Analysis of Regenerative Power Cycle Utilizing Low-Grade Heat Source and LNG Cold Energy

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Abstract—The ammonia-water based power generation cycle with liquefied natural gas (LNG) as its heat sink has attracted much attention, since the working fluid of zeotropic mixture like ammonia-water mixture in power cycle has some thermo-dynamic advantages compared with a pure working fluid and LNG has a great cold energy of 840kJ/kg. This paper presents a thermal performance analysis of a combined power cycle which is consisted of an ammonia-water regenerative Rankine cycle and LNG cycle to utilize low-temperature waste heat in the form of sensible energy. Based on the thermodynamic models of ammonia-water power generation cycles, the effects of the key parameters such as ammonia concentration and condenser outlet temperature on the system performance are investigated. The results show that the ammonia concentration and condenser outlet temperature affect greatly the thermodynamic performance of the combined cycle. It is also founded that there exists an optimum ammonia concentration to reach the maximum system performance.

Keywords— ammonia-water regenerative Rankine cycle, cold energy, liquefied natural gas (LNG), low-grade heat source.

I. INTRODUCTION

The power generation systems using ammonia–water mixture as a working fluid is 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, since the boiling temperature now varies during the phase change and the binary mixture evaporates over a wide range of temperature. The variable-temperature heat transfer process alleviates the temperature mismatch between hot and cold streams in heat exchanging components of the system, which then reduces the exergy destruction in the power cycles. Because the boiling point of ammonia is lower than water, the waste heat of low temperature which does not caused vapor can be used effectively. For this reason, turbine inlet pressure is more lowered, and the circulation flow rate of working fluid is reduced, so operating costs will be conserved. Also, ammonia and water have the similar molecular weights, thus, traditional design of steam turbines can be used in the ammonia-water power cycles only with minor modifications [1], [2].

Ibrahim and Klein [3] developed a methodology based on heat-exchanger network syntheses to study and optimize the performance of an ammonia-water Rankine cycle. They showed that the design of heat exchanger networks can have a significant impact on the performance of power cycles. Wager et al. [4] analyzed the ammonia-water Rankine cycle using scroll expander. Kim et al. [5], [6] studied the Rankine cycle using ammonia-water mixture as working fluid for use of low-temperature waste heat, and they are compared the regenerative Rankine cycle with the simple Rankine cycle. Kim et al. [7] carried out the comparative analysis of ammonia–water based Rankine (AWR) and regenerative Rankine (AWRR) power generation cycles by investigating the effects of ammonia mass concentration in the working fluid on the thermodynamic performances of systems. They closely examined the temperature distributions of fluid streams in the heat exchanging devices at different levels of ammonia concentration.

Natural gas is widely used in many areas for its better environmental characteristic. For the convenience of transport, natural gas liquefied into the liquefied natural gas (LNG) by cryogenic refrigerating after removed the acid and water. During the liquefaction process, LNG has a very low temperature and contains much cold energy after this process. With the increasing demand for clean fuels, LNG is playing a significant role as energy resource. Thus, many researchers employed LNG as heat sink of power system to recover the LNG’s cold energy.

Choi and Chang [8] studied power generation cycle thermodynamically utilizing the LNG cold energy. LNG was used as a heat sink, and power cycles consisted of the open and closed Rankine cycle, the closed Brayton cycle. Miyazaki et al. [9] provided comparison between conventional refuse incineration power cycle and combined power cycle using LNG cold energy. Shi and Che [10] are proposed a combined system consists of the Rankine cycle with ammonia-water mixture as the working fluid and the LNG power generation cycle. Wang et al. [11] proposed an ammonia-water power system with LNG as its heat sink. Kim et al. [12] studied an ammonia-water simple power cycle with LNG as its heat sink. Rao et al. [13] proposed a combined cycle, in which low-temperature solar energy and cold energy of LNG could be effectively utilized together. They
showed that a decrease of nearly 82.2% on the area of solar collector was obtained and the area of heat exchanger was decreased by 31.7% for the combined cycle.

This paper deals with the thermodynamic analysis for a combined power cycle consisted of a regenerative Rankine cycle and a LNG cycle. For the effective use of the low-temperature heat source in the form of sensible energy, ammonia-water mixture is used for the Rankine cycle as a working fluid. Moreover, LNG is used to produce the some power output as well as to condense the ammonia-water mixture as a heat sink. The effects of the key system parameters such as ammonia concentration and condenser outlet temperature on the system performance are extensively investigated.

II. SYSTEM ANALYSIS

A. System descriptions and assumptions

In this study, thermodynamic performance of a combined power generation cycle is analyzed to convert low-temperature heat source in the form of sensible energy to useful work. The combined power generation cycle is consisted of a regenerative Rankine cycle using ammonia-water mixture as the working fluid and a LNG cycle. LNG is supplied at a cryogenic temperature and is assumed to be methane (CH₄) for simplicity. The schematic diagram is shown in Fig. 1. In the ammonia-water Rankine cycle, the working fluid which comes out the heat exchanger II as a saturated liquid at temperature Tc of state 1 is compressed through a pumping process in a pump to pressure of PH₁ of state 2, and preheated in a regenerator to state 3, and further heated in the heat exchanger I to the turbine inlet temperature TH₁ of state 4. Then, it is expanded in a turbine 1 from state 4 to state 5, and cooled down in the regenerator as it heats the cold working fluid coming out the pump 1. And also, it is cooled again in the heat exchanger II and returns back to state 1. In the LNG cycle, meanwhile, LNG of state 7 supplied from a reservoir is pressurized to sate 8 in the pump 2, and then enters the heat exchanger II and releases the cold energy in order to condense the ammonia-water mixture. After the LNG enters the turbine 2 and produces some work, finally comes out to state 10.

In the combined cycle the heat source fluid entering the heat exchanger I is assumed to be a standard air at temperature of Ts. In addition, the heat losses except heat exchangers are ignored, and pressure variations except turbines and pumps are also ignored. Isentropic efficiencies of the pump 1 pump 2, turbine 1 and turbine 2 are η₁, η₂, η₁, η₂, respectively, and assumed to be constant.

The temperature difference between hot and cold fluids in the heat exchangers should be greater than a prescribed pinch point temperature, ΔTₚₚ. In the case of producing power using the low-temperature heat source in the form of the sensible heat, it is important to produce the maximum power from supplied heat source. Therefore, we analyze this system that is driven by conditions of maximum working flow rate. Thus, the minimum temperature difference between the hot and cold streams in the heat exchangers should equal to the prescribed value of the pinch point temperature.

B. Power cycle analysis

When the inlet pressures of turbine 1 and 2 are PH₁, PH₂, respectively and the mass concentration of ammonia in the ammonia-water mixture is xₐ in the system, the thermodynamic properties of ammonia-water mixture from state 1 to state 6 and the thermodynamic properties of LNG from state 7 to state 10 can be determined as follows:

(1) inlet of pump 1 (mixture, state 1);
   saturated liquid, T₁ = Tc

(2) inlet of regenerator (mixture, state 2);
   P₂ = P₂, (h₂ – h₁)/(h₂ₐ – h₁) = η₁

Fig. 1 Schematic diagram of the system
(3) inlet of turbine 1 (mixture, state 4); 
\[ T_4 = T_{H1}, \ P_4 = P_{H1} \] 

(4) outlet of turbine 1 (mixture, state 5); 
\[ P_5 = P_{1}, \ (h_4 - h_5)/(h_4 - h_{5s}) = \eta_{t1} \] 

(5) outlet of LNG reservoir (LNG, state 7); 
saturated liquid, \( P_7 = P_{atm} \) 

(6) inlet of heat exchanger II (LNG, state 8); 
\[ P_8 = P_{H2}, \ (h_{8s} - h_7)/(h_8 - h_{7s}) = \eta_{p2} \] 

(7) inlet of turbine 2 (LNG, state 9); 
\[ T_9 = T_{H2}, \ P_9 = P_{H2} \] 

(8) outlet of turbine 2 (LNG, state 10); 
\[ P_{10} = P_{L2}, \ (h_9 - h_{10})/(h_9 - h_{10s}) = \eta_{t2} \] 

Here, subscript s indicates the isentropic condition. The enthalpies of \( h_3 \) and \( h_6 \) 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 as follows:

\[ h_3 - h_2 = h_5 - h_6 \]  

\[ \min (T_{hot} - T_{cold})_{\text{regenerator}} - \Delta T_{pp} = 0 \]  

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

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

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 [14]. The equilibrium states of liquid and vapor phase are calculated using the modeling of [7]:

\[ \mu^L = \left(\frac{\partial G^L}{\partial N_x}\right)_{T,P,N_x} = \mu^L_x \]  

\[ \mu^V = \left(\frac{\partial G^V}{\partial N_x}\right)_{T,P,N_x} = \mu^V_x \]  

Here, \( N_x, N_w, \) and \( N \) are numbers of moles of ammonia, water, and the mixture, respectively.

Also in order to analyze the LNG cold energy cycle, LNG is assumed to be pure methane, and thermodynamic properties of LNG are evaluated by using the Patel-Teja equation [15], [16];

\[ P = \frac{RT}{v-b} - \frac{a(T)}{v(v+b)+c(v-b)} \]  

Where \( R \) is the universal gas constant.

III. RESULTS AND DISCUSSIONS

The basic data of the system variables is \( T_s = 320^\circ C, \ P_{H1} = 30 \text{bar}, \ T_{H1} = 300^\circ C, \ P_{H2} = 40 \text{bar}, \ P_{L2} = 4 \text{bar}, \ \Delta T_{pp} = 10^\circ C, \ \eta_p = \eta_{p2} = 0.70, \ \eta_{t1} = \eta_{t2} = 0.80, \ \gamma_w = \text{quality limit at turbine exit} = 0.90. \] In this study, the source is air. When the key parameters such as condensing temperature \( T_c \), and ammonia concentration \( x_b \) are also set to \( T_c = 0^\circ C, \ x_b = 70\% \), thermodynamic properties at each point of the system are listed in TABLE I .

The heat exchanger is considered in this work as a counter-flow heat exchanger where heat transfer except between hot and cold streams is negligible, so heat loss from the source fluid is equal to the heat gain of ammonia–water mixture and the mixture enthalpy varies nonlinearly with its temperature within the heat exchanger. The mass flow ratio is defined as the ratio of mass flow rate of the mixture to mass flow rate of ammonia.

![Fig. 2 Plot of mass flow ratio of mixture against ammonia concentration for various condensing temperatures.](image-url)
mass flow rate of working fluid to that of source fluid. For a set of specified conditions, the outlet source temperature decreases as the mass flow ratio increases until the minimum temperature difference between hot and cold streams in the heat exchanger reaches a prescribed value of pinch point temperature difference [2]. Fig. 2 shows the mass flow ratio, which means the maximum allowable mass flow rate of working fluid per unit mass of source fluid, as a function of ammonia concentration for various condenser outlet temperatures. The mass flow ratio increases with the increasing condensing temperature, since the mass flow ratio is proportional to the temperature difference between inlet and outlet of source heat exchanger. As the ammonia mass concentration increases for a specified condensing temperature, the mass flow ratio increases at first and reaches a maximum value and then decreases, so there exists a maximum value of the mass flow ratio with respect to the ammonia mass concentration around at a high ammonia concentration.

The effects of ammonia mass concentration and condensing temperature on the amount of heat addition to the system per unit mass of source fluid \( q_{in} \), are shown in Fig. 3. The heat addition is obtained as the product of the mass flow ratio of the working fluid and the difference of the specific enthalpies at the inlet and outlet of the heat exchanger \( I \). When the turbine inlet temperature and pressure are held at a constant value, lower condensing temperature leads to higher heat addition owing to the bigger temperature difference between inlet and outlet of the heat exchanger \( I \). For a specified condensing temperature, on the other hand, the heat addition increases with the ammonia mass concentration. It is because the heat addition decreases with the ammonia concentration in the range of low concentration mainly due to decreasing vaporization heat of the mixture, but it increases again mainly in the range of high concentration due to the lowered phase change temperature. When the condensing temperature becomes high, the heat addition increases monotonically with the ammonia concentration, since the phenomenon of decrease in the phase-change temperature is dominant.

The effects of ammonia concentration and condenser outlet temperature on the net work production per unit mass of source fluid are shown in Fig. 4. The produced net work in the combined cycle, which is defined as the sum of the net work productions of the ammonia-water power cycle and the LNG cycle, increases with a decrease in the condensing temperature. This is because decreasing of the condensing temperature results in a lower condensing pressure, and so consequently larger pressure ratio and larger enthalpy drop across the turbine 1 in the ammonia-water power cycle. As the ammonia mass concentration increases for a specified condensing temperature, however, the net work production increases at first and then

Fig. 3 Plot of heat addition per unit mass of source fluid against ammonia concentration for various condensing temperatures.

Fig. 4 Plot of net work per unit mass of source fluid against ammonia concentration for various condensing temperatures.

Fig. 5 Plot of thermal efficiency against ammonia concentration for various condensing temperatures.
drops after it’s maximum value. Thus, there exists an optimum value for net work production with respect to the ammonia mass concentration, which occurs generally around at the ammonia concentration from 90% to 95%. This can be explained as follows. An increase in ammonia concentration leads to a decrease in the specific enthalpy drop across the turbine 1, but significant increase in the mass flow rate of ammonia-water mixture, so the net work increases when the ammonia concentration is not very high. However, when the ammonia concentration becomes high, the mass flow rate of ammonia-water mixture decreases, so the net work has a maximum value with respect to the ammonia concentration.

Fig. 5 shows the effects of ammonia mass concentration and condensing temperature on the thermal efficiency of the system, which is defined as the ratio of net work production of the combined system to the heat addition to the combined system. The thermal efficiency of the combined cycle increases with a decrease in the condensing temperature, since a lower condensing temperature leads to a lower net work and a lower heat addition, but the lowering in the net work is more significant than that in the heat addition. On the other hand, the thermal efficiency of the system has a maximum value with respect to the ammonia concentration for higher values of the condensing temperatures.

IV. CONCLUSIONS

In order to produce maximum power from the low temperature heat source in the form of sensible energy and cold energy of LNG, this paper investigates the thermodynamic performance of a combined power cycle consisted of a regenerative Rankine cycle with ammonia-water mixture as a working fluid and a LNG cycle. The main conclusions from the parametric study of the system are summarized as follows:

(1) The mass flow ratio of the ammonia-water mixture to the source fluid increases with the condensing temperature, however, has a maximum value with respect to the ammonia concentration at a high ammonia concentration.

(2) The amount of heat addition to the system per unit mass of source fluid increases with decrease in the condensing temperature. However, it has a peak value with respect to the ammonia concentration in the range of higher condensing temperature, but increases monotonically with the ammonia concentration.

(3) The net work production of the combined cycle, which is the sum of the net works of ammonia-water power cycle and the LNG cycle, increases with the decreasing condensing temperature, however, has a maximum value with respect to the ammonia concentration at from 90% to 95%.

(4) The thermal efficiency of the combined cycle decreases with increasing the condensing temperature and has a peak with respect to the ammonia concentration for higher condensing temperatures.

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