Performance Analysis of Ammonia-Water Power Generation Cycle Utilizing LNG Cold Energy

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***Abstract*—The power generation systems using ammonia–water mixture as working fluid are proven to be one of the feasible methods for utilizing low-grade heat sources. Since the liquefied natural gas (LNG) has a great cold energy, the performance of the power generation system can be improved if the cold energy of LNG is used as its heat sink. In this paper a comparative thermodynamic performance analysis is carried out for the combined power cycle consisted of an ammonia-water Rankine cycle with and without regeneration and a LNG power generation cycle. Based on the thermodynamic models of the combined cycle, the effects of the key parameters such as ammonia concentration and turbine inlet pressure on the system performance are extensively investigated. The results show that the thermodynamic performance of the combined power generation cycle is strongly dependent on the ammonia concentration and turbine inlet pressure.**

***Index Terms*—ammonia-water Rankine cycle, liquefied natural gas (LNG), cold energy, regeneration**

I. Introduction

Since the evaporation takes place as a variable temperature process, non-azeotropic mixture used as working fluid in power cycles has some thermodynamic advantages compared with pure working fluid. The power generation systems based on ammonia-water mixture are proven to be one of the feasible methods for the conversion of low-grade heat sources in the form of sensible energy into useful work. Other than that ammonia is relatively inexpensive, the use of ammonia in the binary mixture with water possesses several merits. Ammonia and water have the similar molecular weights and thus, traditional design of steam turbines can be used in the ammonia-water power cycles after some minor modifications. In addition, the boiling point of ammonia is substantially lower than that of water, which makes it practically useful to utilize the low-temperature waste heat in the power generation systems. Conventional steam cycles can be converted into the ammonia-water power cycles without severe changes [1]-[3].

Ibrahim [1] studied an ammonia-water Rankine cycle and found that the design of heat exchanger networks can have a significant impact on the performance of power cycles. Ibrahim and Klein [4] 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. Zamfirescu and Dincer [5] analyzed trilateral ammonia–water Rankine cycle that uses no boiler, but rather the saturated liquid is flashed by an expander. Roy *et al*. [6] studied ammonia-water Rankine cycle with finite size thermodynamics and their thermodynamic calculations were carried out in the context of reasonable temperature differences in the heat exchangers.

Wager *et al*. [7] analyzed the ammonia-water Rankine cycle using scroll expander. Kim *et al*. [8]-[9] studied the Rankine cycle using ammonia-water mixture as working fluid for use of low-temperature waste heat, and compared the regenerative Rankine cycle with the simple Rankine cycle. Kim *et al*. [10] 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 performance of the systems. They closely examined the temperature distributions of fluid streams in the heat exchanging devices at different levels of ammonia concentration.

It is recognized that liquefied natural gas (LNG) is one of the cleanest fossil fuels and is considered to be the most perspective energy source in forthcoming decades. The natural gas share in the global energy market shows a stable growing tendency. LNG has a high energy density around 600 times higher than that in gaseous form. Transportation of natural gas in its liquid form is also attractive for short time working boreholes, as is also the case with unconventional gas. The LNG share in overall natural gas turnover shows a stable growing tendency and is expected to exceed 25% soon. Due to this observed increase there is a strong interest in improving the economical balance of the whole LNG process chain [11]-[12].

Natural gas is widely used in many areas because of its better environmental characteristics. For the convenience of transport, natural gas is liquefied into the LNG by cryogenic refrigeration after removing 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 cleaner fuels,

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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 [13] thermodynamically studied power generation cycle utilizing the LNG cold energy. LNG was used as heat sink, and the power cycle consisted of the open and closed Rankine cycles, and the closed Brayton cycle. Miyazaki *et al*. [14] compared the conventional refuse incineration power cycle with combined power cycle using LNG cold energy. Shi and Che [15] proposed a combined system consisted of the Rankine cycle with ammonia-water mixture as working fluid and the LNG power generation cycle. Wang *et al*. [3] proposed an ammonia-water power system with LNG as its heat sink. Kim *et al*. [16] studied an ammonia-water regenerative Rankine cycle with LNG as its heat sink. Rao *et al*. [17] proposed a combined cycle, in which low-temperature solar energy and cold energy of LNG can be effectively utilized together.

This paper performs the comparative thermodynamic analyses for a combined power cycle consisted of an ammonia-water Rankine cycle with and without and a LNG cycle. It is considered that LNG is used to produce the some power output as well as to condense the ammonia-water mixture as a heat sink. The effects key system parameters such as ammonia concentration and turbine inlet pressure on the system performance are extensively investigated.

II. System Analysis

A combined power generation cycle consisted of an ammonia-water Rankine cycle with and without regeneration and a LNG cycle is considered. The system uses a low-temperature heat source in the form of sensible energy and uses LNG at a cryogenic temperature of -162oC, as shown in Fig. 1. In the ammonia-water Rankine cycle, the mixture is compressed through a pumping process in pump 1 from state 1 to sate 2, preheated by the heat of the turbine 1 outlet mixture in a regenerator to state 3, and heated with the source air in heat exchanger I to state 4. Then, it is expanded in turbine 1 from state 4 to state 5, cooled down while heating the mixture exiting the pump to state 6, and cooled down again by the heat exchange process with the LNG cycle in heat exchanger II back to state 1. In the LNG cycle, meanwhile, LNG of state 7 supplied from the reservoir is evaporated and pressurized in pump 2 from state 7 to sate 8. Later, LNG enters heat exchanger II and releases the cold energy in order to condense the ammonia-water mixture, and heated by the heat of the mixture to state 9. After that LNG enters turbine 2 and produces some work, finally reaches state 10.

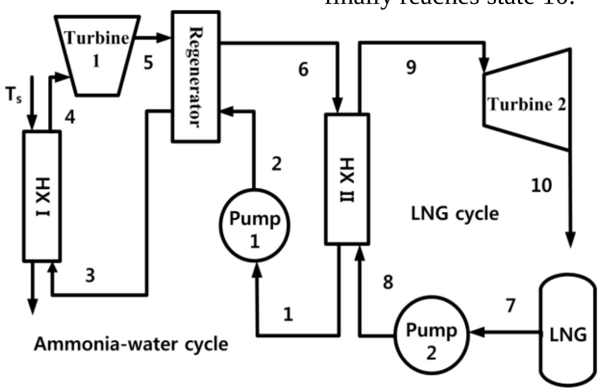

Figure 1. Schematic diagram of the system (with regeneration).

In this paper, the high-temperature heat source of the combined cycle is assumed to be a standard air with an inlet temperature of T_s. In addition, the heat loss except at the heat exchangers and the pressure variation except at the turbines and pumps are ignored. Isentropic efficiencies of pump and turbine are assumed to be constant and have values of η_{P1}, η_{P2}, η_{T1}, η_{T2}, respectively. The temperature difference between hot and cold fluids in the heat exchangers are maintained to be greater than a prescribed pinch point temperature difference ΔT_{pp}, while the minimum temperature difference in the regenerator is equal to ΔT_{pp}. The ammonia-water mixture is heated in heat exchanger I to a temperature lower than the source inlet temperature by ΔT_H.

In the case of producing power using the low-temperature heat sources in the form of sensible heat, it is desirable to produce the maximum power from the supplied heat source. Therefore, we assume that the system is driven under the condition of maximum flow rate of working fluid. In the system, when the inlet pressures of turbine 1 and 2 is P_H, P_{H2}, respectively and mass fraction of ammonia in the ammonia-water mixture is x_b, thermodynamic state of the fluid in each system element is determined from the equation of state, and the mass and energy balance equations.

In this paper, thermodynamic properties of liquid and vapor phase of the ammonia-water mixture are evaluated by using the excess Gibbs free energy G^E as [18];

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

Here, R is the universal gas constant, T is the absolute temperature, and 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. The equilibrium states of liquid and vapor phase are calculated using the approach of Kim *et al*. [10], given by

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

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

Here, μ is the chemical potential, N_a, N_w, and N are numbers of moles of ammonia, water, and the mixture, respectively. Superscripts l and g denote the liquid and gas phase, respectively. The Gibbs free energy of G_m for liquid or gas phase is written as

$$G_m = N_a[G_a + RT\ln x] + N_w[G_w + RT\ln(1-x)] + NG^E \tag{4}$$

Finally, for the analysis of LNG cold energy cycle, LNG is assumed to be pure methane, and its thermodynamic properties are evaluated by using the Patel-Teja equation of state [19]-[20]:

$$P = \frac{RT}{v-b} - \frac{a(T)}{v(v+b)+c(v-b)} \tag{5}$$

$$a(T) = \Omega_a\left(\frac{R^2T_c^2}{P_c}\right)\alpha(T) \tag{6}$$

$$b = \Omega_b\left(\frac{RT_c}{P_c}\right) \tag{7}$$

$$c = \Omega_c\left(\frac{RT_c}{P_c}\right) \tag{8}$$

III. Results and Discussions

In this paper the combined system without regeneration (simple case) and with regeneration (regeneration case) are comparatively investigated. The ammonia concentration, x_b, and turbine inlet pressure of ammonia-water cycle, P_H, are used as the key system parameters and the system performance is investigated for varying values of these parameters. Other basic data of the system variables are as follows: T_s = 200℃, ΔT_H = 20℃, T_c = 5℃, ΔT_{pp} = 10℃, P_{H2} = 30bar, P_{L2} = 4bar, $\eta_{p1} = \eta_{p2}$ = 0.70, $\eta_{t1} = \eta_{t2}$ = 0.80, q_t = 0.90, respectively.

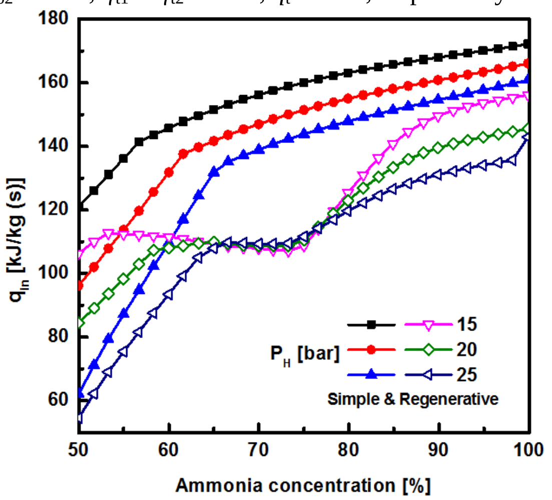

Figure 2. Effect of ammonia concentration on heat addition per unit mass of source for various turbine inlet pressures.

The effect of ammonia concentration and turbine inlet pressure on the amount of heat addition to the system per unit mass of source fluid is shown in Fig. 2. Heat addition is equal to the product of the mass flow rate of working fluid and the enthalpy difference between inlet and outlet of heat exchanger 1. In the simple case the heat addition increases with increasing ammonia concentration and decreases with the turbine inlet pressure, which is mainly due to increasing of mass flow rate of the mixture in the heat exchanger I. In the regeneration case, however, as ammonia concentration increases, the heat addition increases first, and then its increasing rate is reduced or decreases, and increases again, which is mainly due to the behavior of heat transfer of regeneration.

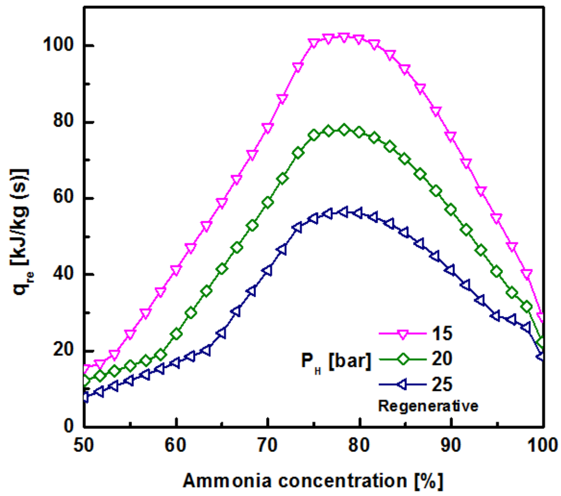

Figure 3. Effect of ammonia concentration on heat transfer of regeneration per unit mass of source for various turbine inlet pressures.

Fig. 3 shows the effect of ammonia concentration and turbine inlet pressure on the heat transfer of regeneration per unit mass of source fluid. The regeneration has a peak value with respect to ammonia concentration for each turbine inlet pressure. However, it decreases with the increase of turbine inlet pressure.

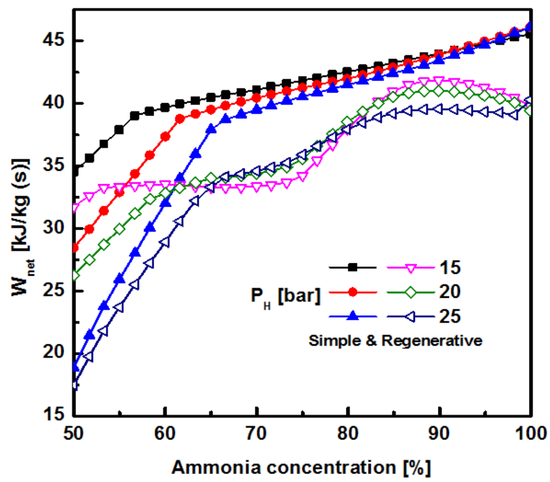

Figure 4. Effect of ammonia concentration on net work per unit mass of source for various turbine inlet pressures.

The effect of ammonia concentration and turbine inlet pressure on the net work production per unit mass of source fluid is shown in Fig. 4. The net work production is equal to the difference between the heat added to the system and heat discharged from the system. In the simple case the net work increases with increasing ammonia concentration and is larger for lower turbine inlet pressures. In the regeneration case, there exists a local maximum value with respect to ammonia concentration.

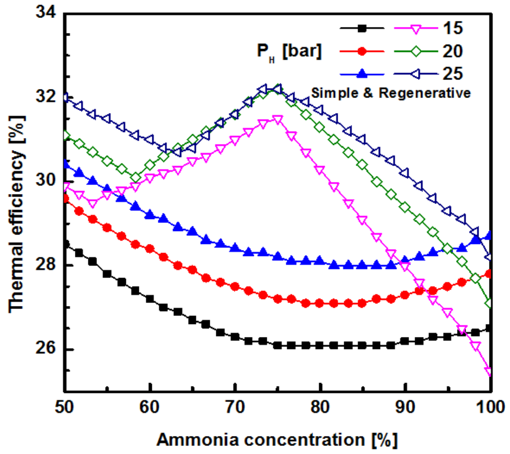

Figure 5. Effect of ammonia concentration on thermal efficiency for various turbine inlet pressures.

Fig. 5 shows the effect of ammonia concentration and turbine inlet pressure on the thermal efficiency of the system. Here, the thermal efficiency of the combined cycle is defined as the ratio of net work production to the heat addition to the system. As ammonia concentration increases in the simple case, it decreases first and reaches a minimum value and the increases again. As ammonia concentration increases in the regeneration case, it decreases first and then increases to a local maximum value and then decreases again. For fixed ammonia concentrations, both the simple and regeneration case with higher turbine inlet pressure yield higher thermal efficiency.

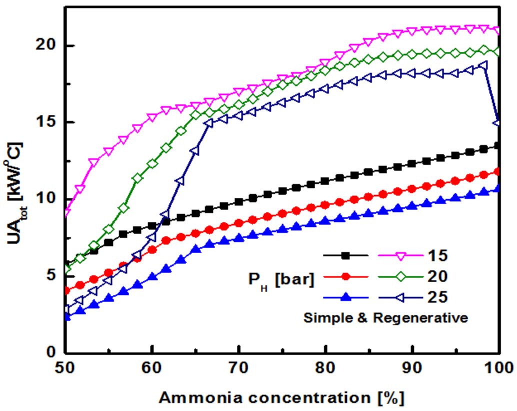

Figure 6. Effect of ammonia concentration on the total thermal conductance for various turbine inlet pressures.

The effect of ammonia concentration and turbine inlet pressure on the total thermal conductance, UA_{tot}, is shown in Fig. 6. The total conductance of the combined system is the sum of the thermal conductance of heat exchangers in the system. The total thermal conductance increases with increasing ammonia concentration and decreases with increasing turbine inlet pressure. For the values of turbine inlet pressure and for a range of ammonia concentration considered the total thermal conductance of regeneration cycle is higher than that of simple cycle.

IV. CONCLUSIONS

In this paper the comparative performance analysis is carried out for the combined cycle of ammonia-water power generation cycle with and without regeneration and a LNG cycle. The main results can be summarized as follows:

- The heat transfer of regeneration has peak values with respect to ammonia concentration.
- The net work of the combined cycle increases with ammonia concentration in simple case, but there exists a peak value in regeneration case.
- There exists a minimum thermal efficiency with ammonia concentration in simple case but a maximum one in regeneration case.
- The total thermal conductance increases with ammonia concentration and decreases with turbine inlet pressure.

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REFERENCES

[1] O. M. Ibrahim, “Design considerations for ammonia-water rankine cycle,” *Energy*, vol. 21, pp. 835-841, 1996.
[2] K. H. Kim, H. J. Ko, and K. Kim, “Assessment of pinch point characteristics in heat exchangers and condensers of ammonia–water based power cycles,” *Applied Energy*, vol. 113, pp. 970-981, 2014.
[3] J. Wang, Z. Yan, M. Wang, and Y. Dai, “Thermodynamic analysis and optimization of an ammonia-water power system with LNG (liquefied natural gas) as its heat sink,” *Energy*, vol. 50, pp. 513-522, 2013.
[4] O. M. Ibrahim and S. A. Klein, “Thermodynamic performance assessment of an ammonia–water rankine cycle for power and heat production,” *Energy Conversion and Management*, vol. 51, pp. 2501-2509, 2010.
[5] C. Zamfirescu and I. Dincer, “Thermodynamic analysis of a novel ammonia-water trilateral Rankine cycle,” *Thermochim. Acta*, vol. 477, pp. 7-15, 2008.
[6] P. Roy, M. Désilets, N. Galanis, H. Nesreddine, and E. Cayer, “Thermodynamic analysis of a power cycle using a low-temperature source and a binary NH_3–H_2O mixture as working fluid,” *Int. J. Therm. Sci.*, vol. 49, pp. 48-58, 2010.
[7] W. R. Wager, C. Zamfirescu, and I. Dincer, “Absorption power cycle,” *Energy*, vol. 21, pp. 21-27, 1996.
[8] K. H. Kim, S. W. Kim, and H. J. Ko, “Study on the Rankine cycle using ammonia-water mixture as working fluid for use of low-temperature waste heat,” *Trans. of the Korean Hydrogen and New Energy Society*, vol. 21, pp. 570-579, 2010.
[9] K. H. Kim, C. H. Han, and K. Kim, “Comparative exergy analysis of ammonia-water based rankine cycles with and without regeneration,” *Int. J. Exergy*, vol. 12, pp. 344-361, 2013.
[10] K. H. Kim, C. H. Han, and K. Kim, “Effects of ammonia concentration on the thermodynamic performances of ammonia–water based power cycles,” *Thermochimica Acta*, vol. 530, pp. 7-16, 2012.
[11] International Energy Agency, “Golden rules for a golden age of gas,” World energy outlook special report on unconventional gas, November 2012.
[12] E. A. Roszak and M. Chorowski, “Exergy analysis of combined simultaneous liquid natural gas vaporization and adsorbed natural gas cooling,” *Fuel*, vol. 111, pp. 755-762, 2013.

[13] K. I. Choi and H. M. Chang, "Thermodynamic analysis of power generation cycle utilizing LNG cold energy," *Superconductivity and Cryogenics*, vol. 1, pp. 48-55, 1999.
[14] T. Myazaki, Y. T. Kang, A. Akisawa, and T. Kashiwagi, "A combined power cycle using refuse incineration and LNG cold energy," *Energy*, vol. 25, pp. 639-655, 2000.
[15] X. Shi and D. Che, "A combined power cycle utilizing low-temperature waste heat and LNG cold energy," *Energy Conversion and Management*, vol. 50, pp. 567-575, 2009.
[16] K. H. Kim, J. H. Oh, and S. W. Kim, "Analysis of regenerative power cycle utilizing low-grade heat source and LNG cold energy," *Int. J. Mining, Metallurgy Mech. Eng.*, vol. 1, pp. 291-295, 2013.
[17] W. J. Rao, L. J. Zhao, C. Liu, and M. G. Zhang, "A combined cycle utilizing LNG and low-temperature solar energy," *App. Therm. Eng.*, vol. 60, pp. 51-60, 2013.
[18] F. Xu and D. Y. Goswami, "Thermodynamic properties of ammonia-water mixtures for power cycle," *Energy*, vol. 24, pp. 525-536, 1999.
[19] K. H. Kim and C. H. Han, "Analysis of transcritical organic rankine cycles for low-grade heat conversion," *Advanced Science Letters*, vol. 8, pp. 216-221, 2012.
[20] T. Yang, G. J. Chen, and T. M. Guo, "Extension of the wong-sandler mixing rule to the three-parameter patel-teja equation of state: Application up to the near-critical region," *Chemical Engineering Journal*, vol. 67, pp. 27-36, 1997.

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