MICROCHANNELS FOR ABSORPTION/DESORPTION OF AMMONIA-WATER IN A COMPRESSION-RESORPTION HEAT PUMP

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Abstract Microchannel performance strongly depends on the heat, mass and momentum transfer processes. In literature different models have been proposed for the prediction of two-phase pressure drop and heat transfer coefficients during evaporation and condensation. These models were mostly based on the experimental data obtained for pure refrigerants in horizontal microchannels. In this work some recent models have been selected based on the operating conditions and number of fluids tested and they have been applied to compute the two-phase pressure drop and heat transfer coefficients for ammonia-water mixture (35% ammonia and 65% water) during absorption and desorption in vertical microchannels. The resulting performance has been evaluated for heat exchangers used in a compression-resorption heat pump system.

Key Words: microchannel, compression-resorption heat pump, heat transfer

1 INTRODUCTION

One of the phenomena where the microfabrication technology contributes with an accelerated advancement is the heat transfer processes in micro-scale heat exchangers. These heat exchangers are fabricated by using multiple parallel microchannels of small diameter (<3 mm) resulting in high overall heat transfer rates and low pressure drops. There are many experimental and theoretical works done to determine the pressure drop and heat transfer coefficient during evaporation and condensation in microchannels and these studies were reviewed in detail in literature (Kandlikar et al. 2006, Cheng et al. 2009, Chen et al. 2008, Thome 2004). Most of these experimental studies were done for common refrigerants such as R-134a, carbon dioxide (CO_2) and water (H_2O).

Different parameters were selected to correlate two-phase pressure drop and heat transfer coefficient. In general, surface tension is an important parameter for a two phase flow in a microchannel. The other parameter to be considered is the channel dimension. From fluid dynamics point of view, the thermodynamic quality is considered important because it is related with the velocity ratio between phases, which means interfacial drag. No generally accepted correlations are available for the calculation of heat transfer coefficients and pressure drop for the design of the compact exchangers.

It is important to select the working fluids and the optimal channel dimensions at the initial step of designing a microchannel system or to verify the performance of an existing system at the selected operating conditions during evaporation and condensation.

In the context of a project, two tasks are defined as modelling/validation of boiling and condensation of the process fluids and heat transfer processes of the working fluids of compression-resorption (CR) and thermoacoustic (TA) heat pumps. A compact exchanger

built with the microchannels is decided to be used in these heat pump systems which will be integrated to a distillation column (Fig. 1). Optimisation efforts are focused on the selection of appropriate operating conditions to maximize the heat transfer and to minimize the pressure drop respectively. Therefore the analysis of existing models to calculate heat transfer coefficient and pressure drop in microchannels is required for the selection and implementation of appropriate model(s) to CR and TA heat pump conditions. This results in the verification of the applicability of these correlations to related fluids, i.e. hydrocarbons and water.

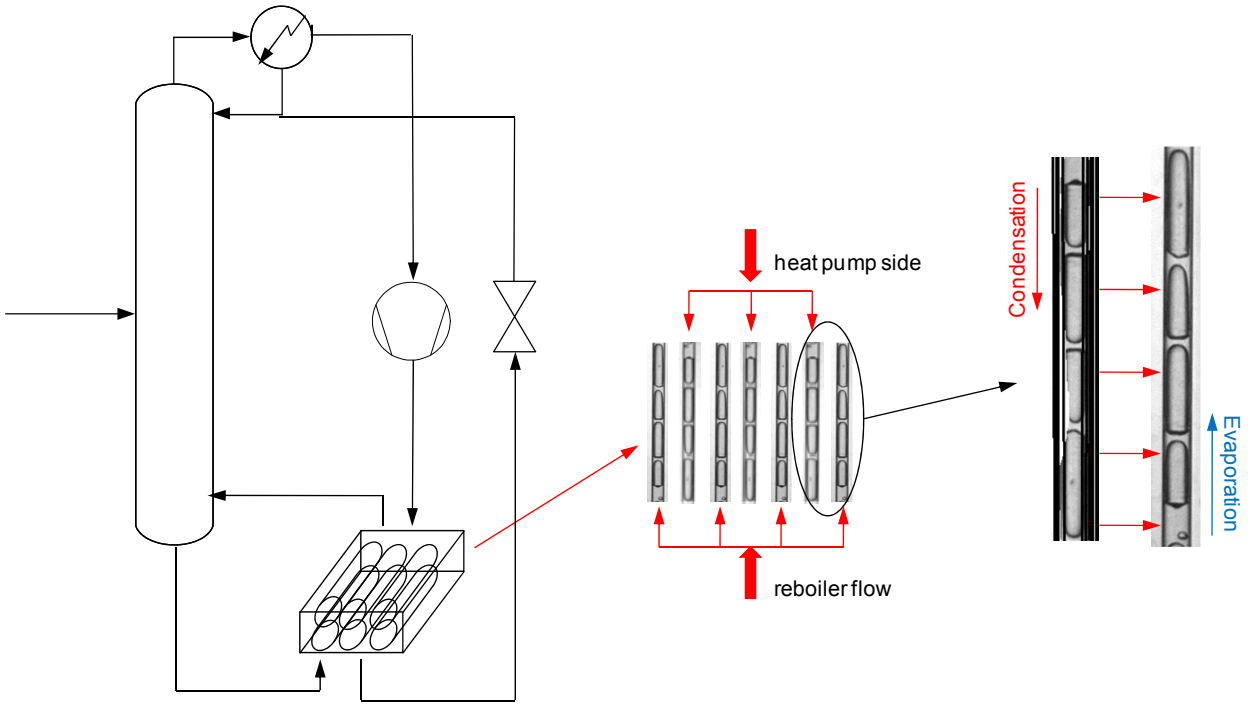


Figure 1. Schematic illustration of a vapor-compression heat pump integrated to a distillation column and the compact heat exchanger of the system built by the microchannels.

In this work, the experimental data found in the literature for n-pentane, propane, R600a and H_2O and different models were implemented to calculate heat transfer coefficient and pressure drop during evaporation and condensation. Same type of analysis was done for ammonia (NH_3) and water (H_2O) mixture (35% w/w NH_3 and 65% w/w H_2O) which was selected as heat pump fluid for the heat exchangers of a CR heat pump system.

The models to be considered for the calculation of heat transfer coefficients and pressure drop during evaporation and condensation were selected based on the number of experimental data they were applied to, the deviation of the calculated heat transfer coefficient values from experimental data and the operating condition ranges for which these models were tested. All studies are dedicated to mini-channel tubes with diameters in the range of 0.2 to 3 mm for heat transfer and 0.5 to 4.91 mm for pressure drop.

2 CALCULATION OF HEAT TRANSFER AND PRESSURE DROP IN MICRO/ MINI-CHANNELS

2.1 Heat Transfer during Evaporation

Although many correlations have been proposed for the heat transfer in micro/minichannels during evaporation, only a few of them have been verified with large sets of data. Most of

these correlations were applied either to the author's own data or to the fluids relevant with the author's experimental data. The correlations suggested by Liu & Winterton 1991, Thome et al. 2004, Lee and Mudawar 2005 and Lee et al. 2010 were selected in this work to calculate the heat transfer coefficient for n-pentane, H_2O and NH_3/H_2O mixture.

The results of the correlations were compared with the experimental data of Brutin and Tadrist 2004 for n-pentane obtained in a tube with a hydraulic diameter of 889 µm (Figs. 2a-d). The Thome et al. 2004 model under predicted the heat transfer coefficient by 36% and the effect of inlet gas phase Reynolds number (Re_{IN}) on the heat transfer coefficient (steady state) is not well represented (Fig. 2b). This could be related to the disagreement with global values of $C_{\delta 0}$ and δ_{min}. Better fit could be obtained if optimum parameters were known as explained in detail for different refrigerants in Dupont et al. 2004. Fig. 2c shows the predictions of the Lee and Mudawar 2005 and Lee et al. 2010 correlations. Both models highly over predicted the heat transfer coefficient by 250% and 256% respectively. As seen in Fig. 2d the Liu and Winterton 1991 correlation also over predicted the heat transfer coefficient by 80%.

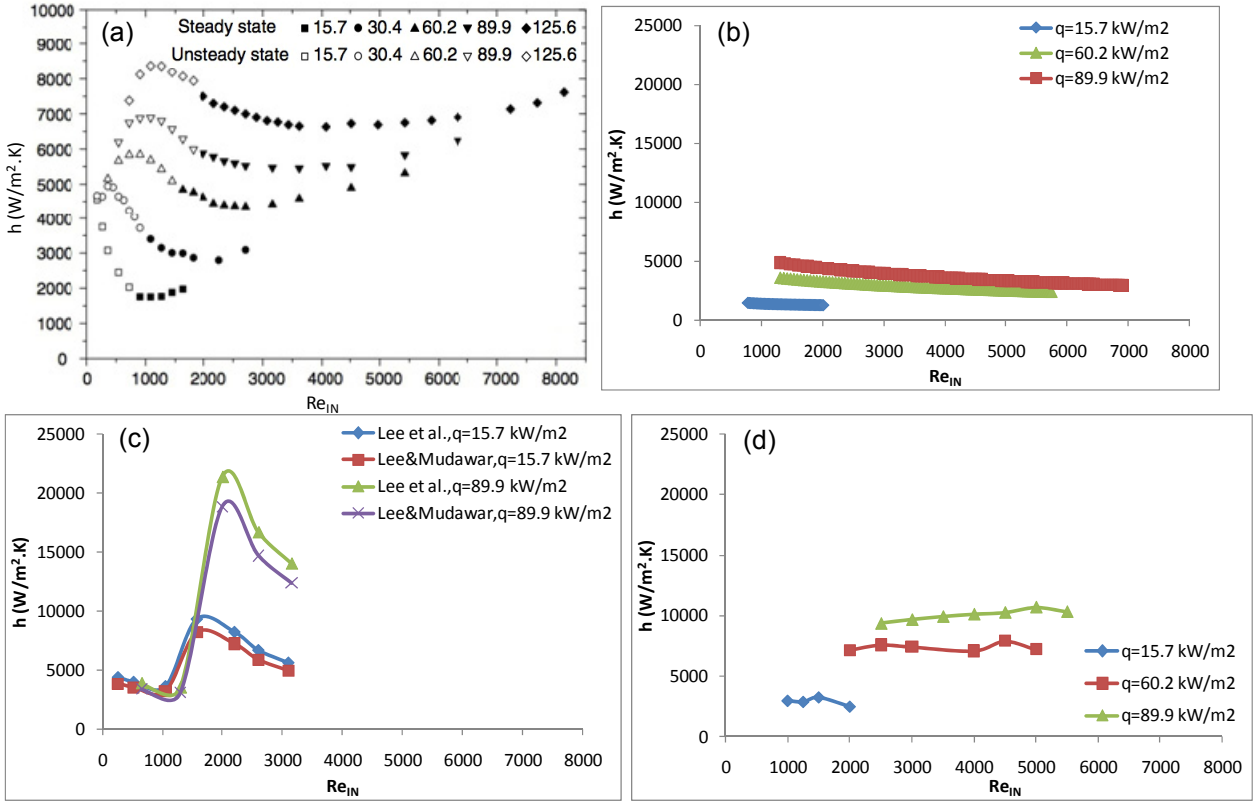


Figure 2. (a) Experimental data of Brutin and Tadrist 2004 for n-pentane, d=889 µm, (b) Thome et al. 2004 correlation, (c) Lee & Mudawar 2005 and Lee et al. 2010 correlations, (d) Liu and Winterton 1991 correlation.

Figures 3a-e show the comparison of the correlations with the experimental data of Sumith et al. (2003) for H_2O obtained with a tube having an inner diameter of 1.45 mm. The effect of the vapor quality on the heat transfer coefficient shows an opposite trend for the Thome et al. 2004, Lee and Mudawar 2005 and Lee et al. 2010 correlations with respect to the experimental data (Figs. 3b-d). In general the Thome et al. 2004 correlation over predicted by 210%. For all mass flux and vapor quality values the Lee and Mudawar 2005 correlation under predicted by 70% and over predicted by 105%. These values for the Lee et al. 2010 correlation is 82% and 130% respectively. However the Liu and Winterton 1991 correlation under predicted the heat transfer coefficient by 47% for mass flux values of 44 kg/m2.s and higher (Fig. 3e).

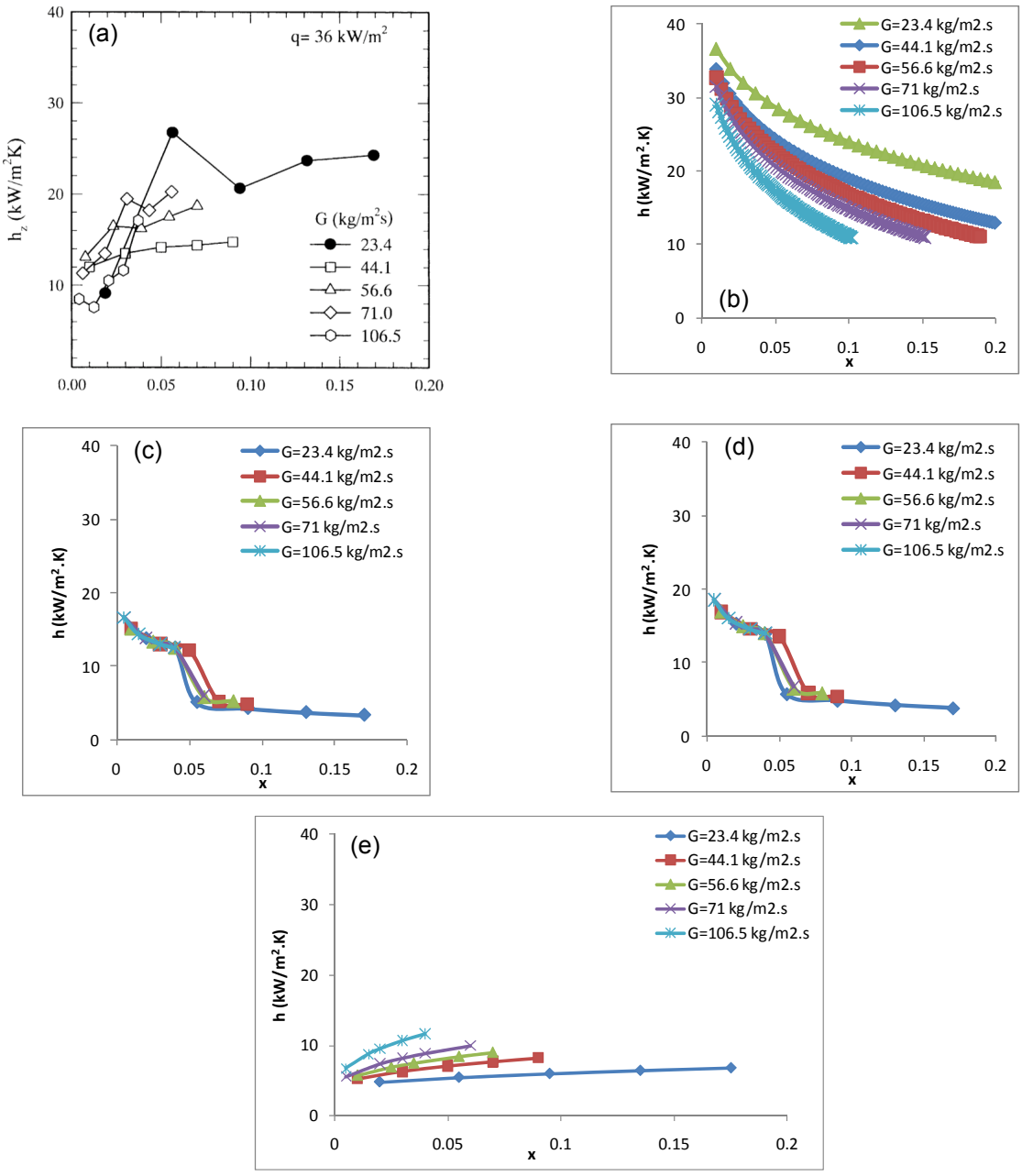


Figure 3. (a) Experimental data of Sumith et al. 2003 for H_2O, d=1.45 mm, (b) Thome et al. 2004 correlation, (c) Lee and Mudawar 2005 correlation, (d) Lee et al. 2010 correlation, (e) Liu and Winterton 1991 correlation.

Based on the results obtained for H_2O above, the correlations of Lee and Mudawar 2005, Lee et al. 2010 and Liu and Winterton 1991 were applied to the experimental data of Steinke and Kandlikar 2004 for H_2O obtained in microchannels with a hydraulic diameter of 207 μm (Figs. 4a-d). Figs. 4b, c show that even if they represent the same trend the Lee and Mudawar 2005, Lee et al. 2010 correlations under predicted by 47% and 40% for the heat flux value of 55 kW/m2 and vapor quality values of 0.05 and lower. These correlations over predicted the heat transfer coefficient 145% and 135% for the other heat flux and vapor quality values. As seen in Figs. 4b, c the heat transfer coefficient values calculated by Lee et al. 2010 are close to the values obtained by Lee and Mudawar 2005. For a constant hydraulic diameter the adjustment factor f is a function of the surface tension. High surface tension values result in f values close to unity. As the heat transfer coefficient values of Lee et al.

2010 are calculated by the division of the Lee and Mudawar 2005 correlation's values by f, similar values are obtained for both models. The results of the Liu and Winterton 1991 correlation are in the opposite trend and it under predicted the heat transfer coefficient by 57% (Fig. 4d).

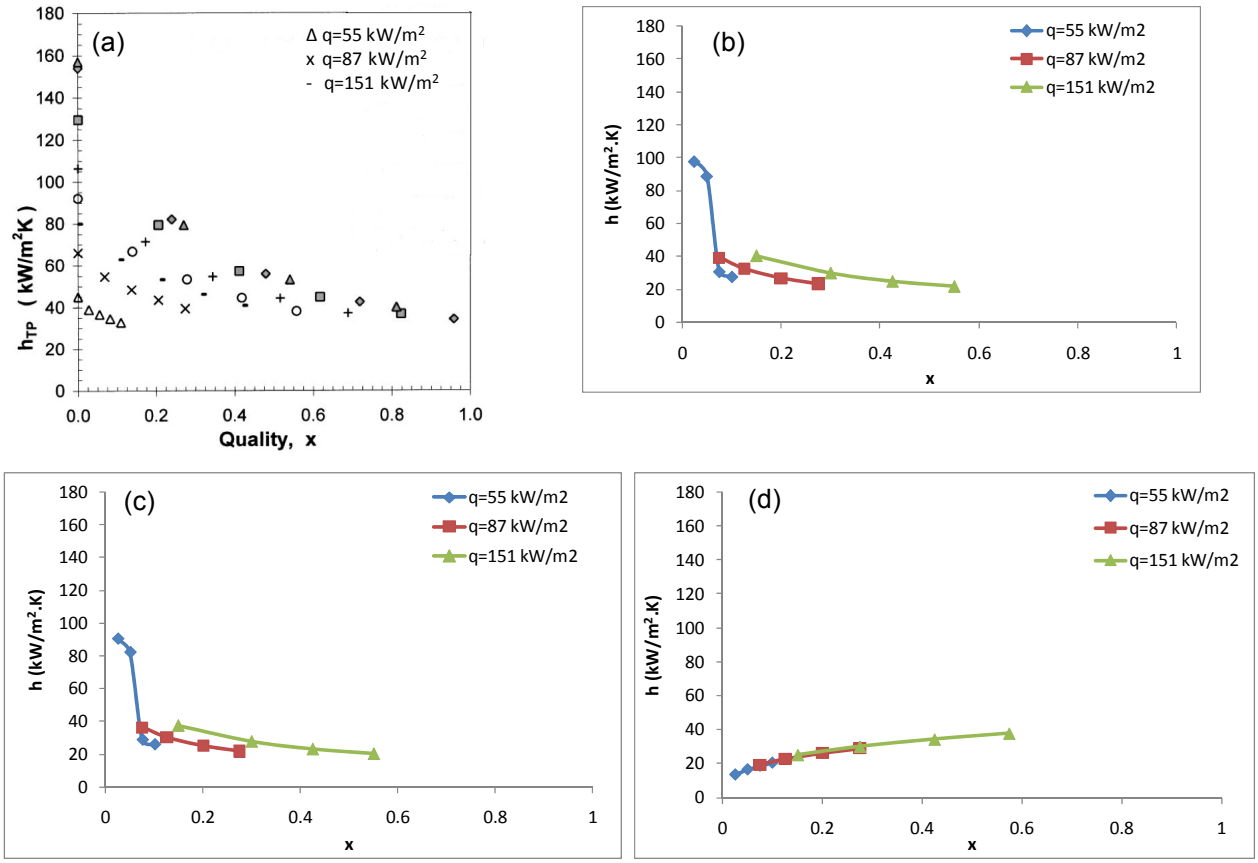


Figure 4. (a) Experimental data of Steinke and Kandlikar 2003 for H_2O, d=207 μm, (b) Lee and Mudawar 2005 correlation, (c) Lee et al. 2010 correlation, (d) Liu and Winterton 1991 correlation.

2.2 Pressure Drop during Evaporation

The Lee et al. 2010 correlation was applied and compared with the experimental data of Brutin and Tadrist 2004 for the pressure drop of n-pentane during evaporation for a tube of 889 μm in diameter (Figs. 5a,b). The pressure drop values for low Reynolds numbers were under predicted by 85.1%.

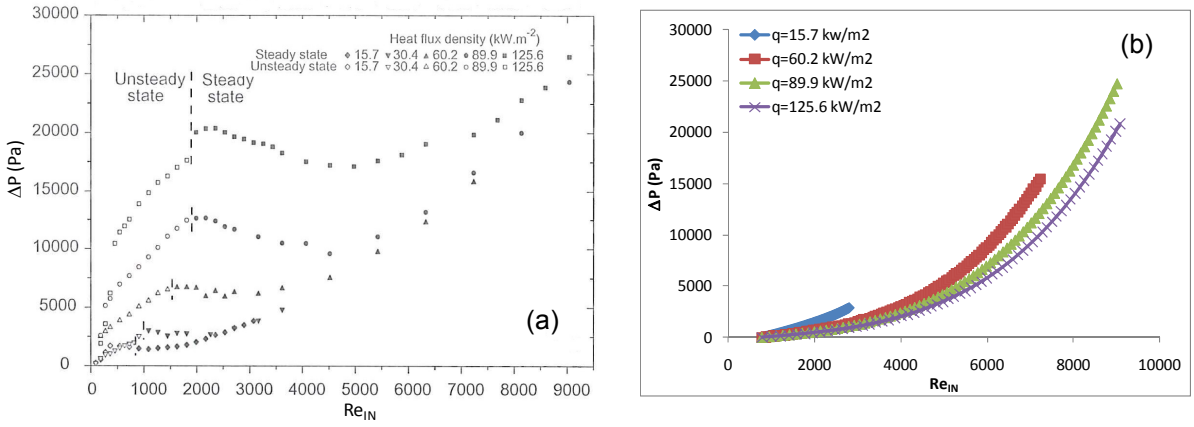


Figure 5. (a) Experimental data of Brutin and Tadrist 2004 for n-pentane, d=889 μm, (b) Lee et al. 2010 correlation.

As seen in Figs. 6a,b same correlation was compared with the pressure drop data of Field and Hrnjak 2007 for propane obtained in a tube of 148 μm in diameter. The Lee et al. 2010 correlation under predicted the pressure drop values by 97.7% for the vapor quality values lower than 0.7 (Fig. 6b). Fig. 6a shows the comparison done by Field and Hrnjak 2007 with other correlations. The Lee et al. 2010 correlation outperforms the Lee and Lee 2001 and Lee and Mudawar 2005 correlations.

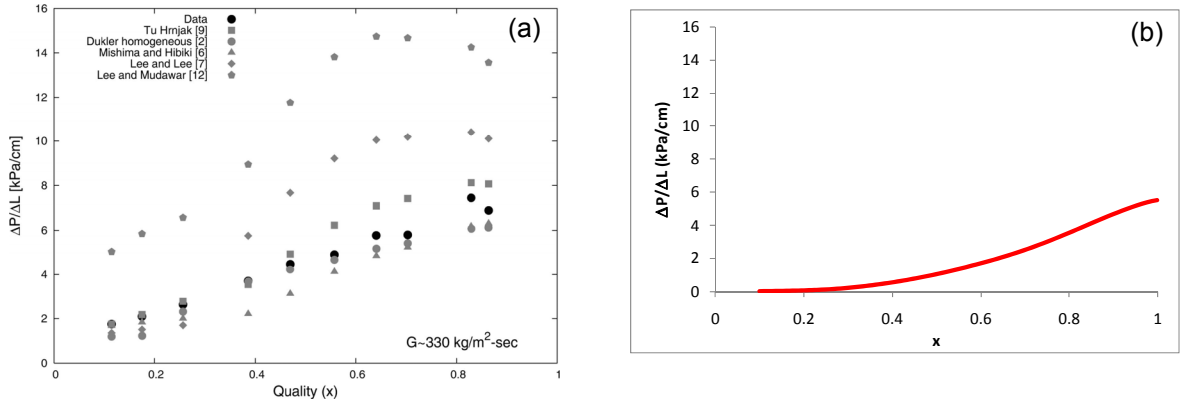


Figure 6. (a) Experimental data of Field and Hrnjak 2007 for propane, d=148 μm, (b) Lee et al. 2010 correlation.

2.3 Heat Transfer during Condensation

The research group of Cavallini performed comprehensive experimental study on the condensation of refrigerants. Different models were applied together with their model to the experimental data. They suggested the disagreement between experimental and calculated values to be searched for in the liquid entrainment. Based on this criterion, they recommended a heat transfer model for condensation in minichannels which takes into account the effect of the entrainment rate of droplets from the liquid film (Cavallini et al. 2006). The agreement between the Cavallini et al. 2006 data for R-134a, R-410A, and R-236ea in an l.4 mm-inner diameter minichannel and predictions from their model is satisfactory.

Bandhauer et al. (2006) developed an experimentally validated model for the calculation of heat transfer coefficients during condensation of R-134a in microchannels with 0.506 < d < 1.524 mm. It was shown that the models developed for larger tubes result in significant deviations from the measured data, primarily because those models were not intended for,

and could not account for, the flow phenomena and interfacial shear behavior specific to microchannels. In view of these observations, a model was developed with the primary difference being the computation of interfacial shear based on pressure drops in microchannels measured and modeled by the authors in earlier work.

Figure 7 shows the comparison of the results obtained by these two correlations with the experimental data of Ağra and Teke 2008 obtained in a tube with 4 mm in diameter for R600a. As seen in Fig. 7 the predictions from these models are satisfactory where the Cavallini et al. 2006 correlation under predicted by 17% and the Bandhauer et al. 2006 correlation under predicted by 6.8% and over predicted up to 17.3%.

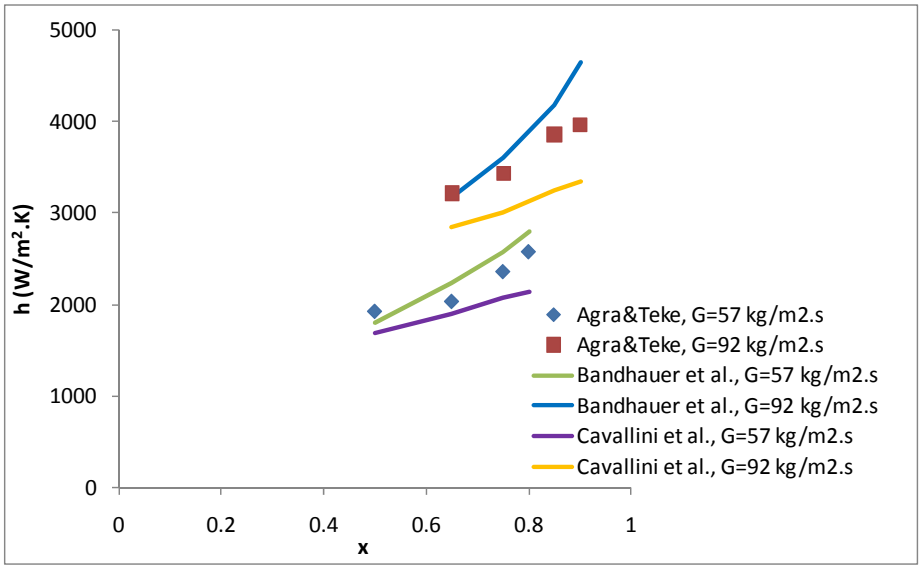


Figure 7. Application of the correlations to the experimental data of Ağra and Teke 2008 for R600a, d=4 mm.

The correlations were also applied to the data of Wu et al. 2008 to compare the experimental and calculated results for steam (Fig. 8). The experimental results were obtained for a tube with 128.5 μm in diameter. The Bandhauer et al. 2006 correlation was not applicable to the given conditions. The heat transfer coefficient was under predicted up to 21% and over predicted up to 18% by the Cavallini et al. 2006 correlation.

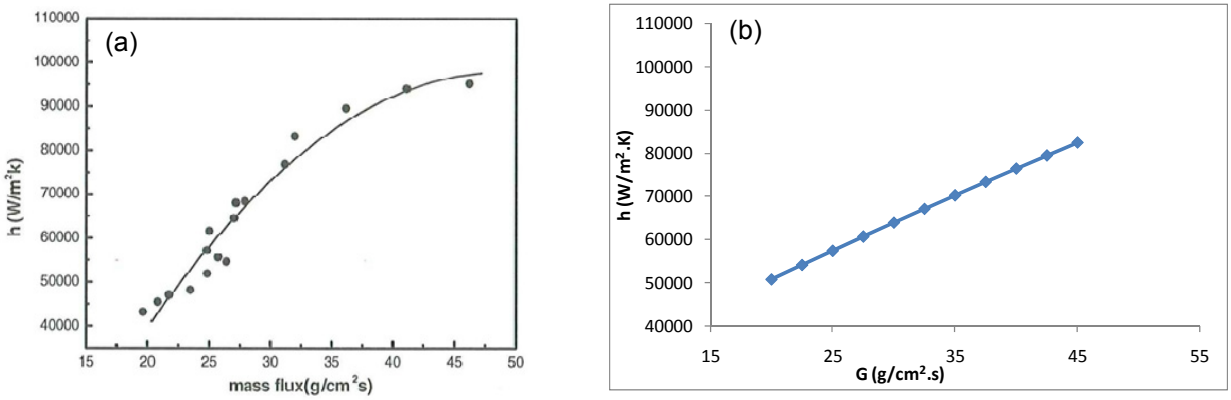


Figure 8. (a) Experimental data of Wu et al. 2008 for propane, d=128.5 μm, (b) Cavallini et al. 2006 correlation.

2.4 Pressure Drop during Condensation

Garimella et al. 2002 measured two-phase pressure drop in five circular channels ranging in hydraulic diameter from 0.5 mm to 4.91 mm. A pressure drop model was developed for a unit cell in the channel based on the observed slug/bubble flow pattern for these conditions. The unit cell comprises a liquid slug followed by a vapor bubble that is surrounded by a thin, annular liquid film. The correlation for non-dimensional unit-cell length based on slug Reynolds number was used to estimate the total pressure drop during condensation.

3 PREDICTION OF HEAT TRANSFER AND PRESSURE DROP FOR NH_3/H_2O MIXTURE

3.1 Heat Transfer during Evaporation

The correlations were applied to calculate the heat transfer coefficient of NH_3/H_2O mixture. The findings for the effect of the vapor quality on the heat transfer coefficient are similar for the Thome et al. 2004 and Lee and Mudawar 2005 correlations. The heat transfer coefficient decreases with the vapor quality at constant mass flux (Fig. 9). However the heat transfer coefficient increases with the vapor quality for the Liu and Winterton 1991 correlation. The Lee et al. 2010 correlation was not plotted because the values obtained with this correlation are very close the ones obtained with Lee and Mudawar 2005 correlation.

As also seen in Fig. 9 the heat transfer coefficient increases with the mass flux slightly for the Lee and Mudawar 2005 correlation and it increases significantly for the Liu and Winterton 1991 correlation whereas it decreases with the mass flux for the Thome et al. 2004 correlation. It can be concluded that experimental data is required for NH_3/H_2O mixture to compare with the correlations.

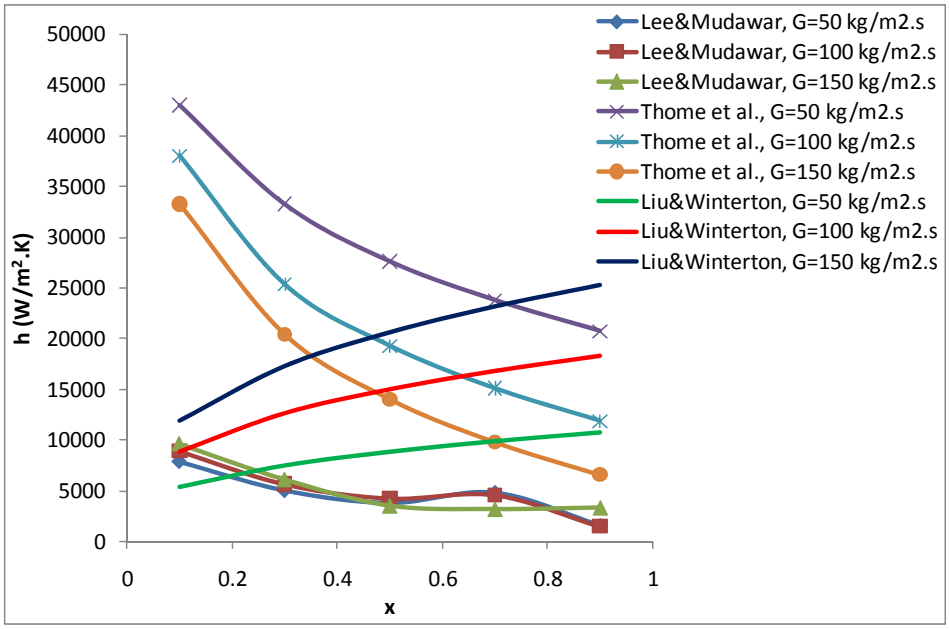


Figure 9. Application of the correlations to NH_3/H_2O mixture, d=0.5 mm.

3.2 Pressure Drop during Evaporation

The Lee et al. 2010 correlation was also applied to NH_3/H_2O mixture to predict the pressure drop during evaporation. As seen in Fig. 10 the exponential increase of the pressure drop with the mass flux is represented as expected. However experimental data is required for the quantitative analysis.

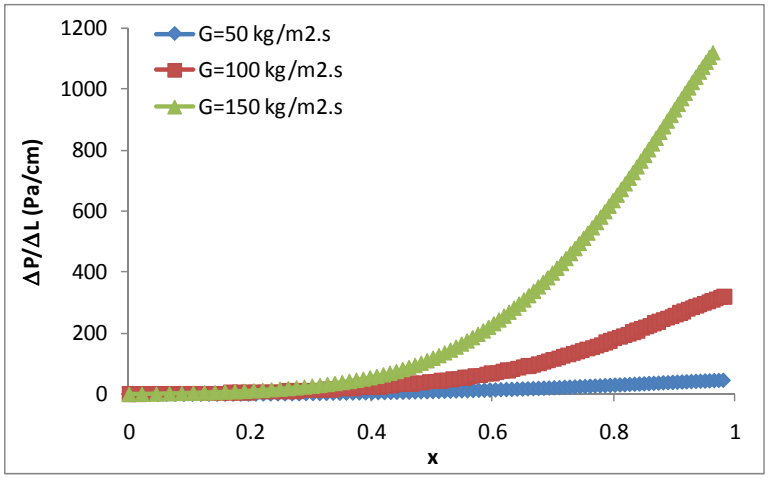


Figure 10. Application of the Lee et al. 2010 correlation to NH_3/H_2O mixture, d=0.5 mm.

3.3 Heat Transfer during Condensation

Cavallini et al. 2006's correlation was applied to NH_3/H_2O mixture to predict the heat transfer coefficient during condensation (Fig. 11). The Bandhauer et al. 2006 correlation was not applicable to NH_3/H_2O mixture. The Cavallini et al. 2006 correlation predicted the effect of vapor quality and mass flux qualitatively as expected but experimental data is essential for the quantitative analysis of the model.

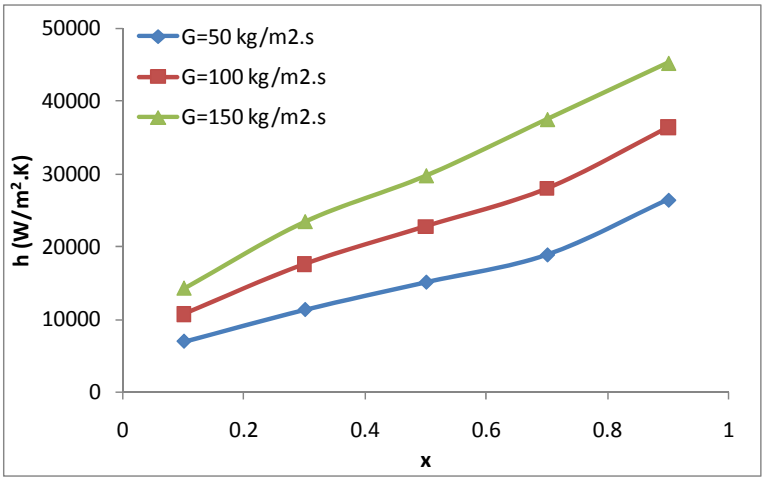


Figure 11. Application of the Cavallini et al. 2006 correlation to NH_3/H_2O mixture, d=0.5 mm.

3.4 Pressure Drop during Condensation

As seen in Fig. 12 the Garimella et al. 2002 correlation was applied to NH_3/H_2O mixture for the calculation of pressure drop during condensation. As mentioned previously for the other correlations, experimental data is needed for the validation of these results.

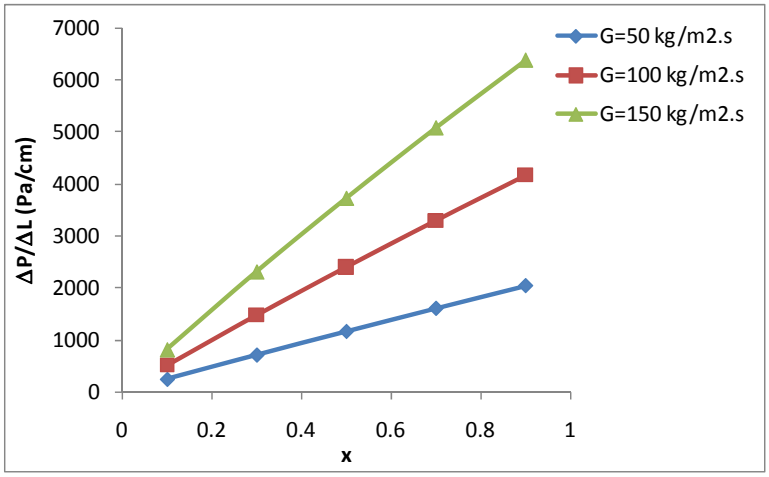


Figure 12. Application of the Garimella et al. 2002 correlation to NH_3/H_2O mixture, d=0.5 mm.

4 RESULTS AND DISCUSSION

The comparisons were done for a tube with 0.5mm in diameter and 0.1m in length at the mass flow rate of 100 kg/m^2.s. The heat flux is calculated as 19.1 kW/m^2. However the heat flux value introduced during the calculation of heat transfer coefficient during evaporation is in the range of 30 to 60 kW/m^2. This shows that longer tube length is needed.

The mean overall heat transfer coefficient is calculated as 5.8 kW/m^2.K if Lee and Mudawar 2005's heat transfer coefficient value is used. The power of the tube is 4.5 W and 222 tubes are needed for a power of 1 kW.

The mean overall heat transfer coefficient is found to be 12.7 kW/m^2.K if Liu and Winterton 1991's heat transfer coefficient value is used. The power is 10 W and 100 tubes are needed for a power of 1 kW.

The above results show the differences during the application of the models to calculate the power of a heat exchanger. Experimental data is needed for the selection of the appropriate model.

5 CONCLUSION

Some recent models have been selected to calculate pressure drop and heat transfer coefficient in micro/mini-channels during evaporation and condensation. The results were compared with the experimental data given in the literature for n-pentane, propane, R600a and H_2O. The models were also applied to predict pressure drop and heat transfer coefficient for NH_3/H_2O mixture. The results were used to calculate the size of a heat exchanger to be used in a CR heat pump system.

- Different results were obtained by different models for the heat transfer during evaporation. Experimental data is required for the selection of appropriate model.
- Pressure drop was found to be predicted as expected for evaporation but experimental data is required for the comparison of the results.
- Experimental data is also required to compare the results for pressure drop and heat transfer during condensation.

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