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Absorption of high concentration NH_3/H_2O in a plate heat exchanger

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Abstract:
High concentration NH_3/H_2O is suitable for Kalina cycles used for the recovery of low grade heat. Plate heat exchangers (PHEs) are compact and reduce the charge of working fluid. This work investigates the absorption of NH_3/H_2O in a PHE, which has a weight concentration of 96%. Being different from normal absorption systems, the concentration difference between vapor and liquid is small, and apparent heat transfer coefficients (HTCs) are used to interpret the phase change process, which assumes that the vapor and liquid are in equilibrium state. The apparent HTCs and frictional pressure drop of NH_3/H_2O are presented and are compared with those of NH_3. The mass transfer resistance has noticeable influences on heat transfer depending on the flow patterns, while the influence on frictional pressure drop is minor.

1. Introduction

The utilization of low grade heat is a promising approach to increase the sustainability of energy systems. The recovery of low grade heat can be implemented making use of Organic Rankine Cycles or Kalina Cycles. During evaporation and condensation, Kalina Cycles utilize the temperature glide of mixtures to match the temperature change of the secondary fluid. NH_3/H_2O is a suitable working fluid because of the large latent heat. NH_3/H_2O can be combined with PHEs to transfer large heat loads with compact structures and reduced charge. The condensation of NH_3/H_2O is characterized by a large temperature glide. This process is also referred to as absorption. In order to obtain uniform temperature difference between NH_3/H_2O and the secondary fluid, the bulk weight concentration is required to be higher than 80%. Thus it is different from the phase change process in normal absorbers where the liquid concentration is in the range of 25%~50% and the vapor concentration is >98% [1].

The absorption of NH_3/H_2O within PHEs has been investigated experimentally. The driving potential for the external heat transfer is the temperature difference between the NH_3/H_2O liquid and secondary fluid. The vapor is almost pure NH_3 and is absorbed into the liquid, releasing heat. The corresponding heat transfer correlations available in the literature are only applicable in the original operating ranges. The analysis of mass transfer is limited to the overall absorbed mass flow rate, which determines the heat generation and is sensitive to the two-phase concentration difference [1, 2]. The temperature glide of NH_3/H_2O changes significantly with concentration, making it difficult to develop widely applicable predicting models. This paper addresses the absorption of NH_3/H_2O with an average weight concentration of 96%.

The authors have studied NH_3 condensation in a PHE including flow patterns, heat transfer and frictional pressure drop [3, 4]. The fluid properties of high concentration NH_3/H_2O are slightly different from NH_3. The pure refrigerant and mixture have similar momentum transport characteristics, but the energy transport characteristics are different owing to the simultaneous heat and mass transfer taking place in the NH_3/H_2O process [5]. This paper experimentally investigates the absorption of high concentration NH_3/H_2O in a PHE, and compares the results with NH_3 condensation to analyse the influence of mass transfer resistance.

2. Background

The determination of bulk concentration is key for the design of Kalina Cycles operating with NH_3/H_2O. The temperature glide is required to match the temperature change of the secondary fluid from heat source and heat sink. Figure 1 shows the temperature glide of NH_3/H_2O, with fluid properties calculated using Refprop [6]. When the concentration is close to 100% and the fluid becomes almost pure NH_3, the temperature glide of NH_3/H_2O is so small that the advantage of Kalina Cycles cannot be fully exploited. When the concentration is too low, the temperature of NH_3/H_2O changes more than the secondary fluid. Moreover, lower concentration brings about larger mass transfer resistance. Thus an optimum concentration exists and is expected to be located in the range of

80%~100%. As shown in Figure 1, the temperature glide between bubble point and dew point is large in this range, while the temperature glide between bubble point and the point of 0.5 vapor quality is relatively small. The availible range is in low and intermediate vapor qualities of high concentration. In real operating conditions of Kalina Cycles, the process starts from two phase and ends up with subcooling. Thus the temperature change of NH_3/H_2O depends on the inlet vapor quality. The optimum concentration is determined by the heat capacity of the secondary fluid and the inlet vapor quality of the condenser. The value is sensitive to the cases and needs to be discussed in the specific conditions. This work investigates the condensation of high concentration NH_3/H_2O, also referred to as absorption. The bulk weight concentration of 96% is presented in this paper, with other concentrations being followed up. This process is different from normal absorption since no rectification is involved in the system. Consequently, the vapor and liquid are close to thermodynamic equilibrium.

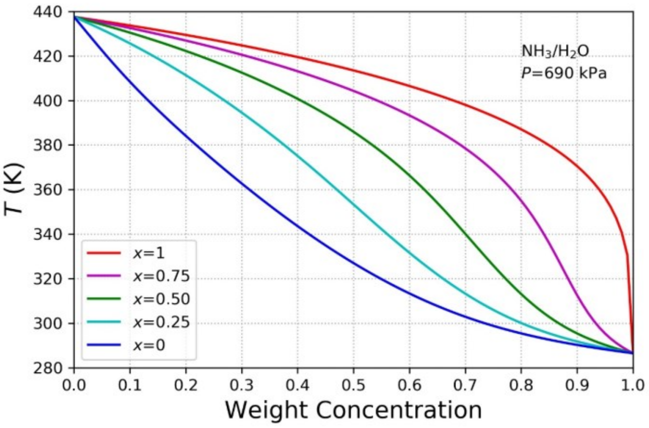

Figure 1 – Temperature glide of NH_3/H_2O with varying weight concentrations. The equilibrium temperatures of bubble point, dew point and three vapor qualities are indicated.

3. Experimental Set-up and Data Reduction

The detailed descriptions of the experimental setup and test section are given in a previous paper [3]. The test section is a gasketed plate heat exchanger with a hydraulic diameter of 2.99 mm and a chevron angle of 63°. The NH_3/H_2O has a bulk weight concentration of 96%. The working fluid is two-phase at the inlet and outlet of the test section. The two phases are mixed at the inlet by spraying the liquid into the vapor flow. The liquid has relatively low NH_3 concentration, while the vapor is almost pure NH_3. NH_3/H_2O flows from the top to the bottom of the test section, and is cooled by cold water flowing upward. Vapor is absorbed into liquid within the test section, releasing heat to the cold water [5].

The bulk NH_3 concentration is determined by measuring the density of the NH_3/H_2O at liquid state together with the local temperature and pressure [5]. In Eq. (1), the heat transfer rate, Q_{test}, is calculated using the energy balance of the water. The apparent HTC of NH_3/H_2O, α_a, is determined by referring to the equilibrium temperature of NH_3/H_2O, T_a. Apparent HTC identifies the deterioration of heat transfer owing to mass transfer, but the mass transfer resistance is not calculated directly. Apparent HTC is more relevant for high concentration NH_3/H_2O at low and intermediate vapor qualities, where the concentration difference between the vapor and liquid is small. Compared with intermediate concentrations or compelete phase change from vapor to liquid, the temperature glide during partial phase change within two-phase region is relatively small. Additionally, apparent HTC is comparable with the HTC of NH_3.

$$Q_{test} =$$

$$= UA\frac{\left(T_{a,in}-T_{w,out}\right)-\left(T_{a,out}-T_{w,in}\right)}{\ln\frac{T_{a,in}-T_{w,out}}{T_{a,out}-T_{w,in}}} = \frac{A}{\frac{1}{\alpha_a}+\frac{d_p}{\lambda_{wall}}+\frac{1}{\alpha_w}}\frac{\left(T_{a,in}-T_{w,out}\right)-\left(T_{a,out}-T_{w,in}\right)}{\ln\frac{T_{a,in}-T_{w,out}}{T_{a,out}-T_{w,in}}} \quad (1)$$

In Eq. (2), the frictional pressure drop, $\Delta P_{fri,a}$, is calculated by subtracting the other components from the measured pressure drop, $\Delta P_{exp,a}$, including the pressure drops of inlet and outlet ports, $\Delta P_{in\,port,a}$ and $\Delta P_{out\,port,a}$, the deceleration pressure rise, $\Delta P_{de,a}$, elevation pressure rise, $\Delta P_{ele,a}$, and the mixing pressure drop, $\Delta P_{mix,a}$ [5].

$$\Delta P_{fri,a} = \Delta P_{exp,a} - \Delta P_{in\,port,a} - \Delta P_{out\,port,a} - \Delta P_{mix,a} + \Delta P_{de,a} + \Delta P_{ele,a} \quad (2)$$

4. Experimental Results and Discussion

According to the visualization experiments of NH_3 condensation in PHEs, the flow patterns are full film flow at large liquid mass fluxes and partial film flow at small liquid mass fluxes [3]. During full film flow, the wall surface of the PHE is completely wetted by the liquid film. For partial film flow, parts of the wall are dry. Flow patterns are the function of two-phase fluid properties, operating conditions and channel geometries. The flow patterns for NH_3/H_2O are considered to be the same as for NH_3. The fluid properties change continuously with concentration, and the properties of high concentration NH_3/H_2O approximate to those of NH_3. The NH_3/H_2O experiments have been operated at the same ranges of mass fluxes and vapor qualities as the NH_3 experiments. Additionally, the same test section has been used. Both full film flow and partial film flow are separated flow, and the influences of liquid and vapor mass fluxes are investigated separately.

Figure 2(a) presents the apparent HTCs of NH_3/H_2O with varying liquid and vapor mass fluxes, whose bulk weight concentration is 96%. The saturated pressure is 690 kPa. The HTCs of NH_3 are shown for comparison in Figure 2(b), which have been published in our previous paper [3]. In Figure 2(a), the apparent HTCs increase with increasing liquid mass fluxes at small values, and stay almost constant at larger values. Partial film flow happens at small liquid mass fluxes. The wall is composed of wetted zones and dry zones. In the wetted zones, the vapor contacts the two-phase interface and is absorbed by the liquid. The heat and mass transfer through the liquid film. In the dry zones, the vapor is in contact with the wall directly. The phase change takes place since the wall temperature is lower than the bubble point of NH_3/H_2O. The heat transfer performance at the wall is inferior to that at the two-phase interface where the two-phase concentration difference drives the mass transfer. The area of the wetted zones increases with liquid mass fluxes, promoting the overall HTCs. Full film flow applies at a certain liquid mass flux when the wall gets wetted completely. All the heat is transferred through the two-phase interface. The apparent HTCs become almost constant. The slope of HTCs is different from that of NH_3 in Figure 2(b). For partial film flow, the heat transfer at the dry zones can be regarded as mixture condensation. The concentration of vapor is higher than 99%. According to the experimental results, even minor H_2O brings about noticeable mass transfer resistance and deteriorates the phase change heat transfer at the wall surface. Consequently, the apparent HTCs of NH_3/H_2O are significantly smaller than the HTCs of NH_3. For full film flow and the wetted zones of partial film flow, the mass transfer resistance hinders the heat transfer. Nevertheless, the concentration difference of NH_3 promotes the absorption of NH_3 vapor into the liquid, which simultaneously drives the heat transfer. These two effects counteract each other. Thus the apparent HTCs of NH_3/H_2O are slightly smaller than the HTCs of NH_3. Larger vapor mass fluxes enhance the heat transfer, which is the same as for NH_3.

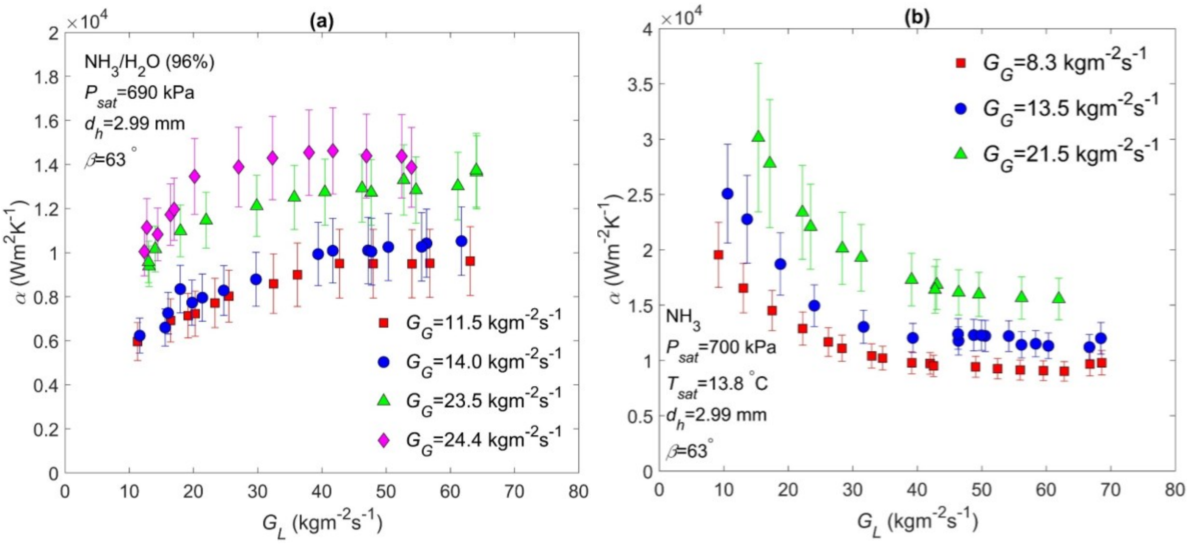

Figure 2 - HTCs with varying liquid and vapor mass fluxes: (a) apparent HTCs of NH_3/H_2O, (b) HTCs of NH_3 [3]

Figure 3 shows the influence of liquid and vapor mass fluxes on frictional pressure drop. For NH_3/H_2O, the frictional pressure drop increases monotonously with both mass fluxes, which is the same as NH_3 [3]. The change of flow patterns does not affect the trend of frictional pressure drop. The sharp trend indicates separated flow and further confirms that the flow patterns of NH_3/H_2O are the same as for NH_3.

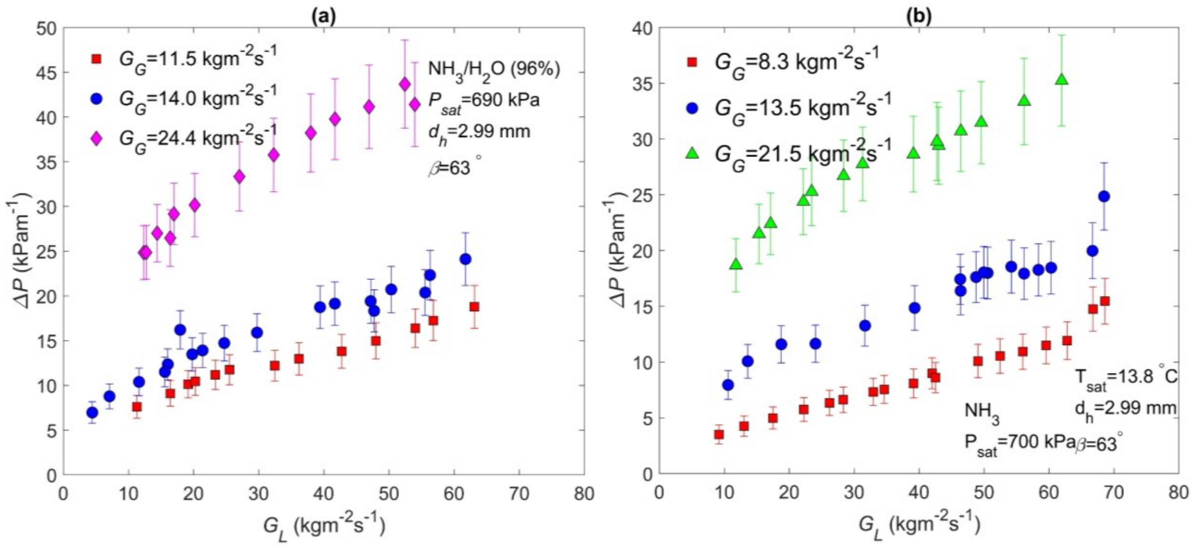

Figure 3 - Frictional pressure drop with varying liquid and vapor mass fluxes: (a) NH_3/H_2O, (b) NH_3 [3]

5. Conclusions

This paper discusses heat transfer and frictional pressure drop during NH_3/H_2O absorption in a PHE, and compares the experimental results with pure NH_3 condensation. The bulk weight concentration is 96% and will be extended to larger ranges in the follow-up work. The flow patterns are considered to be the same as for NH_3 condensation because the fluid properties only change slightly. For full film flow, the phase change takes place at the two-phase interface. The apparent HTCs of NH_3/H_2O are slightly smaller than the HTCs of NH_3. On the one hand, the mass transfer resistance deteriorates the heat transfer. But on the other hand, the two-phase concentration difference of NH_3 drives the mass transfer and promotes the absorption of NH_3 vapor into the liquid. The process is the same at the wetted zones of partial film flow. At the dry zones, the phase change takes place directly at the wall surface. The apparent HTCs of NH_3/H_2O are much smaller than the HTCs of NH_3 because of the mass transfer resistance. The frictional pressure drop of NH_3/H_2O increases sharply with both liquid and vapor mass fluxes, showing the same flow characteristics as for NH_3. The frictional pressure drop is not affected by mass transfer resistance or the change of flow patterns.

6. Acknowledgment

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