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Assessment of pinch point characteristics in heat exchangers and condensers of ammonia–water based power cycles

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HIGHLIGHTS

- Efficient assessment method of pinch point characteristics is proposed for ammonia–water based Rankine power systems.
- The concept of imaginary source and coolant temperatures is introduced to conveniently evaluate the pinch point position.
- The method is useful when pinch point occurs between bubble and dew points during variable temperature phase transition.
- Various pinch point characteristics in heat exchangers and condensers with binary mixture as working fluid are discussed.

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ABSTRACT

In heat exchanging devices of ammonia–water based power generation cycles for the recovery of waste heat in the form of sensible energy, assessment of pinch point (PP) is far more complicated compared to the case of working fluid of pure substance. In this study, efficient and novel method is suggested for PP assessments in source heat exchanger and condenser in ammonia–water based power generation cycles. The concept of imaginary source and coolant outlet temperatures is proposed in the present method and PP characteristics can be efficiently evaluated by using the proposed approach. The present method is especially useful when PP occurs in the middle between bubble and dew points during variable temperature phase transition due to the nature of binary mixture. The effects of system parameters are investigated on the PP characteristics including PP location and the corresponding mass flow ratios of working fluid to source and coolant fluids. The analysis shows that the PP characteristics are affected quite complicatedly and sensitively with changing ammonia concentration or working fluid pressure. Depending on the working conditions, the PP location within heat exchanging devices exhibit abrupt changes between a middle point between bubble and dew points and usual PP locations such as device inlet/exit or bubble point of working fluid.

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1. Introduction

In recent years, the use of non-azeotropic binary mixtures as working fluids in power generation cycles has been attracting much attention, since they are proven to be one of the most feasible methods to achieve a high efficiency especially in converting the sensible energy of low-temperature waste heat sources into useful work. The motivation for using the binary mixtures such as ammonia–water mixture is that they evaporate not at a constant temperature but over a wide range of temperature at a constant pressure, which makes it possible that heat can be supplied or rejected at variable temperature. This variable-temperature heat transfer process significantly alleviates the temperature mismatch between hot and cold streams in heat exchangers [1,2].

While ammonia–water based power cycles can be realized in several different cycle configurations such as ammonia–water Rankine cycle and Kalina cycle, they are considered as a promising technology for efficient conversion of low grade heat source such as solar energy, geothermal energy, power generation using LNG cold energy, ocean thermal energy conversion (OTEC), and waste heat from internal combustion engines. Most notably, in a recent decade, several commercial power plants have been successfully built employing Kalina cycles, which are in fact modified Rankine cycles using ammonia–water mixture as a working fluid [3].

Ibrahim and Klein [1] compared thermodynamic performance of ammonia–water based power cycles for different heat-exchanger sizes and thermal capacitance rates. Ibrahim [2] studied an ammonia–water based Rankine cycle and found that the design of heat exchanger networks can have a significant impact on the performance of power cycles. Jonsson and Yan [4] investigated ammonia–water bottoming cycle and they pointed out that higher

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Nomenclature

c_p	isobaric specific heat, kJ/kg K
D_c	function defined in Eq. (16)
D_s	function defined in Eq. (9)
G	specific Gibbs free energy, kJ/kmol
H	dimensionless enthalpy
h	specific enthalpy, kJ/kg
N	number of moles, kmol
P	working fluid pressure, bar
PP	pinch point
R	universal gas constant = 8.3142 kJ/kmol K
r_H	mass flow ratio of working fluid to source
r_L	mass flow ratio of working fluid to coolant
T	temperature, °C
T_{iso}	imaginary source outlet temperature defined in Eq. (8), °C
T_{ico}	imaginary coolant outlet temperature defined in Eq. (15), °C
w	mass flow rate, kg/s
x	molar fraction of ammonia
x_b	ammonia mass concentration
ΔT	temperature difference of streams, °C
ΔT_{pp}	pinch point temperature difference, °C
μ	chemical potential

Superscripts/Subscripts

a	ammonia
c	coolant
g	gas phase
H	high working fluid pressure
i	inlet
L	low working fluid pressure
l	liquid phase
m	mixture
o	outlet
s	source
w	water

power output accounted for low boiling temperature of the ammonia–water mixture as well as variable-temperature heat transfer. Kiani et al. [5] carried out the analysis for load-leveling hyper energy converting and utilization system (LHECUS) which is a combined power generation and refrigeration cycle using ammonia–water mixture. Zamfirescu and Dincer [6] analyzed trilateral ammonia–water Rankine cycle that does not use a boiler, but rather the saturated liquid is flashed by an expander. Ogriseck [7] presented the integration of the Kalina cycle process in a combined heat and power generation, while Lolos and Rogdakis [8] investigated Kalina cycle using low-temperature heat sources.

Roy et al. [9] 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. Wagar et al. [10] performed thermodynamic analysis on the ammonia–water based Rankine cycles and suggested that each cycle must be optimized upon several parameters due to nonlinear behavior of the working fluid. Bombarda et al. [11] presented comparative analysis on thermodynamic performance of Kalina and organic Rankine cycles (ORC). Arslan [12,13] presented exergoeconomic evaluation and optimization study of Kalina cycle using geothermal resources. Ganesh and Srinivas [14] examined a low-temperature Kalina cycle to optimize the heat recovery from solar collectors. Sun et al. [15] studied a solar-boosted Kalina cycle with an auxiliary superheater. Zhang et al. [3] presented a review of the research on the Kalina cycle including the comparison of the Rankine and Kalina cycles.

Recently, Kim et al. [16–18] investigated the effects of ammonia concentration on the thermodynamic performances of ammonia–water based power generation cycles for the recovery of low temperature heat sources in the form of sensible heat. They showed that the characteristics of temperature distributions of the fluid streams in the heat exchangers vary quite complicatedly and sensitively with changing system parameters such as ammonia concentration or pressure of working fluid. Therefore, the assessment of pinch point (PP) can be a much more difficult task and it requires extraordinary cautions, compared to the relatively simpler cases of using pure substances as working fluid.

In this study, efficient and novel method using the concept of imaginary source and coolant outlet temperatures is proposed for PP assessment in source heat exchanger and condenser in ammonia–water based power generation cycles that specializes in recovery of low temperature waste heat. The present methods can be applied to the PP analysis for the source heat exchangers and condensers in the various ammonia–water based power cycles including ammonia–water based Rankine cycle and Kalina cycle, and furthermore, in any power generating cycles using non-azeotropic working fluids. In order to provide a better understanding on the presently suggested methods, PP characteristics are parametrically investigated for an ammonia–water based Rankine cycle as an example. Also, a special attention is paid to the cases where PP occurs at a location between bubble and dew points, other than inlet or outlet of heat exchangers or bubble point of the working fluid.

2. Pinch point analysis

2.1. System descriptions and thermodynamic property calculations

Although the present methods of PP assessment apply to heat exchanging devices in any power generation cycles using non-azeotropic mixture as a working fluid, a simple ammonia–water based Rankine cycle is considered here in order to illustrate the methodology more clearly, as its schematic diagram is shown in Fig. 1. Note that ammonia–water based Rankine cycle employs the same principle as steam Rankine cycle except using the binary mixture as a working fluid. At the source heat exchanger and condenser in ammonia–water based power cycles including ammonia–water Rankine cycle, heat is transferred with varying temperature of the

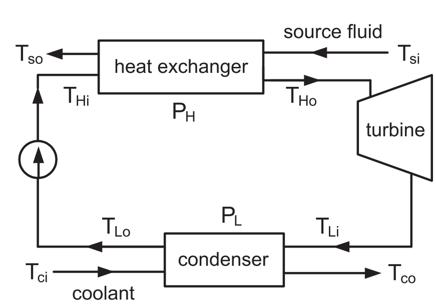

Fig. 1. Heat exchanger and condenser in the ammonia–water based Rankine cycle for the illustration of pinch point assessment.

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