Thermal performance of a modified ammonia–water power cycle for reclaiming mid/low-grade waste heat

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ABSTRACT

A modified Kalina cycle was simulated, which is a triple-pressure ammonia–water power cycle adding a preheater and a water-cooling solution cooler to the original loop. The cycle acquires higher power recovery efficiency by realizing proper internal recuperation and suitable temperature-difference in phase change processes to match both heat source and cooling water. The influences of some key parameters on the thermodynamic performance of the cycle were discussed, including the work and basic concentrations of solution, circulation multiple and the turbine inlet temperature. It is shown that the basic concentration should match the work concentration for higher efficiency. Although higher work concentration could be slightly beneficial to cycle efficiency, the work concentration is mainly determined by considering the suitable turbine inlet/back pressure. Besides, this cycle can be used as a cogeneration system of power and sanitary or heating hot water. The calculation example presented finally with the turbine inlet parameters of 300 °C/6 MPa and the cycle lowest temperature of 30 °C shows that the power recovery efficiency reaches 15.87%, which is about 16.6% higher than that of the steam Rankine cycle. And it also provides 50.7 °C sanitary water with about a quarter of the total heating load reclaimed.

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1. Introduction

Due to the continually stringent supply and expanding demand of energy, generating power from the mid/low grade heat sources, including the solar energy, industrial waste heat, geothermal sources and other renewable energies, has drawn more and more concern [1,2]. Unlike the traditional pure working fluids, the binary mixture such as ammonia–water exhibits a varied evaporation temperature matching well with the heat source, thus the exergy loss in heating process could be reduced. However, the exergy loss in condensation process might be increased with much larger temperature variation of the working medium than that of the cooling water. By virtues of such thermal property, Kalina proposed a bottoming cycle with ammonia–water mixture as working fluid since 1984 [3,4], and unlike the Rankine cycle the absorption condenser is used instead of condenser in the Kalina cycle to reduce the exergy loss in condensation process.

From then on, many scholars and experts studied and researched on the Kalina cycle [5–10], or proposed some modifications on the ammonia–water power cycle successively [11–20]. According to the studies, the Kalina cycle or its modified cycles appears a superior thermal performance than the traditional Rankine cycle in generation power from mid/low temperatures heat sources. Shi and Che [11] studied a combined power cycle using low-temperature waste heat and LNG cold energy. Chen [12] proposed a dual pressure ammonia–water power cycle applicable for the low temperature heat resource under 160 °C, and Hua et al. [13] made a detailed study on the thermal performance of the dual pressure ammonia–water power cycle. Sirko [14] and Wagar et al. [15] studied respectively the Kalina cycle for cogeneration of power and heat. Ricardo and Gokmen [16], Zheng et al. [17], Zhang and Lior [18], Hua et al. [19] and Sadhukhan et al. [20] studied respectively several modification cycles mainly focus on ammonia–water absorption power/refrigeration cogeneration cycles. Nevertheless, these cycles except the one in reference [19] use rich ammonia as refrigerant and adopt the generator-rectifier column. Although the power and refrigeration cogeneration systems may improve integrated thermal efficiency of the whole system, the feasibility of such systems is usually poor. The reasons are that it is usually more complex in composition with cogeneration system, the rectifier is not favourable for thermal performance of the power cycle, and there are problems in mutual restraint between chilling and power loads.

Up to now, the application of Kalina or modified Kalina cycles has faced some obstacles, and it is still not mature in application

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and optimal design. Great efforts are needed on this power cycle family. In this paper, a modified tri-pressure Kalina power cycle is presented and analysed, which is relative simple in component and avoiding the use of rectifier. A preheater and a water-cooling solution cooler are set for higher efficiency and more heat recovery. This cycle configuration makes it possible to build a cogeneration with power and heat, utilising energy more sufficiently.

2. Configuration of the modified Kalina cycle

In this paper, a modified Kalina power cycle, as shown in Fig. 1b, is presented and analysed. This cycle is built for a cogeneration with power and heat, to utilize energy more sufficiently. The modified Kalina cycle discussed in this paper has the following improvements based on the original loop of Kalina cycle, as shown in Fig. 1a:

(1) A preheater (PH) is set, using the rich ammonia vapour from separator to be partially condensed to heat the work solution, through which the absorption load in mid-p-absorber (A2) is decreased, and meanwhile the low-temperature corrosion problem of the evaporator could be avoided with the increased temperature of work solution at the low temperature part of the evaporator.

(2) A water-cooling solution cooler (SC) is set, to cool the dilute solution from separator by the cooling water from mid-p-absorber (A2). The SC takes away part of the heat load in the low-p-absorber by reducing temperature of dilute solution. As the heat transfer coefficient of liquid-to-liquid heat transfer in the SC is much higher than that of the multi-phase-flow-to-liquid one in absorber, the total heat transfer area needed for heat exchangers will be reduced. The temperature of outlet water from the SC is suitable as sanitary or heating hot water, because of the adequate flow rate of the cooling water from mid-p-absorber (A2).

(3) Absorbers are used instead of "absorption-condensers" for A1 and A2. In an absorber, dilute solution sprays on the heat transfer surfaces and absorbs vapour inside the heat exchanger, while in the "absorption-condenser" both fluids, dilute solution and vapour, mix before entering the heat exchanger. The "absorption-condenser" usually has a larger pressure drop, causing the turbine backpressure increases, harmful for recovering more power, whereas the absorber has much smaller internal pressure drop, and its heat and mass transfer can be enhanced by inserting mesh packing layers between the tube rows [21].

The modified Kalina cycle mainly includes the following sub-processes.

2.1. Evaporation process

The work solution (state point 10, write as 10 for short) from the outlet of the mid-p-absorber (A2) is pumped to the high pressure (11) by high-p-pump (P2) and then through the preheater (12) enters the evaporator (E), which comprises sub-cool liquid section, evaporation section and superheat section, and then completes counter-current heat exchange process with heat source.

2.2. Turbine expansion process

The high temperature and high pressure work concentration ammonia–water vapour (15) from the evaporator generates power through expansion in turbine (T).

2.3. Absorption process

The exhaust vapour (16) from turbine releases heat for desorption in recuperator (R) before goes into the low-p-absorber (A1) (17). Simultaneously, the dilute solution (7) sprays on the tube bundle of the low-p-absorber, and it absorbs remaining exhaust vapour (17), with the absorption heat taken away by cooling water (c1–c2), and then the basic solution (1) forms at the outlet of the A1. The state point (18) is a pseudo mixed state of vapour and liquid before absorption in the low-p-absorber for the convenience of calculation.

2.4. Desorption and separation process

The basic solution (1) from the low-p-absorber raises to the mid-pressure (2) by the low-p-pump (P1) and then it splits into two ways. The small part (8) goes directly into the mid-p-absorber. The majority part (3) goes into the recuperator (R) and it is heated to a partially evaporated state (4) before enters a separator (S). The enriched vapour (4″) from the separator releases some condensation heat in the preheater (PH) before enters the mid-p-absorber, while the dilute solution (4′) is cooled (6) in a water-cooling solution cooler (SC), and then through a throttle valve (V2) (7) it enters the low-p-absorber. The warm water from the outlet of the water-cooling solution cooler (SC) could be used as sanitary or heating water.

2.5. Reproduction of work solution process

The small part of basic solution (8) sprays on the tube bundle of the mid-p-absorber (A2), and absorbs the enriched vapour (5), with the absorption heat taken away by cooling water (c3–c4), and the work solution (10) is then reproduced at the outlet of A2. The state