Energy 96 (2016) 96–102

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Performance analysis of low temperature organic Rankine cycle with zeotropic refrigerant by Figure of Merit (FOM)

Thoranis Deethayat*, Attakorn Asanakham, Tanongkiat Kiatsiriroat

Department of Mechanical Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai 50200, Thailand

ARTICLE INFO

Article history:
Received 28 September 2015
Received in revised form
15 November 2015
Accepted 12 December 2015
Available online 8 January 2016

Keywords:
Organic Rankine cycle
Performance analysis
Figure of Merit
Zeotropic refrigerant

ABSTRACT

This paper proposed a dimensionless term, the "Figure of Merit" (FOM), to investigate the thermal performance of a low temperature, organic Rankine cycle using six zeotropic mixtures (R245fa/R152a, R245fa/R227ea, R245fa/R236ea, R245ca/R152a, R245ca/R227ea and R245ca/R236ea) as working fluids. An empirical correlation was developed to estimate the cycle efficiency from the FOM for all working fluids at condensing temperatures of 25–40 °C and evaporating temperatures of 80–130 °C. The model results fit very well with both the experimental data and that from other researchers.

1. Introduction

Excessive utilization of fossil fuels has led to many severe environmental problems, including global warming, ozone layer depletion, acid rain and air pollution. Hence, recovering waste heat from energy conversion or using renewable energy to reduce fossil fuel consumption is essential.

The organic Rankine cycle (ORC), a type of Rankine cycle, uses a working fluid with a low boiling point, and thus can generate electricity from low-temperature heat sources, such as low temperature waste heat, geothermal energy, solar energy or biomass combustion.

The first commercial ORC plant was installed in 1970. After that the ORC market is growing rapidly. According to Quoilin et al. [1], ORC is a mature technology for waste heat recovery and other sources from biomass and geothermal energy. ORC also has the potential to be developed for use with solar heat. Manolakosa et al. [2] designed and built a low-temperature (35–75.8 °C), solar ORC for reverse osmosis desalination. Nguyen et al. [3] designed and developed a small-scale, low temperature solar ORC to generate electricity with an efficiency of 4.3%. Velez et al. [4] reviewed the primary ORC manufacturers and found that most units were on a MW scale. However, the number of small ones (in the kW range) had increased significantly.

To improve ORC efficiency, some researches have focused on zeotropic working fluids with boiling and condensing temperatures changing with heat source and heat sink temperatures, respectively. With temperature differences during heat exchanges at the cycle evaporator and condenser less than those of the single working fluid, then the thermodynamic irreversibilities in these components can be reduced, resulting in a higher work output. Wang et al. [5] experimentally compared the performance of low temperature ORCs using pure fluid (R245fa) and its mixture (R245fa/R152a); the thermal efficiency of the zeotropic mixture was higher than that of pure R245fa. Dong et al. [6] found similar results with a high temperature ORC (heat source at 280 °C) using zeotropic mixtures of siloxanes as working fluids. For heat sources at temperatures of 150–250 °C, Chys et al. [7] found that the cycle efficiency increased 6–16% in ORC systems using zeotropic mixtures as the working fluids. Heberle et al. [8] found that the second law efficiency of an ORC with isobutane/isopentane and R227ea/R245fa as working fluids increased 4.3%–15% for the zeotropic mixtures compared with single isopentane and single R245fa.

The thermal efficiency of an ORC system is directly related to many thermophysical properties. Recently, Kuo et al. [9] studied the relationships of the thermodynamic properties of many working single fluids that affected ORC thermal efficiency. The properties could be consolidated in a dimensionless group, called Figure of Merit (*FOM*), which included the Jacob number and evaporating

---

* Corresponding author.
E-mail address: thoranisdee@gmail.com (T. Deethayat).

http://dx.doi.org/10.1016/j.energy.2015.12.047
0360-5442/© 2015 Elsevier Ltd. All rights reserved.

and condensing temperatures. The lower the *FOM* value, the higher the ORC thermal efficiency could be achieved. The *FOM* could also be used to screen working fluids to achieve higher ORC performance.

In this paper, a technique proposed by Kuo et al. [9] was modified to determine a correlation between the cycle efficiency for small-scale ORC and FOM at evaporating temperatures of 80–130 °C and condensing temperatures of 25–40 °C with zeotropic mixtures in the case of the ideal cycle. A factor to allocate the zeotropic fluid properties in a form of FOM similar to that of single fluids was created and set up in the term of gliding temperature of the working fluid. It could be noted that only dry fluids having positive slope of the saturated vapor line in T-s diagram or isentropic fluid were considered thus the fluids during expansion were superheat.

2. Thermodynamics cycle

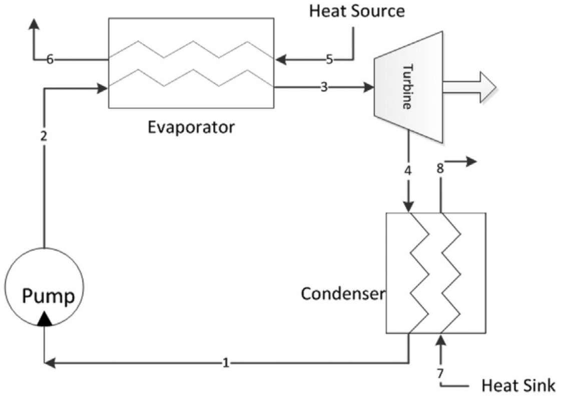
Fig. 1(a) shows the ORC configuration, which consists of a pump, an evaporator, an expander and a condenser. The working fluid leaves the condenser as a saturated liquid (state 1) and it is pumped to the evaporator (state 2) to be heated and vaporized by various heat sources, such as waste heat, hot water from solar heat or geothermal energy. The generated high-pressure vapor (state 3) flows into the expander to generate power and, thereafter, the low pressure vapor exits the expander (state 4) to the condenser, where the vapor is condensed by rejecting heat to cooling water. The condensed working fluid at the condenser outlet is pumped back to the evaporator, and a new cycle begins. All of the above described processes are shown in a temperature versus entropy diagram for ideal ORCs with single and zeotropic working fluids in Fig. 1(b) and (c), respectively.

It can be seen in Fig. 1(c), during heat exchange at the evaporator and condenser of the ORC, there were temperature differences between the streams of the heat source and heat sink with the ORC working fluid, respectively. The temperature differences generated irreversibilities at the cycle components, and then some part of the cycle work was destroyed. As an example, the isothermal phase change during states 2f-3 for the single fluid after replacing by the non-isothermal zeotropic fluid, the temperature difference between the hot fluid stream and the phase change temperature is less and the irreversibility due to the heat exchange is smaller. Similar result is found at the condenser.

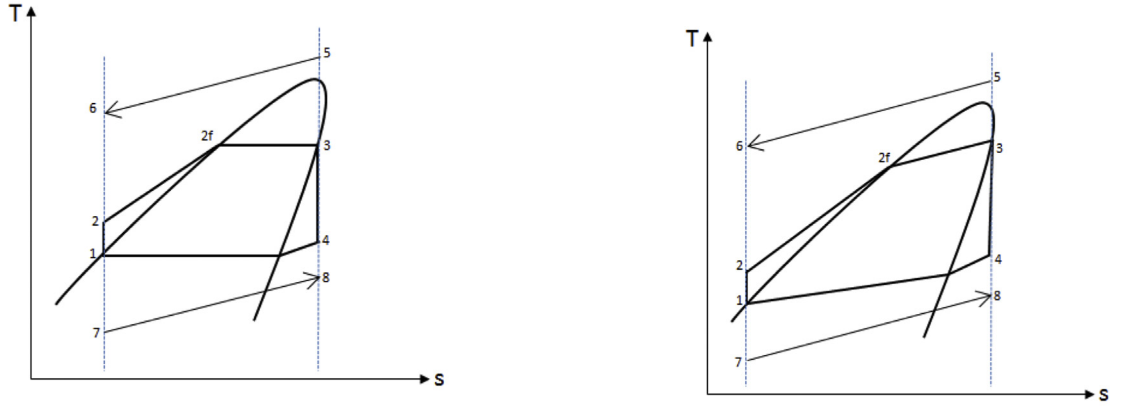
The energy balance at each component can be summarized as follows:

Pump:

$$\dot{W}_p = \frac{\dot{m}v_1(P_2 - P_1)}{\eta_P} \tag{1}$$



a. ORC basic components.



b. T-s diagram of ORC for single fluid.

c. T-s diagram of ORC for zeotropic fluid.

Fig. 1. Thermodynamic cycles of ideal ORC for single and zeotropic working fluids.