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Thermodynamic analysis and multi-objective optimization of various ORC (organic Rankine cycle) configurations using zeotropic mixtures

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ABSTRACT

In this paper, the performance of the ORC (organic Rankine cycle) powered by geothermal water, in three different configurations, including the simple ORC, PTORC (parallel two-stage ORC) and STORC (series two-stage ORC), using zeotrpoic working fluids is investigated from the viewpoints of the energy and exergy. In addition, considering the net power output and TSP (turbine size parameter) as the two objective functions, the multi-objective optimization with the aim of maximizing the first function and minimizing the second one, is performed to determine the optimal values of decision variables including evaporators 1 and 2 pressure, the pinch point temperature difference and the superheating degree. The results show that using zeotropic mixtures as the working fluid instead of a pure fluid such as R245fa, leads to 27.76%, 24.98% and 24.79% improvement in power generation in the simple ORC, PTORC and STORC, respectively and also lower values of TSP.

Moreover, it is observed that STORC has the highest amount of net power output and R407A can be selected as the most appropriate working fluid. The optimization results demonstrate that at the final optimum point achieved by Pareto frontier, the values of the objective functions are gained 877 kW and 0.08218 m, respectively.

1. Introduction

General population growth with economic development causes escalating energy consumption [1]. Global warming, rupturing of the ozone layer and other environmental problems lead to the energy policy consideration. In addition, increasing the electricity price up to a rate of 12% annually motivates the use of waste heat and renewable sources for power generation [2,3]. Possible solutions may be the use of ORC (organic Rankine cycle), KC (Kalina cycle) and other types of the low grade heat power generations. Among the proposed cycles, ORCs are considered as a practical solution because of their simplicity, reliability, and flexibility [4]. Geothermal energy, solar energy, ocean thermal energy and waste heat can be used as heat resources for ORC. Geothermal energy is a low-grade heat source that many researches have been done on these criteria recently.

One of the main problems in ORC based power plants is high exergy destruction in these cycles. Based on Venkatarathnam et al. [5] research, the main source of exergy destruction in ORC is evaporator because of the temperature mismatching between the source and the working fluid as shown in Fig. 1. According to this figure which illustrates the heat transfer process between the working fluid and the thermal source in a HRVG (heat recovery vapor generator), the thermal energy transmission to the working fluid occurs at three steps including preheating, evaporating and superheating. As it is obvious from Fig. 1, the temperature remains constant in the evaporating stage in pure fluids leading to a significant temperature difference between the source and the working fluid especially in the higher values of quality which causes more amount of exergy destruction.

In order to minimize this temperature mismatching and reduce the exergy destruction in the cycle, which leads to efficiency rising, numerous studies have been carried out. There are two main possible solutions which are proposed by researchers up to now, including using the zeotropic mixtures and enhancement of cycle configuration.

A zeotropic mixture is a chemical mixture which is combination of different pure fluids. Zeotropic mixtures have a non-isothermal phase change and they never have the same vapor phase and liquid phase composition at the vapor–liquid equilibrium state.

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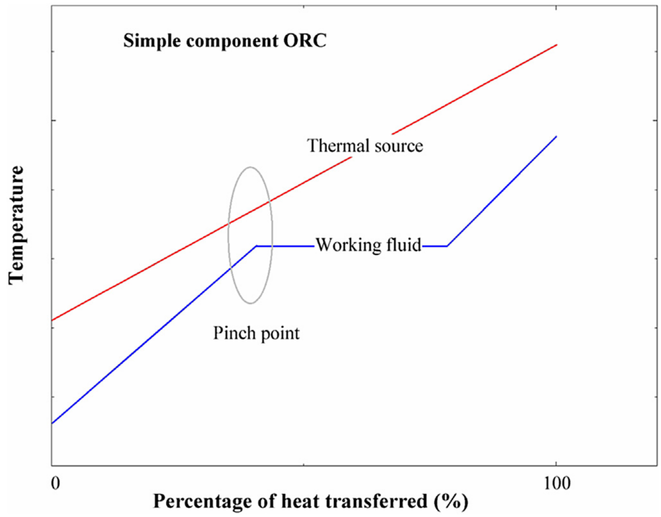

Fig. 1. Temperature mismatching during the heat addition process for a simple component ORC.

Using zeotropic mixtures as a working fluid in the power cycles leads to a temperature variation of the working fluid during the phase change process and causes an improvement of the temperature matching in the evaporator; which is depicted in Fig. 2. By applying this method, the irreversibilities during the vaporization process decreases.

The effects of 10 groups of mixtures on the performance of ORC were analyzed by Kange et al. [6]. The results showed that R245fa/R600a (0.9/0.1) was the most preferable mixture among the working fluids within the scope of this research. Radulovic et al. [7] proposed six zeotropic mixtures for ORC powered by low temperature geothermal heat source. The maximum exergetic efficiency of 47% was achieved by R-143a (0.7)/R-124 (0.3). A comparative analysis between the zeotropic mixtures and R-143a shows that the cycle efficiency can be improved up to 15% at the same operating conditions. Liu et al. [8] studied R600a/R601a mixtures for various mole fractions and proved that the ORC power can be optimized by using this mixture till 11%, 7% and 4% compared to R600a at geothermal water temperatures of 110, 130 and 150 °C, respectively. Yue et al. [9] investigated the performance of a geothermal ORC system using zeotropic working fluids. They concluded that with

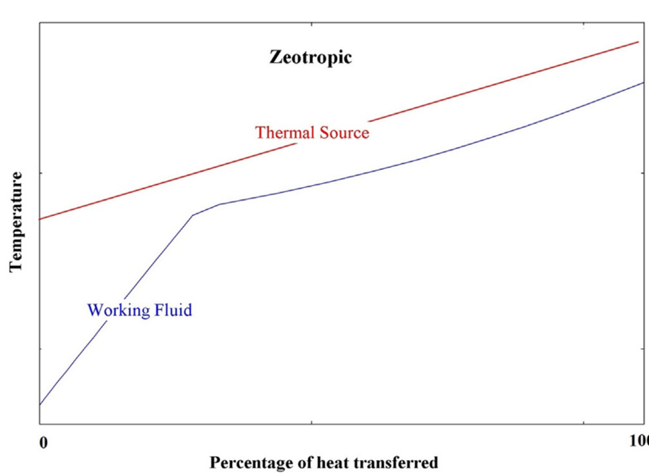

Fig. 2. Improvement of the temperature mismatching during heat addition process for zeotropic mixtures.

use of zeotropic mixtures as the working fluid, the energy and exergy efficiencies increases. Furthermore the results showed that an optimal thermal performance for a certain mole fraction of isopentane in the mixture can be achieved. The thermodynamic analysis of a regenerative ORC with different compositions of R245fa and R152a as the zeotropic working fluid was performed by Deethayat et al. [10]. The results indicated that decreasing the R245fa ratio leads to the reduction of the irreversibilities at the evaporator and condenser. Also, they found that for the mass fraction of R245fa below 80%, the irreversibilities were nearly steady.

S. Lecompte et al. [11] studied the thermodynamic performance of a non-superheated subcritical ORC with zeotropic mixtures as the working fluid from the viewpoint of the exergy. They found that the exergy efficiency increases 7.1%–14.2% compared to the same systems using the pure working fluids. Utilization of the zeotropic mixtures in ORC for waste heat recovery from an industrial boiler is presented by You-Rong Li et al. [12]. They found that comparing the ORC with pure working fluids, the performance of the ORC with zeotropic mixtures is economically improved. Muhsen Habka et al. [13] investigated the potential of organic Rankine cycles using zeotropic mixtures for utilizing the geothermal water. They evaluated the performance of the ORC system with zeotrpic mixtures such as R422A, R22M, R407A and R22D from the viewpoint of the first and second laws of thermodynamics. They reported that R22M and R422A show better performance than the other working fluids in the parallel ORC–CHP system. Heberle et al. [14] studied the exergy efficiency of an ORC using zeotropic mixtures of isobutane–isopentane and R227ea– R245fa as working fluids. They found that compared to the same cycle using pure working fluids, for temperatures lower than 120 °C the second law efficiency increases up to 15%. Moreover, the results showed that the lower mismatching between the working fluid and cooling water temperatures leads to the higher second law efficiency.

Some of the most important investigations for improvement of the cycle configurations are mentioned here. Yari [15] investigated the performance of the various organic Rankine cycles using dry working fluids from the viewpoints of the first and second laws of thermodynamics. The results showed that the energy and exergy efficiency values of the regenerative ORC with an internal heat exchanger is on average 30% more than the simple one. The comparison of a simple ORC, an ORC with an IHE (internal heat exchanger), a regenerative ORC, and a regenerative ORC with an IHE from the energy and exergy point of views was performed by yari [16]. The results demonstrated that the highest amount of the first law efficiency was around 7.65% belonging to the ORC with an IHE and using R123 as the working fluid. Ho et al. [17] investigated several configurations of the OFC (organic flash cycle) in order to power generation enhancement. It is observed that splitting the expansion process into two steps leads to utilization efficiency enhancement around 10% compared to the optimized basic ORC. Exergetic study of a dual-level binary geothermal plant was executed by Kanoglu [18]. As a comparison the results showed that the defined thermal efficiencies of the proposed systems were found 5.8% and 8.9%, respectively. Zhang et al. [19] analyzed a novel system of a dual loop bottoming ORC for waste heat recovery from a diesel engine. They concluded that using the low temperature loop leads to more net power output than that of the high temperature loop. Also, it was shown that in the low load areas, the maximum thermal efficiency can be improved up to nearly 13.15%. Yari et al. [20] studied and compared the performance of three different cycles including: TLC (trilateral Rankine cycle), ORC (organic Rankine cycle) and KC (Kalina cycle) using a low grade heat source from the viewpoint of exergoeconomic. The results indicated that the net power output gained by the TLC system could be greater than that