Performance Analysis of Absorption Power Cycle under Different Source Temperatures

Kyoung Hoon Kim

Abstract—The absorption power generation cycle based on the ammonia-water mixture has attracted much attention for efficient recovery of low-grade energy sources. In this paper a thermodynamic performance analysis is carried out for a Kalina cycle using ammonia-water mixture as a working fluid for efficient conversion of low-temperature heat source in the form of sensible energy. The effects of the source temperature on the system performance are extensively investigated by using the thermodynamic models. The results show that the source temperature as well as the ammonia mass fraction affects greatly on the thermodynamic performance of the cycle.

Keywords—Ammonia-water mixture, Kalina cycle, low-grade heat source, source temperature.

I. INTRODUCTION

OVER the past few decades renewables deployment has been a component of national planning agenda for many developed countries. Since the 1990s, renewable energy sources became linked with sustainable development, forming part of international action aimed at addressing climate change. Many countries and international organizations now view renewables as important elements of energy security, dynamic economic development, environmental protection and greenhouse gas emissions reduction efforts [1].

The research on the conversion of low-grade heat from sources such as geothermal heat, waste heat, low-temperature solar thermal heat, etc. into electrical power or low-temperature energy conversion has become more and more important [2]. The power generation systems using ammonia–water mixture as a working fluid are proven to be the feasible method for utilizing a low-temperature heat source in the form of sensible energy. A major advantage for using zeotropic mixtures as a working fluid in the power generation systems instead of pure working fluids is that heat can be supplied or rejected at variable temperature but still at constant pressure [3]-[7].

Zamfirescu and Dincer [8] carried out thermodynamic analysis of the trilateral ammonia- water Rankine cycle that does not use a boiler, but rather the saturated liquid is flashed by an expander. Ogriseck [9] investigated the integration of the Kalina cycle process in a combined heat and power generation, while Lolos and Rogdakis [10] studied Kalina cycle using low-temperature heat sources. Bombarda et al. [11] performed comparative analysis on thermodynamic performance of Kalina and organic Rankine cycles.

Kim et al. [12]-[15] investigated the characteristics of stream in the heat exchangers used in the ammonia-water based power generation cycles. They also studied the Rankine cycle using ammonia-water mixture as working fluid for recovery of low-temperature waste heat, and they are compared the regenerative Rankine cycle with the simple Rankine cycle. They closely examined the temperature distributions of fluid streams in the heat exchanging devices at different levels of ammonia concentration. Kim and Kim [16] presented thermodynamic analysis of a combined cycle using a low grade heat source and LNG cold energy. The combined cycle consisted of an ammonia-water Rankine cycle with and without regeneration and a LNG Rankine cycle. Ganesh and Srinivas [17] investigated a low-temperature Kalina cycle to optimize the heat recovery from solar collectors. Arslan [18], [19] presented exergo-economic evaluation and optimization study of Kalina cycle using geothermal resources. Sun et al. [20] studied a solar boosted Kalina cycle with an auxiliary superheater. They also performed energy-exergy analysis and parameter design optimization of the KCS-11 solar system with an auxiliary superheater [2]. In this paper a thermodynamic analysis is carried out for a Kalina cycle using ammonia-water mixture as a working fluid for efficient recovery of low-grade heat source. The effects of key system parameters such as source temperature as well as the ammonia mass fraction on the system performance are numerically investigated.

II. SYSTEM ANALYSIS

This study presents a thermodynamic performance analysis for a Kalina cycle using ammonia-water mixture as the working fluid for efficient recovery of a low-temperature heat source in the form of sensible energy to useful work. The schematic diagram of the system is illustrated in Fig. 1.

Let the temperatures of source and coolant be T_s and T_c, respectively, and the basic ammonia mass fraction at pump or condenser be x_b. In the cycle the working fluid which comes out the condenser 2 as a saturated liquid at temperature T_L of state 1 is compressed with a pump to pressure of P_H of state 2, and preheated in a regenerator to state 3. Then the fluid is further heated in the source heat exchanger to the turbine inlet temperature T_H of state 4 and then separated in the separator into a saturated vapor of state 5 and a saturated liquid of state 7. The vapor of state 5 from the separator enters the turbine and produces useful work during the expansion in the turbine to the condensing pressure of state 6. The liquid of state 7 from the separator enters the regenerator and heats the mixture of state 2 exiting the pump to state 6, while it is cooled down to state 8, and then it is expanded in a throttle valve to state 9. The fluids

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of state 6 and state 9 are mixed in a mixer and enter the condenser with state 10.
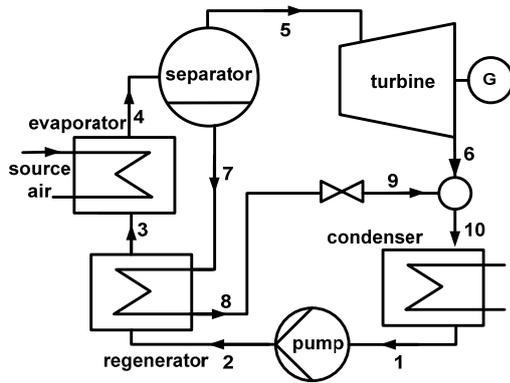
Fig. 1 Schematic diagram of the system

In this work it is assumed that the heat source fluid is standard air at temperature of T_s and the heat losses except heat exchangers are negligible ignored, and pressure variations except the turbine and pump are also ignored. Isentropic efficiencies of the pump and turbine are assumed to be constant at η_P and η_T, respectively. For the maximum flow rate of working fluid and thus for the maximum power generation with a given heat source, it is assumed that the minimum temperature differences between hot and cold fluids in the heat exchangers are equal to a prescribed pinch point, ΔT_{pp}. The mass flow rates of m_6 and m_9 are determined from the mass conservation at the separator and the enthalpies of h_3 and h_8 are calculated from the equation of energy balance and the condition that the minimum temperature difference between hot and cold streams in the regenerator equals to the prescribed value of the pinch point [14]-[16].

In this paper, thermodynamic properties of liquid and vapor phase of the ammonia-water mixture are evaluated by using the Gibbs free energy;

$$G^E / RT = x(1-x)\left[F_1 + F_2(2x-1) + F_3(2x-1)^2\right] \quad (1)$$

Here, x is the mole fraction of ammonia in the mixture, and F_1, F_2, and F_3 are the functions of temperature and pressure [21]. The equilibrium states of liquid and vapor phase are calculated using the modeling of [12];

$$\mu_a^L = \left(\frac{\partial G_m^L}{\partial N_a}\right)_{T,P,N_w} = \left(\frac{\partial G_m^g}{\partial N_a}\right)_{T,P,N_w} = \mu_a^g \quad (2)$$

$$\mu_w^L = \left(\frac{\partial G_m^L}{\partial N_w}\right)_{T,P,N_a} = \left(\frac{\partial G_m^g}{\partial N_w}\right)_{T,P,N_a} = \mu_w^g \quad (3)$$

Here, N_a, N_w, and N are numbers of moles of ammonia, water, and the mixture, respectively.

III. RESULTS AND DISCUSSIONS

In this work it is assumed that the source fluid is a standard air and the mass flow rate of the source fluid is 1 kg/s. The basic data of the system variables are as follows; separator pressure P_H = 20bar, condensation temperature T_L = 25°C, coolant temperature T_c = 15°C, pinch temperature difference ΔT_{pp} = 5°C, isentropic pump efficiency η_p = 0.85, isentropic turbine efficiency η_t = 0.90, quality limit at turbine exit y_t = 0.90. The key parameters in this study are the source temperature and the ammonia mass fraction. It is assumed that the separator temperature is lower than the source temperature by 20°C.
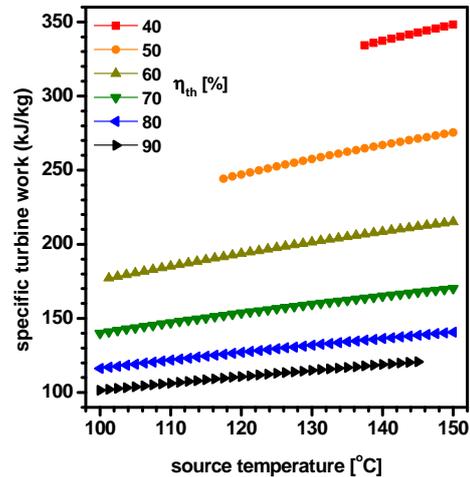
Fig. 2 Plot of specific turbine work against source temperature for various ammonia mass fractions

The specific turbine work which is defined as the work production at turbine per unit mass of working fluid is illustrated in Fig. 2 as a function of source temperature for various ammonia mass fractions. The specific work increases with the increasing source temperature, since the enthalpy of the working fluid at turbine inlet increases with increasing separator temperature. For a specified source temperature, the specific work decreases with increasing ammonia mass fraction, since the vaporization heat of ammonia-water mixture decreases as the ammonia mass fraction increases.
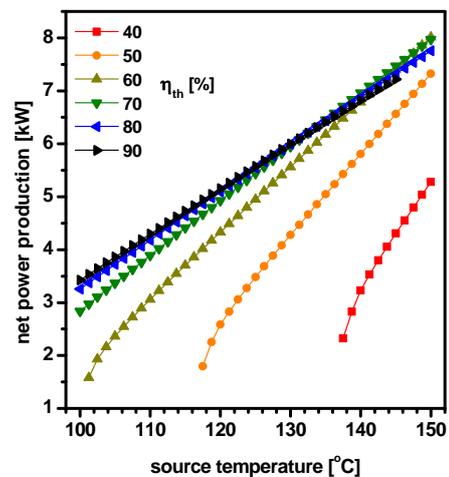
Fig. 3 Plot of net power production against source temperature for various ammonia mass fractions

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The net power production which is obtained as the product of the mass flow rate of working fluid at turbine and the specific turbine work is plotted against source temperature in Fig. 3 for various ammonia mass fractions. For a specified source temperature, the net power production increases with increasing ammonia mass fraction though the specific turbine work decreases with increasing ammonia mass fraction, since as the ammonia mass fraction increases, the increasing rate of the mass flow rate of working fluid at turbine becomes greater than the decreasing rate of the specific turbine work. However, the increasing rate of the net power due to the ammonia mass fraction decreases with increasing ammonia mass fraction, and it can be negative when the ammonia mass fraction becomes very large.

The heat input rate is plotted against source temperature in Fig. 4 for various ammonia mass fractions. It can be seen from the figure that the heat input rate increases as source temperature or ammonia mass fraction increases. The heat input rate is obtained as the product of the mass flow rate of working fluid and the specific heat input from the heat source to the system at the heat exchanger. As the source temperature increases, the mass flow rate decreases for low ammonia mass fractions but increases for high ammonia mass fractions. However, the increasing effect of the specific heat input with increasing source temperature is dominant compared to the decreasing effect of the mass flow rate, so the heat input rate increases with the source temperature.
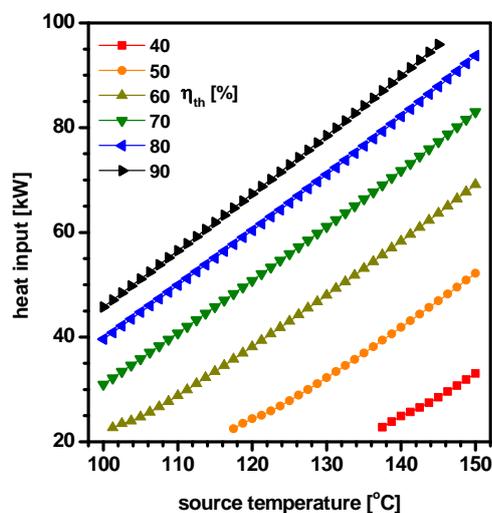
Fig. 4 Plot of heat input against source temperature for various ammonia mass fractions

The thermal efficiency of the cycle which is defined as the ratio of net power production to the heat input rate to the system is plotted against source temperature in Fig. 5 for various ammonia mass fractions. For a given ammonia mass fraction, the thermal efficiency increases with increasing source temperature. It can be observed from the figure that the increasing rate of the thermal efficiency with respect to the source temperature is high for low ammonia mass fractions.

When the ammonia mass fraction is high, however, the increasing rate becomes so low that the efficiency remains almost constant with respect to the source temperature. For a given source temperature, the thermal efficiency decreases with increasing ammonia mass fraction.
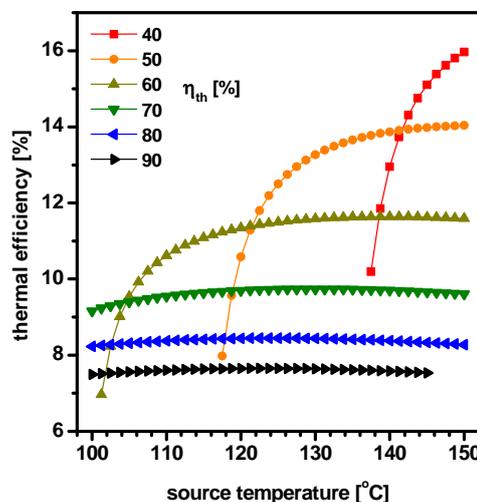
Fig. 5 Plot of thermal efficiency against source temperature for various ammonia mass fractions

IV. CONCLUSION

In this paper a thermodynamic performance analysis was carried for an absorption power generation cycle using ammonia-water mixture as a working fluid in order to produce maximum power from the low-temperature heat source in the form of sensible energy. Special attention is focused on the effects of the source temperature as well as the ammonia mass fraction on the system performance such as specific turbine work, net power production, heat input rate, and thermal efficiency. Results show that the thermodynamic performance of the system is sensitively influenced by the source temperature as well as the ammonia mass fraction of the working fluid. Results also show that as source temperature increases for a specified ammonia mass fraction or turbine inlet pressure, the net power production increases, however, the thermal efficiency remains nearly constant for high ammonia mass fractions.

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