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Thermodynamic Analysis of Ammonia-Water Based Regenerative Rankine Cycle with Partial Evaporation

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Abstract**—**A thermodynamic analysis of a partial evaporating Rankine cycle with regeneration using zeotropic ammonia-water mixture as a working fluid is presented in this paper. The thermodynamic laws were applied to evaluate the system performance. Based on the thermodynamic model, the effects of the vapor quality and the ammonia mass fraction on the system performance were extensively investigated. The results showed that thermal efficiency has a peak value with respect to the vapor quality as well as the ammonia mass fraction. The partial evaporating ammonia based Rankine cycle has a potential to improve recovery of low-grade finite heat source.

Keywords**—**Ammonia-water, Rankine cycle, partial evaporating, thermodynamic performance.

I. Introduction

THE organic Rankine cycle (ORC) has been proven to be a promising technology for recovery of low-grade heat sources. However, the system performance of ORC is restricted by the Carnot cycle efficiency and much exergy is lost in the heat transfer process due to the finite temperature difference [1]. The power generation systems using ammonia–water mixture as a working fluid have been also considered as the feasible method for converting low-grade heat sources into the mechanical work or electricity [2]-[6].

Zamfirescu and Dincer [7] carried out thermodynamic analysis of the trilateral ammonia- water Rankine cycle that did not use a boiler, but rather the saturated liquid is flashed by a turbine. Kiani et al. [8] studied a hybrid cycle which utilizes ammonia–water mixture as the working fluid in a combined power generation and refrigeration cycle. The power generation cycle functions as a Kalina cycle and an absorption refrigeration cycle is combined with it as a bottoming cycle. Roy et al. [9] investigated two Rankine cycles, one with and one without a regenerator, both using an ammonia-water mixture as the working fluid. They showed that an increase of the net power output decreases the exergetic efficiency while at the same time it increases the heat exchangers' surface. Wagar et al. [10] studied an ammonia–water based Rankine cycle for renewable based power production. They showed that changes in its concentration allow thermodynamic cycles to adapt to fluctuations in renewable energy sources due to the nature of the ammonia-water mixture, which is an important advantage with respect to other working fluids.

Bombarda et al. [11] conducted a comparative analysis between the thermodynamic performances of Kalina cycle and an ORC cycle using hexamethyldisiloxane as working fluid for the case of heat recovery from two Diesel engines. They showed that, although the obtained useful powers are actually equal in value, the Kalina cycle requires a very high maximum pressure in order to obtain high thermodynamic performances.

Recently, Zhou et al. [12] proposed a new ORC architecture with partial evaporation using the zeotropic mixture R245fa/R227ea as working fluid. They showed that both the new cycle architecture with partial evaporation and zeotropic mixture working fluid can improve the thermodynamic performance and more importantly they can be combined together to further enhance the system. This paper presents a thermodynamic analysis for a partial evaporation Rankine cycle with regeneration using ammonia-water mixture as a zeotropic working fluid for recovery of low-temperature finite heat source. The effects of system parameters such as ammonia mass fraction and vapor quality at expander inlet on the system performance are extensively investigated.

II. System Analysis

In this paper, the thermodynamic performance is investigated for ammonia based partial evaporating Rankine cycles with regeneration. The schematic diagram of the system is shown in Fig. 1.

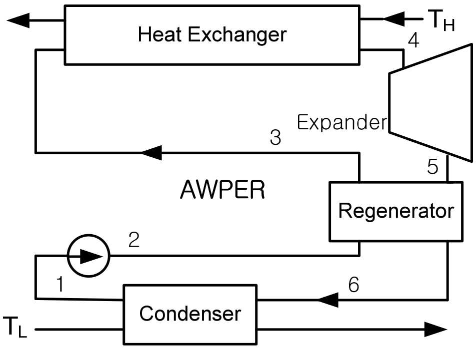

Fig. 1 Schematic diagram of the system

In the cycle, the working fluid of ammonia mass fraction x_b comes out the condenser as a saturated liquid at temperature T_C of state 1, and is compressed in the pump to pressure P_H of state 2, and preheated in the regenerator to state 3. The fluid is then further heated in the source heat exchanger to state 4 where the vapor quality reaches a prescribed value of β. The fluid then enters the expander and produces useful work during the expansion in the expander to the condensing pressure of state 5.

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The working fluid enters then the regenerator and comes out after preheating the working fluid as state 1, and the cycle is completed.

The heat source fluid entering the source heat exchanger is assumed as air at temperature T_H. In addition, the heat losses except heat exchangers and pressure variations except the expander and pump are ignored. Isentropic efficiencies of the pump and expander are η_P and η_T, respectively, and the pinch temperature difference is given as ΔT_{pp}. In the case of producing power using a low-temperature finite heat source, it is desired to produce the maximum power from the supplied heat source. In this paper, therefore, it is considered that the minimum temperature difference between the hot and cold streams in the heat exchanger equals to the prescribed value of the pinch temperature difference, which leads the maximum flow rate of the working fluid for a specified supplied source fluid [3].

The specific heat addition at the source heat exchanger and the specific network of the system per unit mass of the working fluid, q_{in} and w_{net}, can be evaluated as:

$$q_{in} = h_4 - h_3 \tag{1}$$

$$w_{net} = \left(h_4 - h_3\right) - \left(h_2 - h_1\right) \tag{2}$$

where h denotes the specific enthalpy. Then, the heat addition rate Q_{in}, the net power production W_{net}, and the thermal efficiency η_{th} are obtained as:

$$Q_{in} = m_w q_{in} = m_w\left(h_4 - h_3\right) \tag{3}$$

$$W_{net} = m_w w_{net} = m_w\left(h_4 - h_3\right) - m_w\left(h_2 - h_1\right) \tag{4}$$

$$\eta_{th} = W_{net} / Q_{in} \tag{5}$$

where m_w represents the mass flow rate of working fluid.

The thermodynamic properties of ammonia-water mixture are evaluated using the method of Gibbs free energy which was first introduced by Xu and Goswami [13]. At the equilibrium states, the chemical potentials of each element of liquid and vapor phase should be identical to each other as well as the pressure and temperature [14].

$$\mu_a^L = \left(\frac{\partial G_m^L}{\partial N_a}\right)_{T,P,N_w} = \left(\frac{\partial G_m^g}{\partial N_a}\right)_{T,P,N_w} = \mu_a^g \tag{6}$$

$$\mu_w^L = \left(\frac{\partial G_m^L}{\partial N_w}\right)_{T,P,N_a} = \left(\frac{\partial G_m^g}{\partial N_w}\right)_{T,P,N_a} = \mu_w^g \tag{7}$$

Here, N_a, N_w, and N are numbers of moles of ammonia, water, and the mixture, respectively. The Gibbs free energy of G_m for liquid or gas phase is denoted as

$$G_m = N_a\left[G_a + RT\ln x\right] + N_w\left[G_w + RT\ln(1-x)\right] + NG^E \tag{8}$$

III. Results and Discussions

In this work, the source fluid is a standard air with mass flow rate d is assumed as 1 kg/s. The basic data of the system variables are as follows; source temperature T_H = 160 °C, expander inlet pressure P_H = 2 MPa, condensation temperature T_C = 25 °C, coolant temperature T_L = 15 °C, pinch temperature difference ΔT_{pp} = 5 °C, isentropic pump efficiency η_p = 0.85, isentropic expander efficiency η_t = 0.80, respectively.

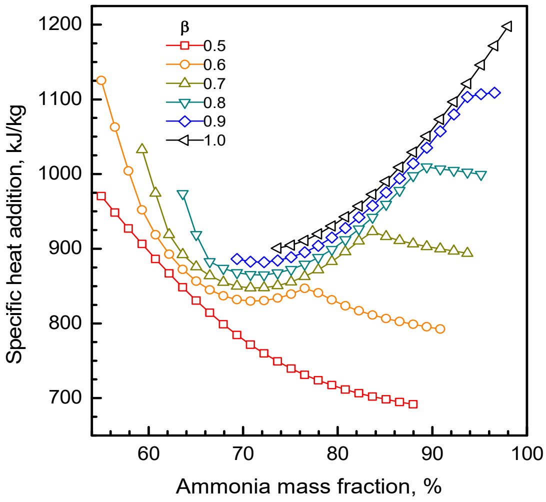

Fig. 2 Effect of ammonia mass fraction on the specific heat addition for various vapor qualities

The effects of the ammonia mass fraction and the vapor quality at expander inlet on the specific heat addition are shown in Fig. 2. For low ammonia mass fractions, the specific heat addition decreases with increasing ammonia mass fraction due to decrease in the vaporization heat. But, for high ammonia mass fractions, the specific heat addition increases due to decrease in the recuperation, which causes lower temperature of the mixture at the heat exchanger inlet. Therefore, the specific heat addition has a minimum value with respect to the ammonia mass fraction. For a specified ammonia mass fraction, the specific heat increases as the vapor quality increases, since the fluid temperature at the heat exchanger exit increases with increase in the vapor quality.

Fig. 3 shows the effects of the ammonia mass fraction on the specific net work. As ammonia mass fraction increases, the specific net work decreases, since as the ammonia mass fraction increases, the expander exit pressure decreases for a specified condensation temperature, which leads to higher expansion pressure across the expander. The specific net work increases with increasing vapor quality for a given ammonia mass fraction. It is because as the vapor quality increases, the temperature and the specific enthalpy of working fluid increase, which causes greater enthalpy difference across the expander.

Fig. 4 presents the mass flow rate of working fluid as a function of ammonia mass fraction for various vapor qualities. The mass flow rate increases with decreasing source exit temperature and decreasing specific heat addition. When the vapor quality is high, the mass flow rate has a peak with respect to ammonia mass fraction. It is because as follows. As the ammonia mass fraction increases, the fluid temperature at the source heat exchanger decreases, which acts as an increasing factor. But, as shown in Fig. 2, the specific heat addition increases with increase in the ammonia mass fraction, which acts as a decreasing factor. For a specified ammonia mass fraction, the mass flow rate increases with increasing vapor quality, since the specific heat addition increases with increase in the vapor quality.

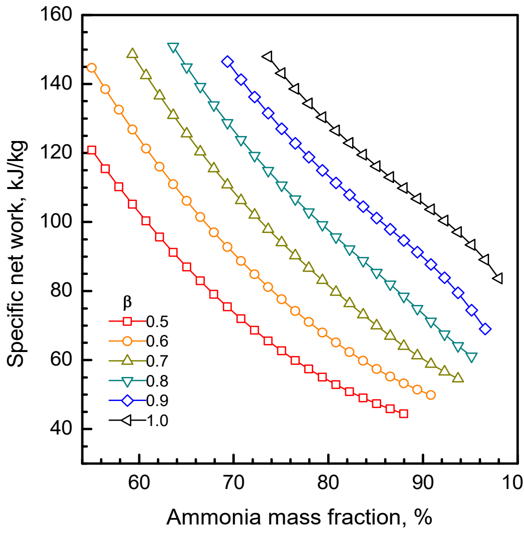

Fig. 3 Effect of ammonia mass fraction on the specific net work for various vapor qualities

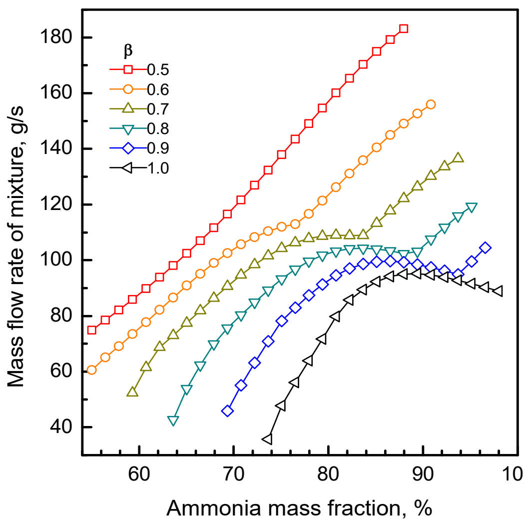

Fig. 4 Effect of ammonia mass fraction on the mass flow rate of working fluid for various vapor qualities

Fig. 5 shows the effects of the ammonia mass fraction on the heat addition rate for various vapor qualities. The heat addition rate is determined from the product of the mass flow rate of the working fluid and the specific heat addition. As the ammonia mass fraction increases, the specific work decreases for low vapor qualities and the mass flow rate has a peak for high vapor qualities. But, it can be seen from the figure that the heat addition rate increases with increasing ammonia mass fraction for all vapor qualities. As the vapor quality increases for a fixed ammonia mass fraction, the specific heat addition increases, but the mass the mass flow rate and the heat addition rate increase, which reveals that the decreasing tendency of mass flow rate with increasing vapor quality plays a more important role.

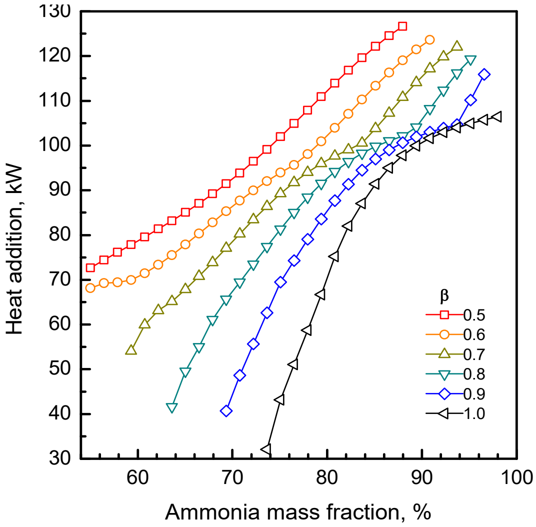

Fig. 5 Effect of ammonia mass fraction on the heat addition rate for various vapor qualities

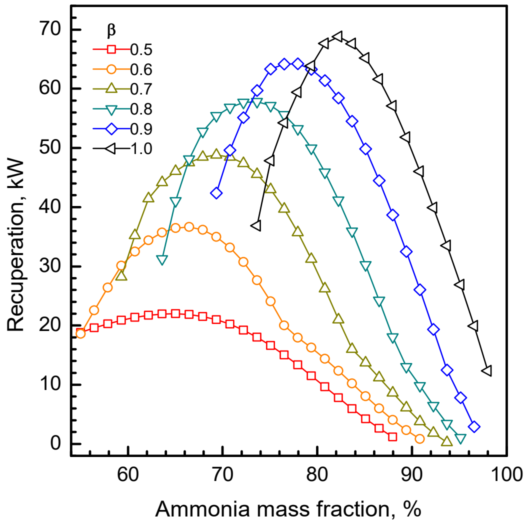

Fig. 6 Effect of ammonia mass fraction on the recuperation heat transfer for various vapor qualities

The effects of the ammonia mass fraction on the recuperation heat transfer are shown in Fig. 6 for various vapor qualities. As the ammonia mass fraction increases, the recuperation firstly increases and reaches the local maximum value and then decreases again, so it has a local maximum value with respect to the ammonia mass fraction. On the other hand, for a given ammonia mass fraction, the recuperation increases with increasing vapor quality, since the mixture temperature at the expander exit increases with increasing vapor quality. It can be seen from the figure that the ammonia mass fraction for the peak value of the recuperation increases as the vapor quality increases.

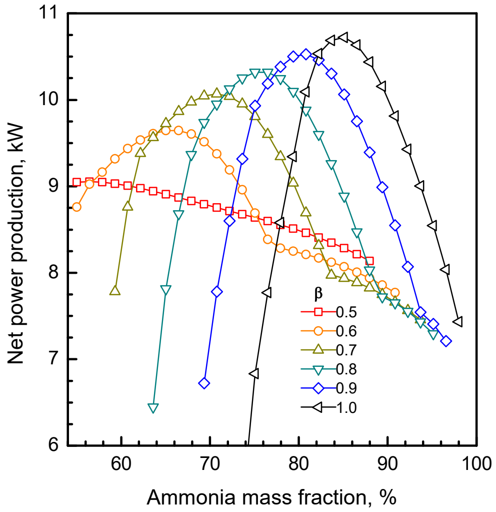

Fig. 7 Effect of ammonia mass fraction on the net power production for various vapor qualities

The effects of the ammonia mass fraction on the net power production are shown in Fig. 7 for various vapor qualities. As the ammonia mass fraction increases, the specific work decreases but the mass flow rate increases for low vapor qualities and has a peak for high vapor qualities. As the vapor quality increases for a fixed ammonia mass fraction, the net power decreases for low ammonia mass fractions but increases for high ammonia mass fractions. It can be seen from the figure that as the vapor quality increases, both the optimum ammonia mass fraction and the maximum net power increase.

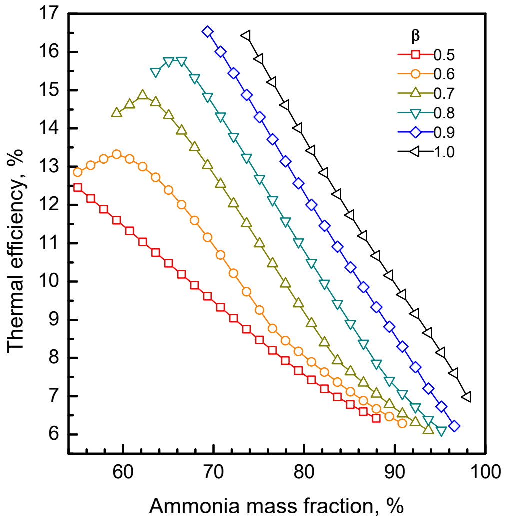

Fig. 8 Effect of ammonia mass fraction on the thermal efficiency for various vapor qualities

Fig. 8 shows the effects of the ammonia mass fraction on the thermal efficiency of the system for various vapor qualities. The thermal efficiency is evaluated as the ratio of the specific net work to the specific heat addition. There exists a low limit of ammonia mass fraction for the valid operation of the regeneration heat transfer. The thermal efficiency has a peak with respect to the ammonia mass fraction, and both the maximum thermal efficiency and the corresponding optimum ammonia mass fraction increase with increasing fluid quality. It is worth noting that the thermal efficiency has a maximum value with respect to vapor quality as well as the ammonia mass fraction. This indicates that the partial evaporating Rankine cycle using zeotropic mixture as working fluid has a potential for efficient recovery of low-grade heat source.

IV. CONCLUSION

This paper investigated the thermodynamic performance of a partial evaporating Rankine cycle using ammonia-water zeotropic mixture as a working fluid for recovery of low-grade finite heat source. The main conclusions from the parametric study of the system are summarized as follows: As the vapor quality increases, the specific heat addition and the specific net wok increase but the mass flow rate decreases. The net power decreases for low ammonia mass fractions but increases for high ammonia mass fractions as the vapor quality increases. The thermal efficiency has a peak with respect to the fluid vapor quality as well as ammonia mass fraction.

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