



Modelling of organic Rankine cycle efficiency with respect to the equivalent hot side temperature



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ABSTRACT

An indicator, namely equivalent hot side temperature (T_{EHST}) is proposed for the organic Rankine cycle (ORC). T_{EHST} is derived from ideal thermodynamic process, but can denote the efficiency of irreversible ORC. Study on 27 fluids shows that given the operating conditions, fluid of higher T_{EHST} generally offers higher ORC efficiency. This relationship is stronger and more universal than those established with respect to the critical temperature, boiling point temperature, Jacobs number and Figure of Merit. An ORC model by the method of error transfer and compensation is further built, in which the efficiency is quantitatively correlated with T_{EHST} . Unlike the conventional ORC efficiency model, this one consists of thermodynamic parameters on the liquid/vapor curve and is independent on fluid properties at superheated state, and hence is more convenient. It has high accuracy especially for basic ORC and the relative deviation of the estimated efficiency from that calculated by the conventional model is from -0.7% to 3.4% . The novel model is applied for the thermodynamic performance prediction of a recently developed fluid of HFO1336mzzZ based on the phase equilibrium data. The results indicate HFO1336mzzZ is more efficient than R245fa on the conditions of high evaporation temperature and low pump efficiency.

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1. Introduction

Organic Rankine cycle (ORC) has been proven to be one of the most promising and efficient technologies for converting low-grade heat e.g. solar thermal energy, geothermal energy, industrial waste heat, biomass energy and ocean thermal energy into electricity [1,2]. In the past decade, effect of working fluid on the performance of the ORC system has been studied intensively. Different indicators have been proposed such as vapor density, liquid specific heat, molecular entropy, enthalpy ratio, boiling point temperature, critical temperature, Jacobs number and Figure of Merit (FOM). These indicators are good guidelines for the ORC performance assessment.

Low vapor density is accompanied by high volume flow rate which leads to large pressure drop across the heat exchanger. The size of the expander must be also increased which significantly affects the cost of the system [3,4]. Low liquid specific heat of the

working fluid can decrease work done by the pump and increase work output indirectly [3,5,6]. For subcritical ORC systems, fluids having lower molecular entropies result in higher thermal efficiencies [7]. The effect of the boiling point temperature of working fluids on the ORC performance has been investigated, and higher boiling point temperature causes higher evaporation pressure [8]. Enthalpy ratio (ratio of the latent heat of vaporization to the sensible heat) strongly influences the energetic and exergetic efficiency of ORC system. Higher enthalpy ratio elevates the amount of heat during phase change process. Hence, higher ORC efficiency is achieved while avoiding superheat and regeneration [9].

Jacobs number has been proposed [10], which is correlated to the latent and sensible heat.

$$Ja = C_p dT / H_v \quad (1)$$

where $C_p dT$ is the sensible heat and H_v is the vaporization latent heat. Thermal efficiency of the ORC system decreases with the increment in Jacobs number. A dimensionless FOM combining Jacobs number, evaporation temperature and condensation temperature has been further put forward by Kuo et al. [11]. Similarly,

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thermal efficiency decreases with the increment in FOM.

$$\text{Figure of Merit} = Ja^{0.1} \left(\frac{T_{cond}}{T_{evp}} \right) \quad (2)$$

Among the properties of the working fluid, the critical temperature is one of the most relevant indicators that affect the thermodynamic performance of ORC. The influence of fluid critical temperature on the efficiencies of isolated ORC [8,12,13], geothermal ORC [14], waste heat recovery [8,15,16] and solar ORC [3] has been evaluated by lots of researchers. More efficient power conversion can be facilitated by using fluid of higher critical temperature. This conclusion is applicable for most working fluids.

Besides, extensive investigation has been performed on the resultant role of working fluid properties in the net power output [17–19], ratio of power output to heat exchanger area [20,21], net output per unit mass flow rate [22], installation cost per net power output [23–27], exergy efficiency [28–32] and overall system performance [33–35].

The aforementioned indicators are linked with the ORC behavior. They make the working fluid selection more commodious. However, the quantitative relationship between the ORC efficiency and these indicators is lacked. In the present study, an equivalent hot side temperature (T_{EHST}) is proposed. It is a new indicator rooted in the fundamental of thermodynamics. The effect of T_{EHST} on the ORC efficiency is examined on various operating conditions. A mathematical model of the ORC efficiency in view of T_{EHST} is further established. This model can overcome some disadvantages of the conventional ORC efficiency model. For the latter, thermodynamic information (enthalpy, entropy et al.) on expander outlet must be known in order to ascertain the cycle efficiency. The parameters at superheated state are correlated with the fluid PVT (pressure-volume-temperature) behavior. It is a cumbersome process to get accurate PVT behavior in a wide range of temperature and pressure. Many fluids especially newly developed fluids are unavailable in commercial database such as REFPROP and CoolProp. Their ORC efficiencies cannot be predicted in a convenient way using the traditional model. For the novel model, only thermodynamic parameters at liquid-vapor equilibrium state are involved. The enthalpy and entropy at superheated state are dispensable. The deduction, accuracy and applicability of the model are investigated in the following sections.

Twenty-seven dry and isentropic working fluids are selected. For dry fluids, optimum ORC efficiency can be achieved since they operate along the saturation vapor curve without being superheated [36–38]. Similarly, in case of an isentropic fluid a nearly vertical vapor saturation curve can be obtained. Vapor remains saturated till the end of expansion process and there is no need for regeneration [39].

2. Derivation of the equivalent hot side temperature

The T - s diagram of ORC is depicted in Fig. 1. An ideal ORC cycle (1-2s-3-4s-1) is comprised by four basic processes: (1) isentropic pressurization by the pump; (2) isobaric heating in the evaporator; (3) isentropic expansion through the expander; (4) isobaric cooling in the condenser.

Thermal efficiency of the ideal ORC is expressed by

$$\eta_{t,id} = 1 - \frac{q_{o,id}}{q_{i,id}} \quad (3)$$

The input and output heat are equal to

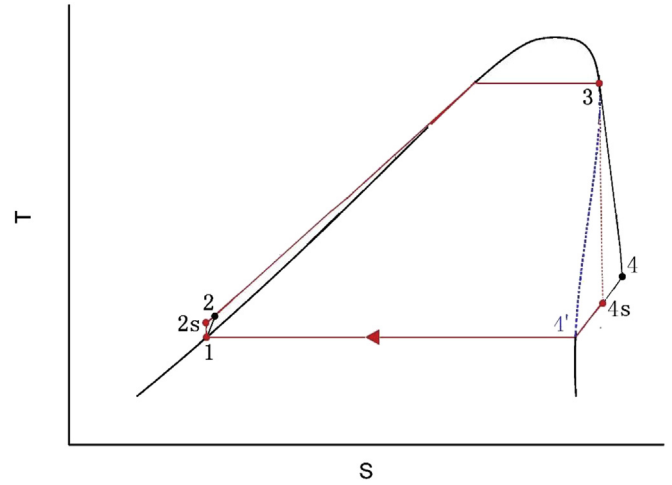


Fig. 1. T - s diagram of ORC.

$$q_{i,id} = \int_{2s}^3 T ds = h_3 - h_{2s} \quad (4)$$

$$q_{o,id} = \int_1^{4s} T ds = h_{4s} - h_1 \quad (5)$$

The equivalent hot side temperature is determined by

$$T_{EHST} = \frac{q_{i,id}}{\Delta S} = \frac{h_3 - h_{2s}}{s_3 - s_{2s}} \quad (6)$$

T_{EHST} has a physical meaning. A higher T_{EHST} represents a stronger force driving the ORC. Analogously, the equivalent cold side temperature is

$$T_{ECST} = \frac{q_{o,id}}{\Delta S} = \frac{h_{4s} - h_1}{s_{4s} - s_1} \quad (7)$$

Therefore, with $s_3 = s_{4s}$ and $s_1 = s_{2s}$, the ORC thermal efficiency can be calculated by

$$\eta_{t,id} = 1 - T_{ECST}/T_{EHST} \quad (8)$$

Most ORC fluids at liquid state are not compressible and most of the heat is taken out by the condensation process. Therefore,

$$h_{2s} \approx h_1 + v_1(p_{2s} - p_1) \quad (9)$$

$$T_{ECST} \approx T_1 \quad (10)$$

$$T_{EHST} = \frac{h_3 - h_{2s}}{s_3 - s_{2s}} \approx \frac{h_3 - h_1 - v_1(p_3 - p_1)}{s_3 - s_1} \quad (11)$$

The right side of Eq. (11) consists of specific enthalpy, specific entropy, specific volume and pressure on the saturation liquid/vapor curve. p_3 , h_3 and s_3 are pressure, specific enthalpy and entropy of the saturation vapor at T_3 , respectively, while s_1 , p_1 , h_1 and v_1 are the parameters of the saturation liquid at T_1 . Given a fluid, T_{EHST} is a function of the evaporation temperature (T_3) and condensation temperature (T_1). T_1 is generally subject to the environment temperature and ranges from 20 °C to 40 °C, so T_{EHST} is mainly determined by T_3 .

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