COMPARATIVE THERMODYNAMIC PERFORMANCE ANALYSIS OF KALINA AND ORGANIC RANKINE CYCLES

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Abstract - The Kalina and organic Rankine cycles have been considered as the alternatives to the conventional Rankine cycle to be used as a bottoming cycle for combined cycle power plant. In this paper thermodynamic performance assessment is carried out for Kalina cycle system (KCS) and organic Rankine cycle (ORC) for recovery of low-grade heat sources. Effects of the working fluid, turbine inlet pressure, and mass fraction of ammonia on the system performance are systemically investigated. Results show that for a specified source fluid, KCS does not show higher net power production but higher thermal efficiency than ORC.

Index Terms - Organic Rankine cycle (ORC), Kalina cycle system(KCS), ammonia-water mixture, low-grade heat source.

I. INTRODUCTION

For recent years the organic Rankine cycle (ORC) and the power generating system using binary mixture as a working fluid have been considered as the most feasible methods to achieve high efficiency in converting the low-grade thermal energy to more useful forms of energy [1]-[4]. The ORC is a Rankine cycle where an organic fluid is used instead of water as the working fluid. The ORC has many advantages and has become a field of intense research in recent years [5]-[8]. System efficiency can be optimized by selecting a proper working fluid operated at suitable working conditions. In terms of disadvantages, dry fluids in general generate superheated vapor at the turbine exit, and this reduces the area of net work in the T-s diagram [9]. The efficiency and economy of a binary geothermal power plant can be significantly improved by combined heat and power generation. The choice of a suitable working fluid is crucial in the case of power generation but the selected criteria differ fundamentally from each other [10]. Thermodynamic characteristics and performances of different fluids have been analyzed for selection as working fluids in a low-temperature ORC and several criteria have been used for comparison [11]-[13].

A major advantage for using mixtures as a working fluid in the power generation systems instead of pure working fluids is the variable-temperature heat transfer process which can alleviate the temperature mismatch between hot and cold streams in heat exchanging components of the system and then reduce the exergy destruction in the power cycles [14]-[16]. The Rankine power cycle using an ammonia-water mixture as working fluid can operate with considerably high exergetic efficiencies even if the source considered is a low temperature, low exergy one [17]. Due to the nature of the ammonia–water mixture, changes in its concentration allow thermodynamic cycles to adapt to fluctuations in renewable energy sources, which is an important advantage with respect to other working fluids. The non-linearity of the working fluid's behavior imposes that each cycle must be optimized based upon several parameters [18].

A combined cycle consisted of an ammonia-water Rankine cycle and a LNG Rankine cycle has been suggested for efficient recovery of low grade heat source and LNG cold energy. The net work of the LNG power cycle is comparable to the ammonia-water power cycle, so the performance of the power generation system can be improved by the power generation in the LNG cycle as well as by the use of LNG cold energy as a heat sink [19]. The Kalina cycle was introduced in 1984 as an alternative to the conventional Rankine cycle. It uses a zeotropic mixture of ammonia and water as its working fluid, instead of pure water. The composition of the ammonia-water mixture could be varied by changing the ammonia mass fraction which is defined as the ratio of the mass of ammonia in the mixture to the total mass of the mixture. Since its introduction, several uses for the Kalina cycle have been proposed such as in a geothermal power plant, for waste heat recovery, in solar power plants, etc. [20].

The main purpose of this work is to analyze a comparative thermodynamic performance analysis for a Kalina cycle of KCS-11 and an organic Rankine cycle for recovery of low-grade heat source. Effects of the working fluid, turbine inlet pressure, and ammonia mass fraction on the system performance are parametrically investigated.

II. SYSTEM ANALYSIS

The schematic diagram of the ORC (a) and (b) KCS are illustrated in Fig. 1. The ORC system considered consists of a heat exchanger, turbine, condenser and pump, while the KCS considered consists of an

evaporator, separator, turbine, throttle valve, condenser, pump, and regenerator. In ORC, the fluid comes out the condenser as a saturated liquid at temperature T_L (state 1) and is pressurized to the turbine inlet pressure P_H (state 2). After the fluid is heated with the source fluid in the heat exchanger to the turbine inlet temperature T_H (state 3), enters the turbine and comes out the turbine after producing a mechanical work during expansion (state 4) and enters the condenser. In KCS, the working fluid used is ammonia-water mixture which is zeotropic. The fluid is partially evaporated in the evaporator (state 4) and is separated in the separator into a pure vapor (state 5) and a pure liquid (state 7).

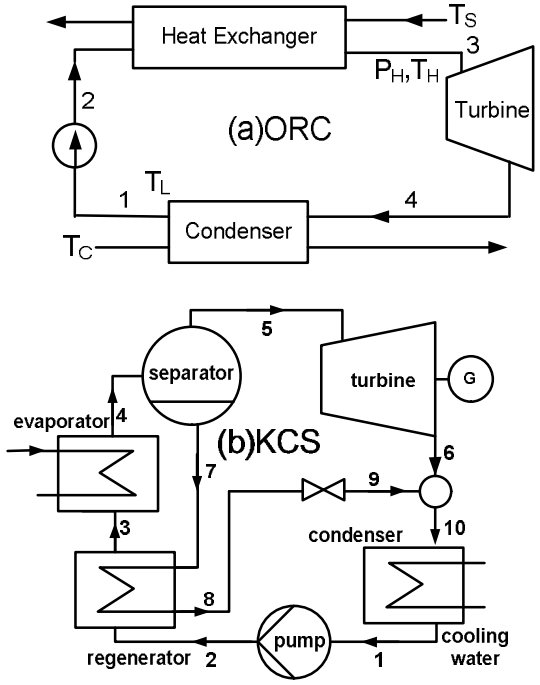


Fig. 1. Schematic diagram of the (a) ORC and (b) KCS.

In this work it is assumed as follows [21]:

1) The flow is steady and all components are well insulated.

2) The fluid is a pure vapor at the turbine inlet.

3) The isentropic efficiencies of the pump and turbine are constant.

4) The turbine inlet pressure is lower than the critical pressure of the working fluid, so the cycle is a subcritical one.

5) Each of the heat exchangers is assumed to be operated with a pinch point condition, which means that the minimum temperature difference between the hot and cold streams in the heat exchanger reach the prescribed value of the pinch temperature difference.

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

$$Q_{in} = m_2(h_3 - h_2) \quad (1)$$

$$Q_{out} = m_4(h_1 - h_4) \quad (2)$$

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

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

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 [22]. However, in this work, the equilibrium conditions are determined by equating the chemical potentials of each phase for each element [23].

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

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

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

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

In this study six working fluids of R134a, R600a, R600, R245fa, R123, and R601a for ORC are considered. The thermodynamic properties of the working fluids are evaluated by the Patel-Teja equation of state using MathCAD programming [24]-[25].

III. RESULTS AND DISCUSSIONS

In this paper it is considered that the source is air with 1 kg/s. The basic operation data used 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, pinch temperature difference, ΔT_{pp} = 8°C, isentropic efficiencies of pump and turbine, η_p = 0.85 and η_t = 0.85. The basic ammonia mass fractions are considered as x_b = 10%, 20%, 30%, 40%, 50%, and 60%.

Fig. 2 illustrates the effects of turbine inlet pressure on the mass flow rate of the working fluid. In ORC, the mass flow rate of working fluid decreases with increasing pressure, because an increase in the turbine inlet pressure leads to an increase in the source exit temperature and consequently decrease in the mass flow rate of the working fluid. For a specified pressure, the mass flow rate of working fluid is the highest when the working fluid is R134a and the lowest when the working fluid is R601a. It is to be noted that the decreasing rate is the highest when the working fluid

is R123. In KCS, the mass flow rate of working fluid increases 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 ORC are higher than those in KCS.

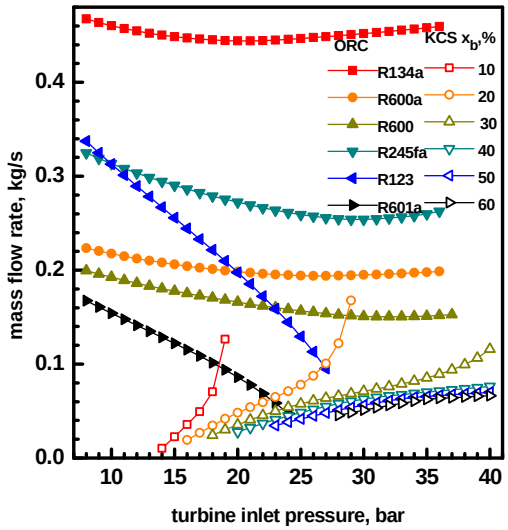


Fig. 2. Effects of turbine inlet pressure on the mass flow rate.

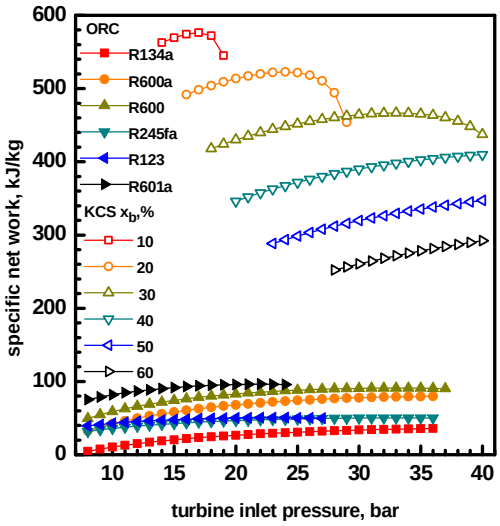


Fig. 3 Effects of turbine inlet pressure on the specific net work.

Fig. 3 shows 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 ORC the specific net work increases with increasing turbine inlet pressure due to increase in the pressure ratio across the turbine so the larger expansion in the turbine. The specific net work is the highest for R601a and the lowest for R134a. In KCS the net work increases with increasing turbine inlet pressure. But for low ammonia mass fractions as 10% or 20%, the net work decreases with increasing turbine inlet pressure for higher pressure, due to decrease in the vaporization heat. It is also to be noted that the specific net work of KCS is much higher than that of ORC.

Fig. 4 demonstrates 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 ORC, the net power production increases with increasing turbine inlet pressure for R134a, R600a, R600, and R245fa, however, exhibits a peak with respect to turbine inlet pressure for the working fluids with higher critical temperature like R123 and R601a. It is because the mass flow rate of working fluid decreases but the specific net work increases as the turbine inlet pressure increases. In KCS, 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, which is similar to the regenerative ammonia-water Rankine cycle [21].

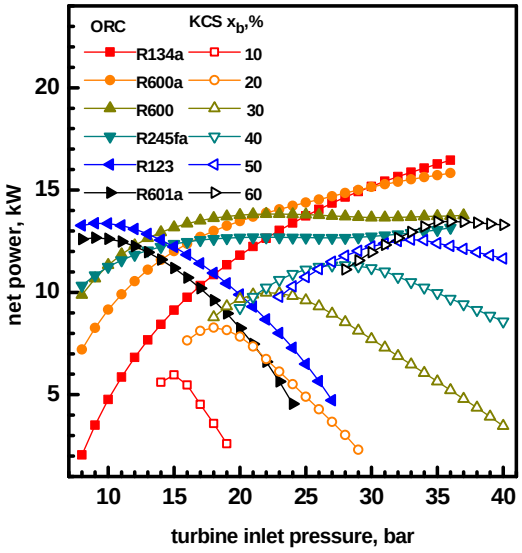


Fig. 4 Effects of turbine inlet pressure on the net power production.

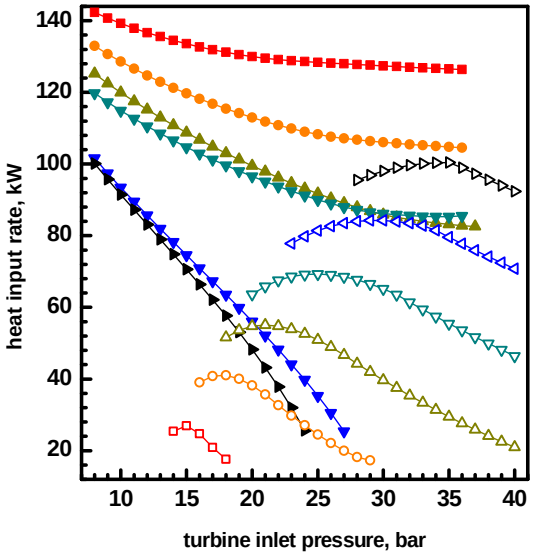


Fig. 5 Effects of turbine inlet pressure on the heat input rate.

Fig. 5 shows 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 ORC, as the turbine inlet pressure increases, the heat input rate decreases due to rise in the evaporation temperature and consequently rise in the exit temperature of source fluid. For a specified turbine inlet pressure, the heat input rate decreases as the critical temperature of the working fluid increases, so is the highest for R134a and the lowest for R601a. In KCS, 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. It can be seen from the figure that each of the maximum heat input rate and the corresponding turbine inlet pressure increase as the mass fraction of ammonia increases.

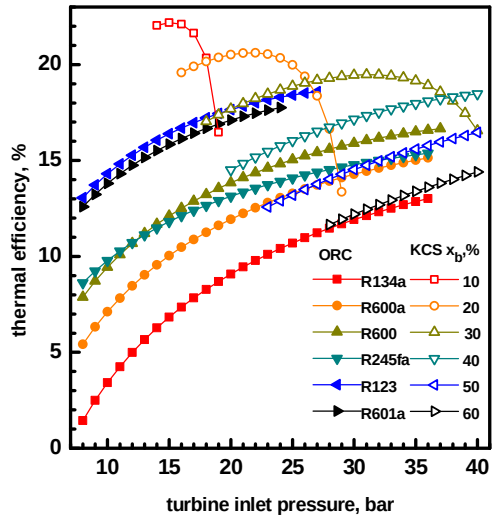


Fig. 6 Effects of turbine inlet pressure on the thermal efficiency.

Fig. 6 shows 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 ORC, the thermal efficiency increases with increasing turbine inlet pressure for all working fluids. As previously mentioned, the net power production may increase or decrease with increasing turbine inlet pressure depending on the working fluid. Therefore, it can be seen that the decreasing effect of heat input rate with respect to the turbine inlet pressure is dominant effect. The thermal efficiency is the lowest for R134a and the highest for R123. In KCS, the thermal efficiency exhibits a peak with respect to the turbine inlet pressure for lower ammonia mass fractions of 10% to 30%, but increases simply with increasing turbine inlet pressure for higher ammonia mass fractions of 40% to 60%. It can be seen from the figure that the maximum thermal efficiency is the highest for 10% mass fraction of ammonia and the lowest for 60% mass fraction of ammonia.

Fig. 7 shows 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 ORC, 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 R601a. In KCS, the specific flow rate exhibits a local minimum value for low ammonia mass fractions of 10% to 30%, but simply decreases with increase in the turbine inlet pressure for higher ammonia mass fractions of 40% to 60%.

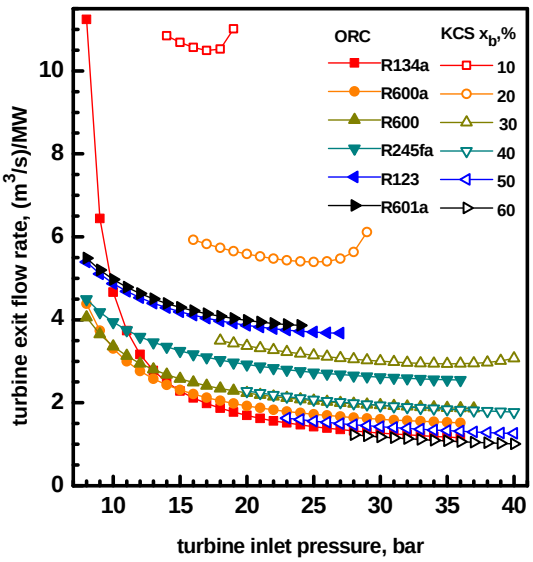


Fig. 7 Effects of turbine inlet pressure on the turbine-exit flow rate.

CONCLUSIONS

This paper presented a thermodynamic performance analysis for organic Rankine cycle (ORC) and Kalina cycle using ammonia-water mixture as the working fluid. Main results are as follows: In ORC, the net power production increases with increasing turbine inlet pressure or exhibits a peak with respect to turbine inlet pressure, which depends on the working fluid. But the thermal efficiency increases with increase in the turbine inlet pressure for all working fluids. In KCS, the thermal efficiency increases with increasing turbine inlet pressure or exhibits a peak with respect to turbine inlet pressure, which depends on the ammonia mass fraction. But the net power production exhibits always a peak value with respect to the turbine inlet pressure. KCS show lower power production but higher thermal efficiency compared to ORC.

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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 of ammonia–water based power cycles," Thermochimica Acta, 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 working fluids 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 geothermal organic 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 of organic Rankine cycle (ORC) for low grade waste heat recovery," Energy Convers. Manag., vol. 50, pp. 576-582.

[12] B. F. Tranche, G. Papadakis, G. Lambrinos, and A. Frangoudakis, "Fluid selection for a low-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 vapor compression cycle for power and refrigeration cogeneration," Appl. Therm. Eng., vol. 91, pp. 964-974, 2015.

[14] V. A. Prisyazhniuk, "Alternative Trends in Development of Thermal Power Plants," Appl. Therm. Eng., vol. 28, pp. 190-194, 2008.

[15] 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

[16] C. Zamfirescu, and I. Dincer, "Thermodynamic Analysis of a novel ammonia-water trilateral Rankine Cycle," Thermochimica Acta, vol. 477, pp. 7-15, 2008.

[17] P. Roy, M. Desilets, N. Galanis, H. Nesreddine, and E. Cayer, "Thermodynamic analysis 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.

[18] W. R. Wagar, C. Zamfirescu, and I. Dincer, "Thermodynamic performance assessment of an ammonia-water Rankine cycle for power and heat production," Energy Convers. Manag., vol. 51, pp. 2501-2509, 2010.

[19] K. H. Kim and K. C. Kim, "Thermodynamic performance analysis of a combined power cycle using low grade heat source and LNG cold energy," Appl. Therm. Eng., vol. 70, pp. 50-60, 2014.

[20] A. Modi, F. Haglind, "Thermodynamic optimisation and analysis of four Kalina cycle layouts for high temperature applications," App. Therm. Eng., Vol. 76, pp. 196-205, 2015

[21] K. H. Kim, "Thermodynamic Assessment of Regenerative Organic Rankine Cycle and Ammonia-Water Rankine Cycles," Int. J. Mechanical Production Eng., Vol. 5, pp. 150-154, 2017.

[22] F. Xu, and D.Y. Goswami, "Thermodynamic properties of Ammonia-Water Mixtures for Power-Cycle Applications," Energy, vol. 24, pp. 525-536, 1999.

[23] J. M. Smith, H. C. Van Ness, and M.M. Abbott, "Introduction to Chemical Engineering Thermodynamics," 7th Ed. McGraw-Hill, 2005.

[24] T. Yang, G. J. Chen, and T. M. Gou, "Extension of the Wong-Sandler mixing rule to the three parameter Patel-Teja equation of state: Application up to the near-critical region," Chem. Eng. J., vol. 67, pp. 27-36, 1997.

[25] J. Gao, L. D. Li, S. G. Ru, "Vapor-liquid equilibria calculation for asymmetric systems using Patel-Teja equation of state with a new mixing rule," Fluid Phase Equilibrium, vol. 224, pp. 213-219, 2004.

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