points to recover energy from lower temperature heat sources. As shown in Fig. 1, the present subcritical/supercritical organic Rankine cycle is composed of an evaporator, a turbine, a condenser and a feed pump. Two types of cycle configurations are considered with the only difference in the presence of the internal heat exchanger (IHX) as show in Fig. 1(b).

2.1. Significance of heat transfer pinch point

Some important factors should be in consideration for selecting parameters of ORC:

(1) Supercritical ORC doesn't always match better than subcritical ORC. Supercritical ORC matches well with the heat source, of which the inlet and outlet temperature difference is large. However, when the temperature difference is small, subcritical ORC with a horizontal phase-change curve could match better. Thus the selection of working fluid and operating pressure not only depends on heat source inlet temperature, but also on outlet temperature of heat source and heat transfer pinch point.

(2) Outlet temperature of heat source is not as lower as better. As shown in Fig. 2, for the given inlet temperature of heat source and minimum temperature difference of evaporator, when the outlet temperature of heat source is $t_{6'}$,working fluid can absorb more heat. However, the evaporating pressure is lower for the limitation of pinch point. Thus, the cycle