EFFECTS OF SOURCE TEMPERATURE ON ENTROPY GENERATION IN AMMONIA-WATER BASED HRVG

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Abstract - The use of a zeotropic binary mixture of ammonia and water as working fluid in the power generating system has been considered as a proven technology for the efficient recovery of energy from the low-temperature finite heat sources. This paper carries out a thermodynamic performance analysis for a heat recovery vapor generator (HRVG) using ammonia-water mixture as working fluid. The effects of the ammonia mass fraction and the temperature of source fluid heating the working fluid are extensively investigated on the exergy performance of the system. The results show that these parameters have a great influence on the system performance of HRVG such as effectiveness and exergy efficiency.

Index Terms - Ammonia-water mixture, entropy, exergy, heat recovery vapor generator (HRVG), source temperature.

I. INTRODUCTION

Current energy generation as well as utilization patterns directly lead to considerable wasted energy either at medium or high availabilities. The waste heat systems have been designed primarily for thermal recovery through simple recuperative heat exchangers. However, the conversion systems which upgrade a heat source to higher forms such as work, electricity, and cooling, have been less viable due to large component sizes and system complexity [1]. The efficient technologies for conversion of low grade heat sources in the form of sensible energy have become more and more important [2]-[4].

The motivation for using mixtures is that heat can be supplied or rejected at variable temperature but constant pressure. The variable-temperature heat-transfer processes reduce the temperature mismatch between the hot and cold streams and the cycle, which reduces the availability destruction in heat-exchangers [5]-[6]. In the past decades the use of ammonia-water mixture as working fluid in power generation cycles has been investigated by many researchers for the purpose of reducing the thermal irreversibilities in the heat introduction process, particularly between the heat source and the evaporating working fluid [7]-[9].

There are many ways to assess energy system performance, and the most common energy system performance assessment criteria are based on the first law. They are useful for assessing the efficiency of energy use, and can be easily converted to energy cost efficiencies if the prices of the energy forms of the useful outputs and paid inputs are known. Since such energy-based criteria do not account for the quality of energy, expressed as exergy, exergy-based criteria are also appropriate as they account better for use of energy resources and give much better guidance for system improvement. They also can be converted to exergy cost efficiencies if the exergy values of useful output and paid input are rationally priced [10]-[13]. When heat is transferred in a heat exchanger, the degradation of energy occurs due to irreversibility, and the irreversibility of the heat exchange process can be characterized by the amount of entropy generation [14]-[16]. Kim et al. [17]-[20] investigated the thermodynamic performances of ammonia-water based power generation cycles for the recovery of low-temperature heat sources. They showed that the characteristics of temperature distributions in the fluid streams of the heat exchangers vary quite complicatedly and sensitively with changing system parameters. They also presented the first and second thermodynamic law analysis for a heat recovery vapor generator (HRVG) of ammonia-water mixture when the heat source is low-temperature energy in the form of sensible heat [21]-[22].

The main purpose of this paper is to investigate the thermodynamic characteristics of entropy and exergy in HRVG of ammonia-water mixture to covert the energy of low-temperature heat source to a useful form of energy. The HRVG consists of preheater, evaporator, and superheater, and the heat source is in the form of sensible energy. Special attention is focused on the effects of the source temperature and the ammonia concentration of the mixture on the system performance.

II. SYSTEM ANALYSIS

A HRVG of ammonia-water mixture to be considered is schematically shown in Fig. 1. The mixture changes its state from liquid to superheated vapor by the heat released from a counter stream of source fluid.

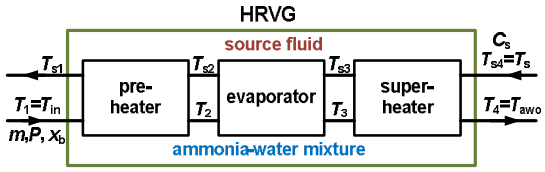


Fig. 1. Schematic diagram of HRVG.

The important assumptions in the present system analysis are as follows [21]: 1) The fluid flow and heat transfer rates are steady. 2) HRVG is thermally well insulated. 3) Pressure drop due to flows inside the heat exchangers is negligible so that the pressure inside the heat exchangers remains constant. 4) The changes of kinetic and potential energy of the fluids in and out of the heat exchangers are negligible. 5) The longitudinal heat conduction in the tube walls is negligible.

Let us denote the mass flow rate, the ammonia mass concentration, and the inlet and outlet temperatures of the ammonia-water mixture, by m, x_b, and T_{in} (= T_1) and T_{awo} (= T_4), respectively. The constant pressure of the mixture in the heat exchangers is P, and the inlet temperature and thermal capacity of source fluid are T_s (= T_{s4}) and C_s, respectively. Recall that C_s is equal to the product of its mass flow rate m_s and isobaric specific heat c_{ps}. If all these parameters are specified, then the source fluid temperatures T_{s1}, T_{s2} and T_{s3} depicted in Fig. 1 can be obtained from the energy balance equations in HRVG as follows [21]:

$$Q_{ph} = m(h_2 - h_1) = C_s(T_{s2} - T_{s1}) \quad (1)$$

$$Q_{ev} = m(h_3 - h_2) = C_s(T_{s3} - T_{s2}) \quad (2)$$

$$Q_{sh} = m(h_4 - h_3) = C_s(T_{s4} - T_{s3}) \quad (3)$$

$$Q_{tot} = m(h_4 - h_1) = C_s(T_{s4} - T_{s1}) \quad (4)$$

Here, h is the specific enthalpy of the mixture, and Q is the heat transfer rate of the heat exchanger. The subscripts ph, ev, sh, and tot stand for preheater, evaporator, superheater, and total system of HRVG, respectively. Note that h_2 and h_3 are the specific enthalpies at the bubble point and the dew point of the mixture, respectively, for the prescribed conditions of pressure and ammonia mass concentration.

The effectiveness of heat exchanger ε is defined as the ratio between actual heat transfer rate and the maximum possible heat transfer rate and it can be approximated as follows:

$$\varepsilon = \frac{T_s - T_{s1}}{T_s - T_{in}} \quad (5)$$

The rates of entropy generation, which are equal to the difference of the rates of entropy outflow from the system and entropy inflow to the system, can be obtained as follows [21]:

$$\Delta S_{ph} = m(s_2 - s_1) - C_s \ln(T_{s2}/T_{s1}) \quad (6)$$

$$\Delta S_{ev} = m(s_3 - s_2) - C_s \ln(T_{s3}/T_{s2}) \quad (7)$$

$$\Delta S_{sh} = m(s_4 - s_3) - C_s \ln(T_{s4}/T_{s3}) \quad (8)$$

$$\Delta S_{tot} = m(s_4 - s_1) - C_s \ln(T_{s4}/T_{s1}) \quad (9)$$

where s is the specific entropy of the mixture.

The exergy efficiency of a heat exchanger η is defined as the ratio of the increased exergy of cold stream to the decreased exergy of hot stream. The exergy efficiencies of each heat exchanger and total system of HRVG can be obtained as follows [22]:

$$\eta_{ph} = \frac{m}{C_s}\frac{(h_2 - h_1) - T_0(s_2 - s_1)}{(T_{s2} - T_{s1}) - T_0 \ln(T_{s2}/T_{s1})} \quad (10)$$

$$\eta_{ev} = \frac{m}{C_s}\frac{(h_3 - h_2) - T_0(s_3 - s_2)}{(T_{s3} - T_{s2}) - T_0 \ln(T_{s3}/T_{s2})} \quad (11)$$

$$\eta_{sh} = \frac{m}{C_s}\frac{(h_4 - h_3) - T_0(s_4 - s_3)}{(T_{s4} - T_{s3}) - T_0 \ln(T_{s4}/T_{s3})} \quad (12)$$

$$\eta_{tot} = \frac{m}{C_s}\frac{(h_4 - h_1) - T_0(s_4 - s_1)}{(T_{s4} - T_{s1}) - T_0 \ln(T_{s4}/T_{s1})} = \frac{\Delta E_w}{\Delta E_s} = 1 - \frac{T_0 \Delta S_{tot}}{\Delta E_s} \quad (13)$$

Here, the subscript 0 indicates the corresponding dead state of the system.

The thermodynamic properties of ammonia-water mixture are computed using the method of Gibbs free energy, which was first introduced by Xu and Goswami [23]. However, in this work, the equilibrium states of liquid and vapor phases are determined by equating the chemical potentials of each phase for each element [17].

$$\mu_a^L = \left(\frac{\partial G_m^L}{\partial N_a}\right)_{T,P,N_w} = \left(\frac{\partial G_m^g}{\partial N_a}\right)_{T,P,N_w} = \mu_a^g \quad (14)$$

$$\mu_w^L = \left(\frac{\partial G_m^L}{\partial N_w}\right)_{T,P,N_a} = \left(\frac{\partial G_m^g}{\partial N_w}\right)_{T,P,N_a} = \mu_w^g \quad (15)$$

Here, the subscripts a, w, and m indicate ammonia, water, and mixture, respectively, and the superscripts L and g indicate the liquid phase and gas phase, respectively. N and G_m are number of moles of each element and the Gibbs free energy of mixture. G_m for each phase is calculated as

$$G_m = N_a[G_a + RT\ln x] + N_w[G_w + RT\ln(1-x)] + NG^E \quad (16)$$

Here, G means the Gibbs free energy and the superscript E indicates the equilibrium state [17].

III. RESULTS AND DISCUSSIONS

In the present study, thermodynamic analysis of the HRVG of ammonia-water mixture is carried out. The basic data of the system variables are as follows:

mixture inlet temperature T_{in} = 30°C, mixture mass flow rate m = 3 kg/s, dead state temperature T_0 = 298.15 K, thermal capacity of source C_s = 10 kW/K, pressure P = 15 bar. The key parameters of the system analysis are the ammonia mass concentration and the source temperature. The ammonia mass fraction is considered to vary from 50% to 100%. The source temperatures considered are from 100°C to 200°C with an interval of 20°C, while the mixture outlet temperature T_{awo} is set 10°C below the source temperature.

The effectiveness of HRVG is plotted against the ammonia mass concentration in Fig. 2 for various source temperatures. When the ammonia mass concentration increases for the source temperatures lower than 180°C, the effectiveness firstly increases, reaches a peak value, and then keeps on decreasing. It follows that there exists an optimum value of concentration giving a maximum effectiveness for given source temperature. The value of optimum concentration decreases as the source temperature increases. The optimum concentration value falls below 50% for high enough source temperature, which is the lower bound of the considered concentration range. As a result, the effectiveness simply decreases with increasing ammonia concentration for the source temperatures of 180°C and 200°C. When the ammonia concentration is high enough, the effectiveness gets worse with raising the source temperature. For the relatively low ammonia concentrations, the dependence of the effectiveness on the source temperature is not uniform.

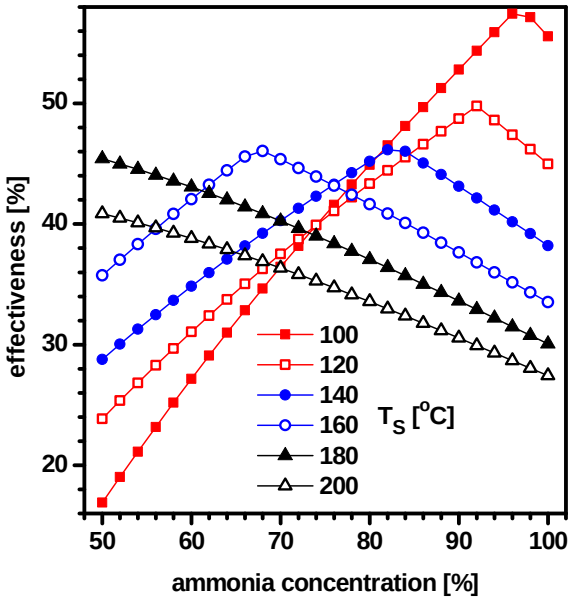


Fig. 2. Effectiveness of HRVG as a function of ammonia mass concentration for various source temperatures.

An entropy generation ratio at a component is defined as the ratio of entropy generation at the component to the total entropy generation. Fig. 3 shows the entropy generation ratio at the preheater as a function of ammonia mass concentration for various source temperatures. It shows a monotonically and quite rapidly decreasing behavior with respect to the ammonia concentration for any source temperature considered. This is because the bubble point of the mixture drops as the ammonia mass concentration increases under constant pressure. For a specified ammonia mass concentration, the entropy generation ratio at the preheater gets lower as the source temperature is raised. This is because the total heat transfer becomes higher as the source temperature increases, while the heat transfer at the preheater where the working fluid is in liquid state is fixed [21]. The entropy generation ratio at the evaporator is plotted in Fig. 4 as a function of ammonia mass concentration for various source temperatures. When the ammonia mass concentration is increased for a given source temperature, the entropy generation ratio at the evaporator shows a first increasing and then decreasing behavior and results in a convex upward curve. The reason of this behavior is because as the ammonia mass concentration increases, the decreasing effect of bubble-point enthalpy becomes dominant for low ammonia mass concentration, but the decreasing effect of vaporization becomes dominant for higher ammonia mass concentration. If the ammonia mass concentration is relatively low, the entropy generation ratio at the evaporator is higher for the hotter source fluid; the behavior is reversed for high enough values of ammonia mass concentration.

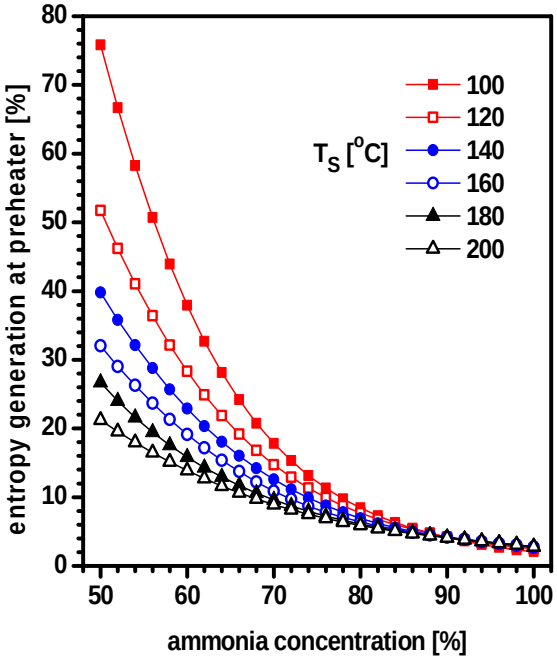


Fig. 3. Entropy generation at the preheater vs. ammonia mass concentration for various source temperatures.

The superheater is the last component of HRVG where the working fluid finally leaves out of it with the

highest temperature. The entropy generation ratio at the superheater as a function of ammonia mass concentration for various source temperatures is plotted in Fig. 5. For a specified source temperature, the entropy generation ratio monotonically increases with increasing ammonia mass concentration, since the enthalpy of dew point decreases with increasing ammonia mass concentration. For the same ammonia mass concentration, the entropy generation ratio is higher at the preheater heated by a hotter source stream. This is because the fraction of superheated vapor of the working fluid increases with increasing source temperature.

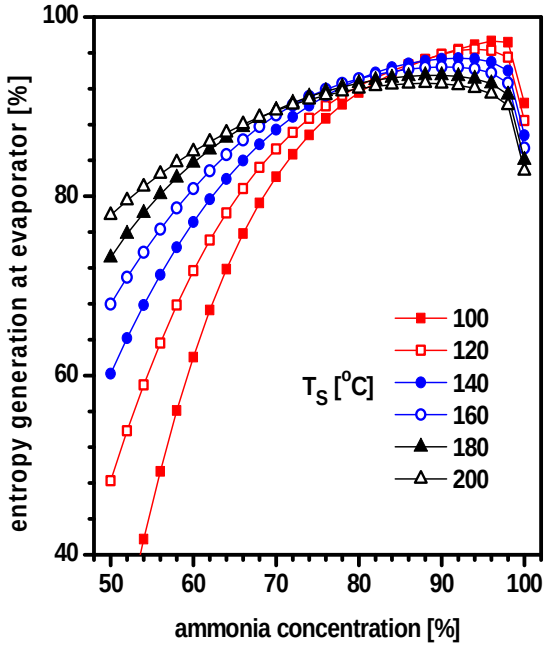


Fig. 4. Entropy generation at the evaporator vs. ammonia mass concentration for various source temperatures.

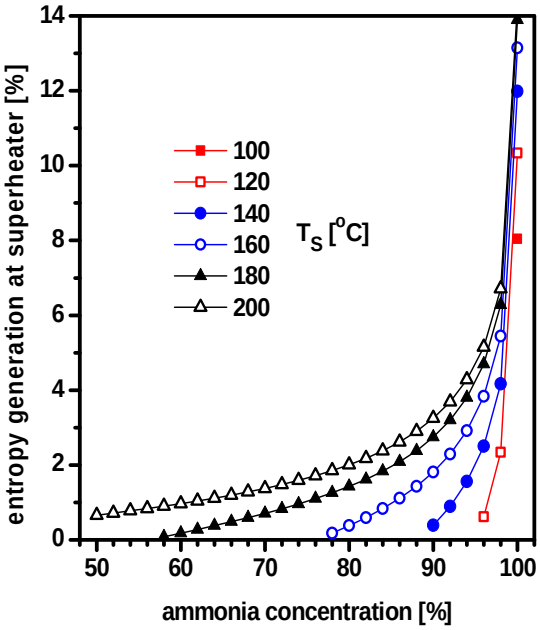


Fig. 5. Entropy generation at the superheater vs. ammonia mass concentration for various source temperatures.

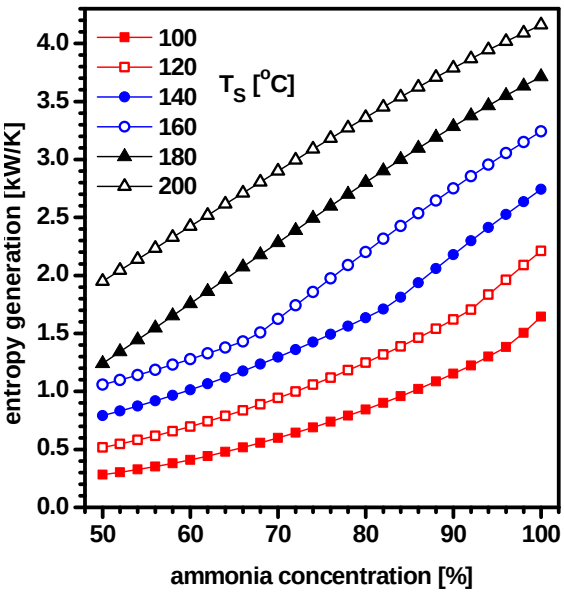


Fig. 6. Total entropy generation rate of HRVG vs. ammonia mass concentration for various source temperatures.

Fig. 6 illustrates the effects of ammonia mass concentration and source temperature on the total entropy generation rate of HRVG system. For a specified source temperature, the total rate of entropy generation increases with increasing ammonia mass concentration, since as the ammonia mass concentration increases, the enthalpy difference between the fluid at inlet and outlet decreases, which leads to lower heat transfer at HRVG, low mass flow rate of source fluid, consequently larger temperature difference between hot and cold streams in the HRVG. If the ammonia mass concentration is specified, the total entropy generation rate of HRVG increases with increasing source temperature due to the effect of increased temperature difference between the fluids at inlet and outlet of HRVG.

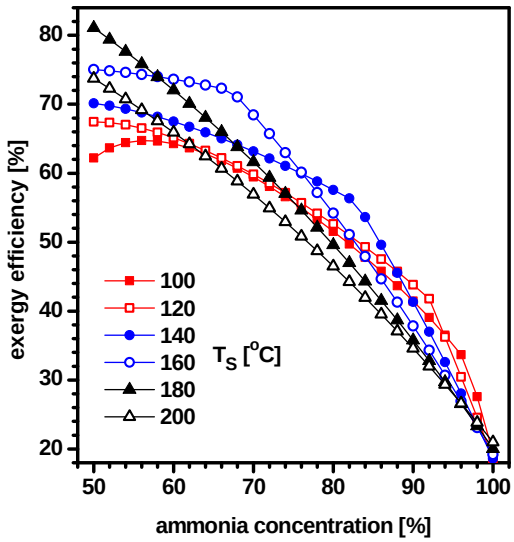


Fig. 7. Exergy efficiency as a function of ammonia mass concentration for various source temperatures.

Fig. 7 shows the effects of ammonia mass concentration and source temperature on the exergy efficiency which is defined as the ratio of the increased exergy by the cold fluid stream to the exergy supplied by the hot fluid stream. It reveals clearly that the exergy efficiency decreases with increasing ammonia mass concentration. This is because of the increased temperature difference between the hot and cold fluid streams and the consequent increased entropy generation in the HRVG system. There is no uniform rule of dependence of the exergy efficiency on the source temperature for each fixed ammonia mass concentration. However, it can be said that the exergy efficiency is less sensitive to the source temperature for the mixtures with very high ammonia concentration.

CONCLUSIONS

Effects of the ammonia mass concentration and the source temperature on the thermodynamic performance of a heat recovery vapor generator (HRVG) using ammonia-water mixture as working fluid are investigated based on the first and second laws of thermodynamics. HRVG consists of preheater, evaporator, and superheater and the heat source is low-temperature heat source in the form of sensible energy. The ammonia mass concentration of the mixture and the source temperature are considered as the key parameters. The results show that the ammonia mass concentration and the source temperature have a great influence on the system performance such as the effectiveness of heat exchanger, entropy generation and exergy efficiency. As the ammonia mass concentration increases, the total entropy generation increases while the exergy efficiency decreases. As the source temperature increases, the total entropy generation increases. However, the effect of source temperature on the exergy efficiency is quite complicated.

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