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Theoretical analyses of pressure losses in organic Rankine cycles

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ABSTRACT

The thermodynamic efficiency of Organic Rankine Cycle (ORC) obtained from experimental systems has been obviously lower than theoretical results. One of the reasons is that some elements affecting the efficiency, such as pressure losses in evaporator, condenser and pipes, have not been deeply discussed and optimized. The present manuscript detailed and examined the influences of pressure losses on ORC thermodynamic efficiency. Pressure losses in ORC system were divided into three categories: High Pressure Loss of the first category (HPL1), High Pressure Loss of the second category (HPL2) and Low Pressure Loss (LPL). A formula was developed to describe the relationships between three categories of pressure losses and ORC thermodynamic efficiency. Through analyses of the formula, it is found that the adverse impacts of pressure losses on thermodynamic efficiency are very different, mainly depending on the characteristic specific volume of working fluid in certain state. Because the very different specific volume, under a same value of pressure loss, LPL mostly leads to the largest thermodynamic efficiency drop of ORC system, HPL1 does less and HPL2 does the least. The influences of LPL are normally 3–21 times larger than that of HPL1, and 30–50 times larger than that of HPL2. The conclusions will serve as a guide for engineering applications of ORC system.

1. Introduction

One of the approaches to conserving energy and reducing emissions is producing power from low grade heat, such as geothermal energy and industrial waste heat. In this field, Organic Rankine Cycle (ORC) is one of the most promising technologies because it has many advantages, such as suitable working pressure, high efficiency and simple configuration. Therefore, ORC has become a research hotspot in recent years. However, the thermodynamic efficiency of ORC obtained from experiments is obviously lower than theoretical results [1]. Pressure losses, which cannot be avoided in evaporator, condenser, pipes, lubricant separator, flow meter and filters of actual ORC system, might be an important reason limiting the thermodynamic efficiency of ORC system.

Pressure losses were commonly neglected in many works. For example, Bamgbopa et al. [2] developed a quasi-dynamic model of solar-ORCs. The transient operation characteristics of the solar-ORCs were carefully studied. However, the pressure losses in evaporator and condenser were not taken into account. In addition, Sun et al. [3], Nazari et al. [4] and Wu et al. [5] all neglected pressure losses in their works.

In recent years, many works laid focus on heat transfer and pressure loss characteristics of organic fluids in evaporators and condensers for ORCs. Hu et al. [6] experimentally investigated plate evaporators with R245fa in ORC system. It was found that the heat transfer coefficients and pressure losses are both very sensitive to heat flux and working fluid mass flow rate. Zhang et al. [7] investigated the flow boiling heat transfer and pressure loss characteristics of R134a, R1234yf and R1234ze in a plate heat exchanger for ORC units. Based on experimental results, new heat transfer and pressure loss correlations were obtained. In addition, Wang et al. [8], Imran et al. [9], Walraven et al. [10] and Rohmah et al. [11] conducted similar investigations on ORC heat exchangers. In order to reduce pressure loss in ORC condenser, liquid separation condenser was introduced and examined by a few investigators. Luo et al. [12,13] developed mathematical modeling of liquid separation condenser used in ORC system. Using the modeling, the geometries, tube-pass arrangements, the tube side heat transfer coefficients and tube side pressure losses were optimized.

In the simulations and optimizations of ORC, pressure losses were taken into account by a few investigators. Miao et al. [14] and Yuan et al. [15] assumed that the pressure losses in evaporator and condenser were fixed at 10 kPa or 20 kPa. However, the influences of pressure losses on ORC thermodynamic efficiency were not discussed. Lei et al. [16] specifically investigated the influences of pressure loss in lubricant oil separator on ORC thermodynamic efficiency, and they reported that a same value of pressure loss in the separator located at the expander inlet leads to much less expander power drop than that located at the expander outlet. Chen et al. [17] investigated a novel cascade ORC

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Nomenclature

h	enthalpy [$J \cdot kg^{-1}$, $kJ \cdot kg^{-1}$]
p	pressure [Pa, kPa, MPa]
q_1	specific heat absorbed by working fluid [$J \cdot kg^{-1}$, $kJ \cdot kg^{-1}$]
Δp_{H1}	high pressure loss of the first category [Pa, kPa, MPa]
Δp_{H2}	high pressure loss of the second category [Pa, kPa, MPa]
Δp_L	low pressure loss [Pa, kPa, MPa]
v	specific volume [$m^3 \cdot kg^{-1}$]
T	thermodynamic temperature [K]
ΔT_{min}	minimum of heat transfer temperature difference [K]
q_m	mass flow rate [$kg \cdot s^{-1}$]
s	Entropy [$J \cdot (kg \cdot K)^{-1}$, $kJ \cdot (kg \cdot K)^{-1}$]

Greek symbol

η_P	isentropic efficiency of the circulation pump [–]
η_t	isentropic efficiency of the expander [–]
η_{ORC}	thermodynamic efficiency of ORC system [–]

Subscripts

1	inlet state of the expander (for theoretical ORC system)
1′	inlet state of the expander (for actual ORC system with pressure losses)
1_s	isentropic outlet state of the expander (corresponding to expander inlet state 1)
$1'_s$	isentropic outlet state of the expander (corresponding to expander inlet state 1′)
2	outlet state of the expander (corresponding to expander inlet state 1)
2′	outlet state of the expander (corresponding to expander inlet state 1′)
3	inlet state of the pump
4	outlet state of the pump (for theoretical ORC system)
4′	outlet state of the pump (for actual ORC system with pressure losses)

Abbreviations

ORC	Organic Rankine Cycle
HPL1	High Pressure Loss of the first category
HPL2	High Pressure Loss of the second category
LPL	Low Pressure Loss

system for waste heat recovery of truck diesel engines. The pressure losses in the condenser and the evaporator were assumed to be a fixed value of 10 kPa, while those in the pipes were neglected. They noticed that the ORC system with cyclopentane was quite sensitive to pressure loss in condenser. The results showed that if the pressure loss was increased by 10 kPa, the system net power output would be reduced by 4.8%.

From above presentations, it is known that only a few works reported the influences of pressure losses on ORC performances. There is still lack of systematic and deep investigation on ORC pressure losses especially that reveals the relationships between ORC thermodynamic efficiency and pressure losses, which can provide clear guidance on the optimizations of actual ORC systems. From the practices of ORC system construction, improvement and operation, it can be found that the thermodynamic efficiency of ORC system are sensitive to some pressure losses, while not that sensitive to other kinds of pressure losses. Improving the thermodynamic efficiency of actual ORC system needs full considerations of the pressure losses in all the components of ORC system. Therefore, the present work will specially investigate the influences of pressure losses in ORC system, reveal the relationships between ORC thermodynamic efficiency and pressure losses, and provide a guide for optimizing the pressure losses and improving ORC thermodynamic efficiency.

2. Analysis model of the pressure losses in ORC system

In actual ORC system, due to the viscosity of organic fluids, friction losses cannot be avoided in flowing fluid, and pressure decrease will be thus produced by friction losses in the direction of flow. The pressure decrease produced by friction losses in flowing fluids is called pressure loss. Pressure losses will occur in evaporator, condenser, filters, flow meters and the pipes connecting them. In order to evaluate the effects of pressure losses on ORC thermodynamic efficiency, a benchmark including two following items for the comparisons between ideal ORC and actual one with pressure losses was created.

(1) **The same thermodynamic state at the pinch point.** The pinch point has the minimum heat transfer temperature difference between heat source and organic fluids. Guo et al. [18] and Li et al. [19] reported that the pinch point mostly occurs at the entrance to the evaporator for normal sub-critical ORC systems (vaporization start point). According to this, the Point 5 in Fig. 1 is the pinch point. The processes 4-5 and 4′-5 in Fig. 1 are the preheat processes, which occur in the economizer. Some other investigators [20] noticed that the pinch point would move towards the economizer at higher pressures. In the present paper, it is considered that the ideal ORC system and actual one with pressure losses have identical thermodynamic state of working fluids at the pinch point, and the pressure of working fluids at the point is considered as the evaporating pressure of ORC system.

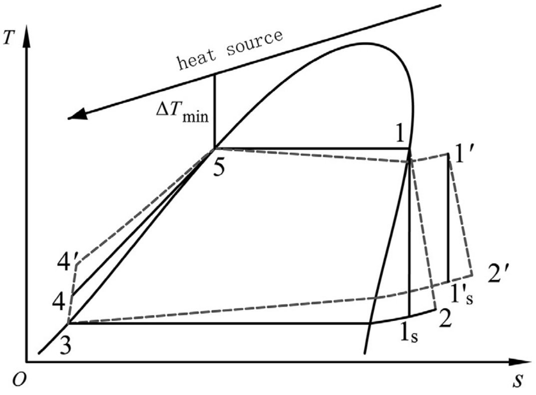

Fig. 1. ORC with pressure losses and ideal cycle.

(2) **The same thermodynamic state at the condenser outlet**. With same cooling conditions, it is considered that the working fluids are condensed into saturated liquid with the same state (the Point 3 in Fig. 1) in both ideal ORC and actual one with pressure losses, and the pressure of the organic liquid at this state is considered as the condensing pressure of ORC system.

According to above benchmark, Fig. 1 presents an ideal ORC 1-2-3-4-5-1 and an actual ORC 1′-2′-3-4′-5-1′ with pressure losses. As for the evaporation process 5-1 (without pressure loss) and 5-1′ (with pressure loss), it can be considered that the process 5-1′ was obtained by adding a throttling process to the process 5-1. When the State point 1 is in saturated vapor, the organic fluid in State 1′ will get superheated, and it must be: