THE RMODYNAMIC ASSESSMENT OF REGENERATIVE ORGANIC AND AMMONIA-WATER RANKINE CYCLES

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Abstract - For recent decades the organic Rankine cycle and the ammonia-water based power generating system have attracted much attention as they are proven to be the most feasible methods in converting the low-grade thermal energy to useful forms of energy.In this paper thermodynamicperformance analysis is carried out for regenerative organic Rankine cycle (ORCR) and ammonia-water based regenerative Rankine cycle (AWRCR). Effects of the system parameters such as working fluid, turbine inlet pressure, and mass fraction of ammonia on the system performance are systemically investigated. Results show that AWRCR does not show higher thermal efficiency than ORCR, however, shows lower volumetric flow rate of working fluid than ORCR.

Index Terms - Organic Rankine cycle, Ammonia-Water Rankine Cycle, Regeneration, Low-Grade Heat Source.

I. INTRODUCTION

Since the conventional power generation system becomes inefficient and economically infeasible as the temperature of source decreases, efficient conversion of low-grade heat sources into electrical power and low-temperature energy conversion has become more and more important [1]-[3]. For recent decades the organic Rankine cycle (ORC)and the power generating system using binary mixture as a workingfluid have attracted much attention as they are proven to be themost feasible methods to achieve high efficiency in converting thelow-grade thermal energy to more useful forms of energy [4].

The ORC is a Rankine cycle where an organic fluid is used instead of water as the working fluid. The selection of working fluid matching with the available heat source is essential to its successful conversion into useful energy. ORC has many advantages such as adaptability to various heat sources, proven mature technology, lesser complexity and lesser maintenance, possibility of small scales, distributed generation systems, low investments, good market availability, and well-known market suppliers. Therefore, ORC has become a field of intense research in recent years [5]-[8].

Hung *et al.* [9] conducted examinations of Rankine cycles using organic fluids which are categorized into three groups of wet, dry and isentropic fluids. Heberle and Brueggemann [10] performed an analysis of a combined heat and power generation for geothermal resources with series and parallel circuits of an ORC. Dai *et al.* [11] reported isobutane and R236ea as efficient working fluids by using a generic optimization algorithm. Tchanche*et al.* [12] carried out a comparative performance analysis of solar organic Rankine cycle using various working fluids. Kim and Perez-Blanco [13] presented a thermodynamic analysis of cogeneration of power and refrigeration based on ORC activated by low-grade sensible energy. Gao et al. [14] performed an analysis of a supercritical organic Rankine cycle system driven by exhaust heat using 18 organic working fluids.

To use of an ammonia-water mixture instead of water as working fluid is a possible way to improve efficiency of the system. A major advantage for using mixtures as a working fluid inthe power generation systems instead of pure working fluids isthat heat can be supplied or rejected at variable temperaturebut still at constant pressure, since the boiling temperature nowvaries during the phase change and the binary mixture evaporatesover a wide range of temperature. The variable-temperature heattransfer process alleviates the temperature mismatch between hotand cold streams in heat exchanging components of the system,which then reduces the exergy destruction in the power cycles[15]-[16].

Zamfirescu and Dincer [17] analyzed the trilateral ammonia-waterRankine cycle, which does not use a boiler but rather a saturatedliquid is flashed by an expander.Roy et al. [18] studied ammonia–water Rankine cycle with finite size thermodynamics and their thermodynamic calculations were carried out in thecontext of reasonable temperature differences in the heat exchangers. Wagner et al. [19] performed a thermodynamic performance analysis of ammonia-water Rankine cycle for renewable-based power and heatproduction. They point out that each cycle must be optimized based upon several parameters due tothe non-linearity of the working fluid's behavior. Kim et al. [4] investigate the effects of ammoniamass concentration on the thermodynamic performance of ammonia-water Rankine and regenerativeRankine cycles for use of low grade heat source. Kim and Kim [20] conducted a 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 withoutregeneration and a LNG Rankine cycle.

In this work a thermodynamic performance analysis is carried out for a regenerative organic Rankine cycle and a regenerative ammonia-water Rankine cycle for recovery of low-grade heat source. Special attention is focused on the effects of variation of working fluid, turbine inlet pressure, and ammonia mass fraction on the system performance.

II. SYSTEM ANALYSIS

The system considered in this work consists of condenser,pump, turbine, regenerator, pre-heater, boiler, and super-heaterand its schematic diagram is shown in Fig. 1.The schematic diagram of the system is illustrated in Fig. 1. At point 1, the fluid is saturated liquid at T_L and the corresponding saturated pressure P_L is the low pressure of the system. When the evaporating temperature is T_E, the corresponding saturation pressure P_H is the high pressure of the system. The thermodynamic properties at point 4 are determined with the temperature T_H and the pressure P_H. The thermodynamic properties at points 2 and 5 are determined with the isentropic efficiencies of pump and turbine, η_p and η_t, respectively.

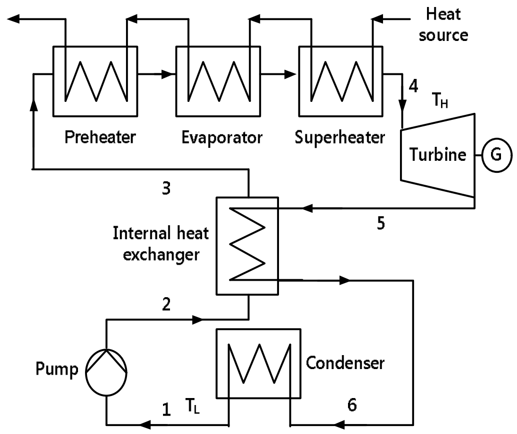

Fig. 1 Schematic diagram of ORC and condenser

In this work it is considered that a low-grade sensible energy is supplied to the system and turbine inlet pressure is lower than the critical pressure of the working fluid so the cycle is subcritical. Important assumptions used in this work are as follows.The working fluid leaves the condenser as saturated liquid at temperature of T_L.The minimum temperature difference between the hot and cold streams in the regenerator is operated at a prescribed pinch point, ΔT_{PP}.Pressure drop and heat loss of the systems are negligible.

Then heat input rate Q_{in}, heat rejection rate Q_{out}, net power W_{net}, and thermal efficiency η_{th} are be obtained as follows:

$$Q_{in} = m_3(h_4 - h_3) \quad (1)$$

$$Q_{out} = m_6(h_6 - h_1) \quad (2)$$

$$W_{net} = Q_{in} - Q_{out} \quad (3)$$

$$\eta_{th} = W_{net} / Q_{in} \quad (4)$$

where h denotes the specific enthalpy, m the mass flow rate at each position.

The thermodynamic properties of ammonia-water mixture are computed using the method of Gibbs free energy which was first introduced by Xu and Goswami [21]. However, in this work, the equilibrium conditions are determined by equating the chemical potentials of each phase for each element [22].

$$\mu_a^L = \left(\frac{\partial G_m^L}{\partial N_a}\right)_{T,P,N_w} = \left(\frac{\partial G_m^g}{\partial N_a}\right)_{T,P,N_w} = \mu_a^g \quad (5)$$

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

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

$$G_m = N_a\left[G_a + RT\ln x\right] + N_w\left[G_w + RT\ln(1-x)\right] + NG^E \quad (7)$$

When considering the condensing property at low temperatures and thermal stability at high temperatures in ORCR, four fluids, R600a, R134a, R245fa, and R123 were selected. In this study, the thermodynamic properties of the working fluids were evaluated by the Patel-Teja equation of state using MathCAD programming [23]-[24].

$$P = \frac{RT}{v-b} - \frac{a(T)}{v(v+b)+c(v-b)} \quad (8)$$

$$a(T) = \Omega_a\left(\frac{R^2T_c^2}{P_c}\right)\alpha(T) \quad (9)$$

$$b = \Omega_b\left(\frac{RT_c}{P_c}\right) \quad (10)$$

$$c = \Omega_c\left(\frac{RT_c}{P_c}\right) \quad (11)$$

III. RESULTS AND DISCUSSIONS

In this paper it is considered that the source is water with 1 kg/s. The basic operation data use for the simulation of this study are as follows; source temperature, T_S = 200°C, turbine inlet temperature, T_H = 185°C, condensation temperature, T_L = 30°C, coolant temperature, T_C = 15°C, turbine inlet pressure, P_H = 15 bar, pinch temperature difference, ΔT_{pp} = 8°C, isentropic efficiencies of pump and turbine, η_p = 0.80 and η_t = 0.85.The basic ammonia mass fractions are considered as x_b = 50%, 60%, 70%, and 80%.

Figure 2 displays the effects of turbine inlet pressure on the mass flow rate of the working fluid. In ORCR, the mass flow rate of working fluid decreases with increasing turbine inlet pressure, however, the decreasing rate becomes lowered when the turbine inlet pressure is high. It is because as the turbine inlet pressure increases, the evaporation temperature increases, which leads to increase the source exit temperature and consequently to increase the mass flow rate of the working fluid. For a specified turbine inlet pressure, the mass flow rate is the highest when the working fluid is R134a and the lowest when the working fluid is R600a. In AWRCR, the mass flow rate of working fluid decreases as the turbine inlet pressure increases or the mass fraction of ammonia decreases. It can be seen from the figure that the mass flow rates in ORCR are higher than those in AWRCR.

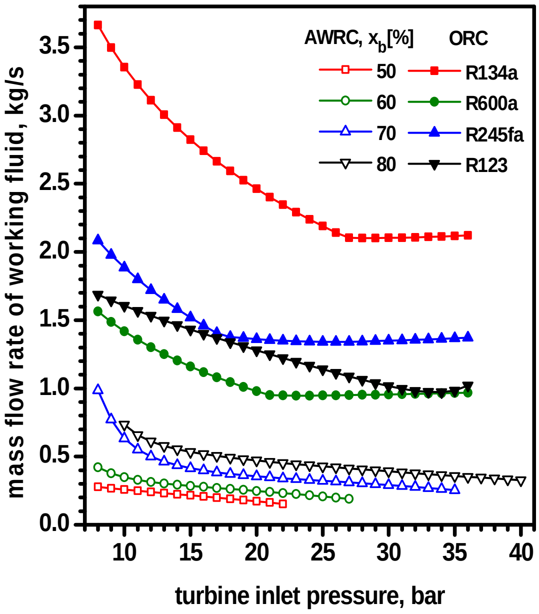

Fig. 2 Effects of turbine inlet pressure on the mass flow rate of working fluid.

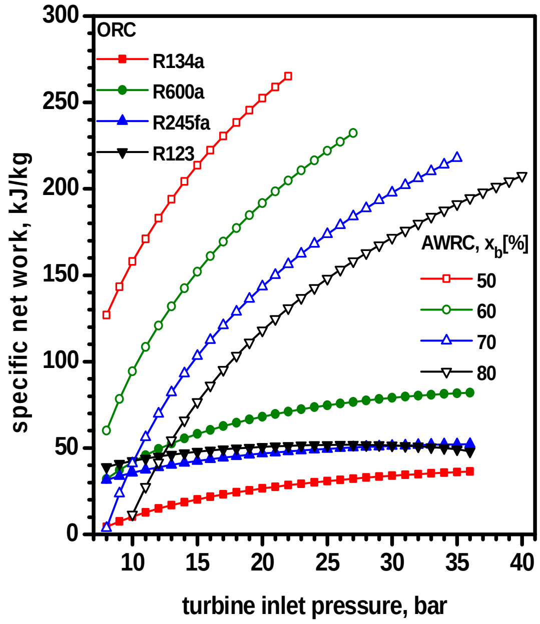

Fig. 3 Effects of turbine inlet pressure on the specific net work.

Figure 3illustrates the effects of turbine inlet pressure on the specific net work which is defined as the net work of the system per unit mass of the working fluid. In ORCR, the specific net work increases with increasing turbine inlet pressure, since as the turbine inlet pressure increases, the pressure ratio of the turbine increases, which leads to larger expansion across the turbine. For a specified turbine inlet pressure, the specific net work decreases as the critical temperature of the working fluid increases. In AWRCR, the specific net work increases also as the turbine inlet pressure increases due to higher pressure ratio of the turbine. It can be seen from the figure that there exists an optimum ammonia mass fraction for the maximum specific net work.

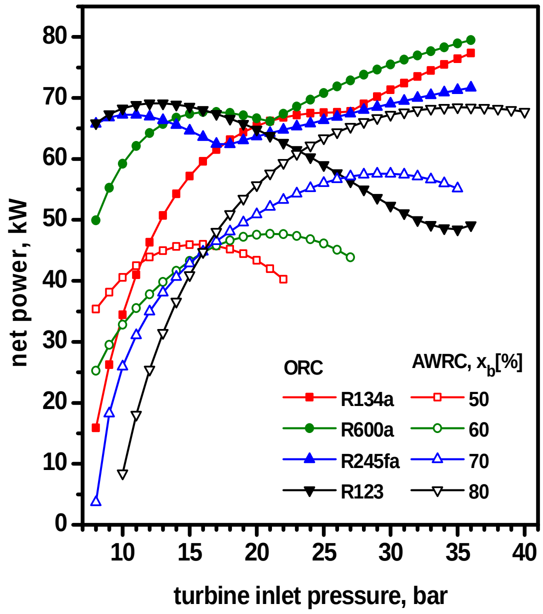

Fig. 4Effects of turbine inlet pressure on the net power production.

Figure 4shows the effects of turbine inlet pressure on the net power production of the system which is obtained as the product of the mass flow rate of the working fluid and the specific net work. In ORCR, the net power production increases with increasing turbine pressure for R134a and R600a, however, exhibits a peak with respect to turbine inlet pressure for R245fa and R123. It is because the mass flow rate of working fluid decreases but the specific net work increases as the turbine inlet pressure increases. In AWRCR, the net power production has a peak value with respect to the turbine inlet pressure. It can be seen from the figure that both the maximum net power and the optimum turbine inlet pressure increase as the mass fraction of ammonia increases.

Figure 5displays the effects of turbine inlet pressure on the heat input rate of the system which is obtained as the product of the mass flow rate of the working fluid and the specific heat input at the heat exchangers. In ORCR, as the turbine inlet pressure increases, the heat input rate firstly decreases for low turbine inlet pressures, and reaches a local minimum value, and then increases again for high turbine inlet pressures, thus it has a local minimum value with respect to the turbine inlet pressure. For a specified turbine inlet pressure, the heat input rate decreases as the critical temperature of the working fluid increases. Therefore, the heat input rate is the highest for R134a and the lowest for R123. In AWRCR, as the turbine inlet pressure increases, the heat input rate firstly increases for low turbine inlet pressures, and reaches a local maximum value, and then decreases again for high turbine inlet pressures. Therefore, it has a local maximum value with respect to the turbine inlet pressure. For a specified turbine inlet pressure, the heat input rate is the highest for 80% mass fraction of ammonia, and the lowest for 70% mass fraction of ammonia when the turbine inlet pressure is low but for 60% mass fraction of ammonia when the turbine inlet pressure is high.

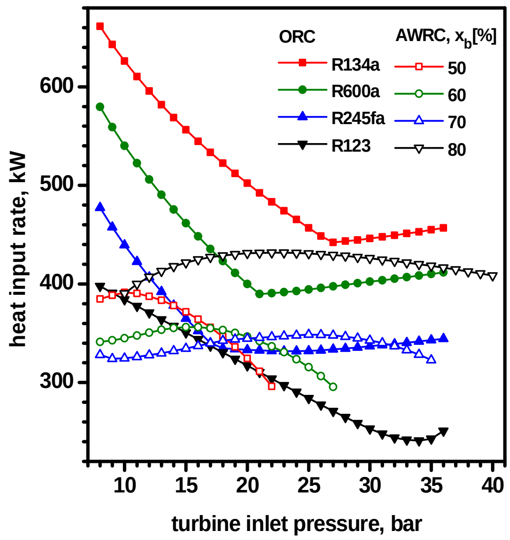

Fig. 5Effects of turbine inlet pressure on the heat input rate.

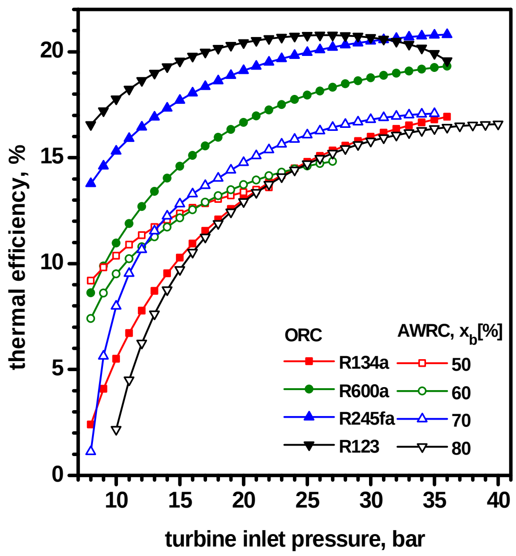

Fig. 6 Effects of turbine inlet pressure on the thermal efficiency.

Figure 6illustrates the effects of turbine inlet pressure on the thermal efficiency of the system which is defined as the ratio of the net power production to the heat input rate of the system. In ORCR, the thermal efficiency increases with increasing turbine inlet pressure for R134a, R600a, and R245fa, however, exhibits a peak with respect to turbine inlet pressure for R123. For a specified turbine inlet pressure, the thermal efficiency increases with increasing critical temperature of the working fluid, so it is the lowest for R134a and the highest for R123. In AWRCR, the thermal efficiency increases with increasing turbine inlet pressure. It can be seen from the figure that for a specified turbine inlet pressure, the thermal efficiency is the highest for 70% mass fraction of ammonia and the lowest for 80% mass fraction of ammonia.

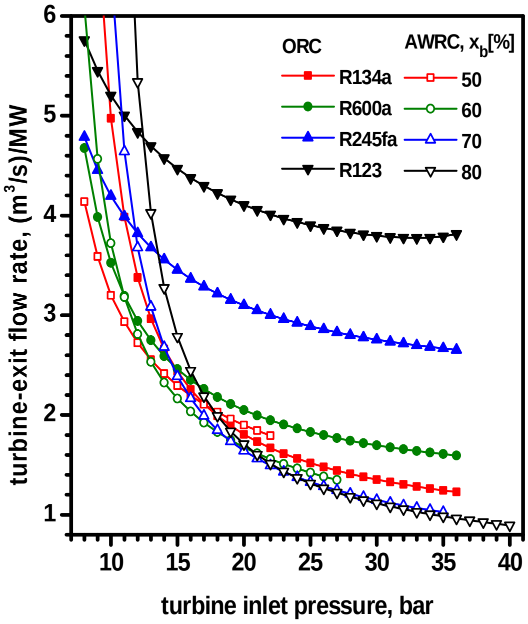

Fig. 7 Effects of turbine inlet pressure on the turbine-exit flow rate.

Figure 7shows the effects of turbine inlet pressure on the specific turbine-exit volume flow rate which is obtained as the ratio of the volume flow rate of working fluid at the turbine exit to the net power production of the system. In ORCR, the specific flow rate decreases with increasing turbine inlet pressure. For a specified turbine inlet pressure, it increases with increasing critical temperature of the working fluid, so it is the lowest for R134a and the highest for R123. In AWRCR, the specific flow rate decreases with increasing turbine inlet pressure. For a specified turbine inlet pressure, the specific flow rate increases with ammonia mass fraction for low turbine inlet pressure but decreases with increasing ammonia mass fraction for high turbine inlet pressures. It can be seen from the figure that the specific flow rate in AWRCR is lower than that in ORCR. The specific flow rate is related with the cost of the turbine, therefore, the turbine size in AWRCR can be smaller than that in ORCR for a same power production of the system.

CONCLUSIONS

This paper presented a thermodynamic performance analysis for regenerative organic Rankine cycle (ORCR) and ammonia-water based regenerative Rankine cycle (AWRCR). Parametric analysis is carried out to investigate the effects of several system parameters such as working fluid, turbine inlet pressure, and mass fraction of ammonia,on the system performance. Main results are as follows.

In ORCR, the thermal efficiency increases with increasing turbine inlet pressure or exhibits a peak with respect to turbine inlet pressure, which depends on the working fluid. In AWRCR, the thermal efficiency increases with increasing turbine inlet pressure. For a specified turbine inlet pressure, the thermal efficiency in AWRCR is lower than that in ORCR. However, the turbine-exit flow rate in AWRCR is lower than that in ORCR for a same power production of the system, which indicates that the turbine size in AWRCR can be smaller than that in ORCR for a same power production of the system.

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REFERENCES

[1] M. Aguirre, and G. Ibikunle, “Determinants of renewable energy growth: A global sample analysis,” Energy Policy, vol. 69, pp. 374-384, 2014.
[2] F. Sun, W. Zhou, Y. Ikegami, K. Nakagami, and X. Su, “Energy-exergy analysis and optimization of the solar-boosted Kalina cycle of the solar-boosted Kalina cycle system 11 (KCS-11),” Renewable Energy, vol. 66, pp. 268-279, 2014.
[3] 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.
[4] K. H. Kim, C. H. Han, and K. Kim, “Effects of ammonia concentration on the thermodynamic performances ofammonia–water based power cycles,”ThermochimicaActa, vol. 530, pp. 7-16, 2012.
[5] T. Lu, and K. S. Wang, “Analysis and optimization of a cascading power cycle with liquefied natural gas (LNG) cold energy recovery,” Appl. Therm. Eng., vol. 29, pp. 1478-1484, 2009.
[6] X. Shi, and D. Che, “A combined power cycle utilizing low-temperature waste heat and LNG cold energy,” Energy, vol. 50, pp. 567-575, 2009.
[7] H. Wang, X. Shi, and D. Che, “Thermodynamic optimization of the operating parameters for a combined power cycle utilizing low-temperature waste heat and LNG cold energy,” Appl. Therm. Eng., vol. 59, pp. 490-497, 2013.
[8] J. Wang, Z. Yan, and M. Wang, “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.
[9] T.C. Hung, S.K. Wang, C.H. Kuo, B.S. Pei, and K.F. Tsai, “A study of organic workingfluids on system efficiency of an ORC using low-grade energy sources,” Energy, vol.35, pp. 1403-1411, 2010.
[10] F. Heberle and D. Brueggemann, “Exergy based fluid selection for a geothermalorganic Rankine cycle for combined heat and power generation,” Appl. Therm.Eng., vol. 30, pp. 1326-1332, 2010.
[11] Y. Dai, J. Wang, and L. Gao, “Parametric optimization and comparative study oforganic Rankine cycle (ORC) for low grade waste heat recovery,” EnergyConvers. Manag., vol. 50, pp. 576-582.
[12] B.F. Tranche, G. Papadakis, G. Lambrinos, and A. Frangoudakis, “Fluid selection for alow-temperature solar organic Rankine cycle,” Appl. Therm. Eng., vol. 29, pp. 2468-2476, 2009.
[13] K. H. Kim, and H. Perez-Blanco, “Performance analysis of a combined organic Rankine cycle and vaporcompression cycle for power and refrigeration cogeneration,” Appl. Therm. Eng., vol. 91, pp. 964-974, 2015.
[14] H. Gao, C. Liu, C. He, X. Xu, S. Wu, and Y. Li, “Performance analysis andworking fluid selection of a supercritical organic Rankine cycle for lowgrade waste heat recovery,” Energies, vol. 5, pp. 3233-3247, 2012.
[15] V.A. Prisyazhniuk, “Alternative Trends in Development of Thermal Power Plants,” Appl. Therm. Eng., vol. 28, pp. 190-194, 2008.
[16] S. Ogriseck, “Integration of Kalina Cycle in a Combined Heat and Power Plant, a Case Study,” App. Therm. Eng., vol. 29, pp. 2843-2848, 2009
[17] C. Zamfirescu, and I. Dincer, “Thermodynamic Analysis of a novel ammonia-water trilateral Rankine Cycle,” ThermochimicaActa, vol. 477, pp. 7-15, 2008.
[18] P. Roy, M. Desilets, N. Galanis, H. Nesreddine, and E. Cayer, “Thermodynamicanalysis of a power cycle using a low-temperature source and a binary NH3-H2O mixture as working fluid,” Int. J. Therm. Sci., vol. 49, pp. 48-58, 2010.
[19] W.R. Wagar, C. Zamfirescu, and I. Dincer, “Thermodynamic performance assessmentof an ammonia-water Rankine cycle for power and heat production,”Energy Convers. Manag., vol. 51, pp. 2501-2509, 2010.
[20] K. H. Kim and K. C. Kim, “Thermodynamic performance analysis of a combined power cycleusing low grade heat source and LNG cold energy,” Appl. Therm. Eng., vol. 70, pp. 50-60, 2014.
[21] F. Xu, and D.Y. Goswami, “Thermodynamic properties of Ammonia-Water Mixtures for Power-Cycle Applications,” Energy, vol. 24, pp. 525-536, 1999.
[22] J.M. Smith, H.C. Van Ness, and M.M. Abbott, “Introduction to Chemical Engineering Thermodynamics,” 7th Ed. McGraw-Hill, 2005.
[23] T. Yang, G. J. Chen, and T. M. Gou, “Extensionof the Wong-Sandler mixing rule to the threeparameterPatel-Teja equation of state: Applicationup to the near-critical region,” Chem. Eng. J., vol. 67, pp. 27-36, 1997.
[24] J. Gao, L. D. Li, S. G. Ru, “Vapor-liquid equilibriacalculation for asymmetric systems using Patel-Tejaequation of state with a new mixing rule,” FluidPhase Equilibrium, vol. 224, pp. 213-219, 2004.

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