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Experimental investigation of heat transfer and pressure drop characteristics of ammonia–water in a mini-channel annulus

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ABSTRACT

The ammonia–water mixture is commonly used in absorption and compression–resorption heat pumps. The heat transfer performance of a vertically oriented mini-channel annulus operated with an ammonia–water mixture under absorption conditions has been experimentally investigated. Heat exchangers comprised of annuli can be used in compression–resorption heat pumps. Measurements have been executed in a channel with a hydraulic diameter of 0.4 mm and a length of 0.8 m with an average eccentricity of 0.6. The experiments are used to determine the heat transfer coefficient and pressure drop during absorption for different operating conditions along the channel. The measured heat transfer coefficients vary from 1000 to 10,000 W m^{-2} K^{-1}. Results are presented as function of heat flux, mass flux and vapor quality in order to investigate the dependency of heat transfer coefficients on the given variables. Mass flux is directly measured; vapor quality is obtained from equations of state with pressure and temperature at the inlet and outlet of each channel as input, assuming equilibrium conditions. The heat transfer coefficient increases with increasing mass flux, increasing inlet vapor quality and increasing heat flux. The heat transfer coefficient increases sharply between mass fluxes of 120 and 175 kg m^{-2} s^{-1} at low inlet vapor qualities and constant heat flux. The pressure drop shows an increasing trend with increasing mass flux and vapor inlet quality. The pressure drop measurements have been compared against empirical models from literature originally designed for tubes. One of these models is able to predict the measured pressure drop in the current channel within 25% deviation. The heat transfer performance was compared against empirical models from literature, which show very little agreement with the results from the experiments. The models are intended to predict condensation heat transfer in tubes, so they cannot fully take the annular geometry, eccentricity and mass transfer resistances into account, causing large discrepancies between predicted and experimental heat transfer coefficients.

1. Introduction

It has been shown that the application of high temperature heat pumps like compression–resorption heat pumps can be an attractive way to improve the efficiency of distillation processes. However, such heat pumps require relatively large heat exchangers. In order to reduce the size and cost of these heat exchangers, the application of mini-channel heat exchangers can be beneficial. Mini-channel heat exchangers have similar or smaller diameters than the capillary constant,

$$d = \sqrt{\frac{2\sigma}{g(\rho_L - \rho_V)}}$$

For mini-channels it has been long known that decreasing the channel size in heat exchangers increases heat and mass transfer performance. Reducing the channel size also results in larger heat transfer area per unit of volume which could possibly lead to cost reductions and lower material use. Experiments have been executed on a diversity of fluids in mini channels of different shapes [1,2]. However, the heat and mass transfer performance in mini-channel size annuli has not been investigated often. Heat and mass transfer data for ammonia–water mixture, a fluid used in absorption and compression–resorption heat pumps, is missing. For single phase flow the use of annuli proved to increase the Nusselt numbers of laminar flows and thus the heat transfer coefficient [3]. Similar advantage is expected when using mini channel annuli in heat pumps.

A significant amount of experimental work has been done on condensation in annuli, although data in open literature is still limited. Honda et al. [4] and Nozu et al. [5] performed experiments in

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Nomenclature

A	area
d	diameter
f	friction factor
g	gravitational constant
h	enthalpy
L	length
$\dot{m}$	mass flow
Nu	Nusselt number
P	pressure
Pr	Prandtl number
q	vapor quality
$\dot{Q}$	heat transfer rate
Re	Reynolds number
r	radius
T	temperature
U	overall heat transfer coefficient
u	velocity
x	molar concentration
z	axial coordinate

Greek symbols

α	heat transfer coefficient
ρ	density
λ	thermal conductivity
μ	viscosity
σ	surface tension

Subscript

ann	annulus
avg	average
h	hydraulic
i	internal
L	liquid
o	outside
V	vapor
w	wall

the annulus of a double tube coil heat exchanger with 4 straight lengths and 3 u-bends with surface enhancements on the inner tube using R-11 and R-113 and using the non-azeotropic mixture R-114/R-113 (Nozu et al. [6]). In these experiments the inner tube had an outer diameter of 19.1 mm and the outer tube had an inner diameter of 24.8, 25.0, 27.2 and 29.9 mm. Mass fluxes ranged from 50 to 300 kg m^{-2} s^{-1}. The heat transfer coefficient was shown to be larger at higher vapor qualities and in U-bends, and the variation of the heat transfer coefficient between U-bends and straight sections was shown to be decreasing for lower vapor qualities. The vapor mass transfer coefficient for the mixture showed the same behavior. The local heat transfer coefficient was increased by 2–13 times compared to an annular tube without enhancements. In [4] an empirical equation for the local heat transfer coefficient was developed in which surface tension controlled flow models were introduced for flows with low vapor velocities and vapor shear controlled flow models were introduced for high vapor velocity flow regimes.

Wang and Du [7] discuss an analytical model for vapor flowing through horizontal annuli accounting for gravity, vapor shear and surface tension. They concluded that the vapor shear stress and surface tension influenced the condensing flow by influencing the distribution of liquid over the tube. Comparing their model with experiments led to the conclusion that the Nusselt number for most data is predicted within 30% accuracy.

Yan and Lin [8] numerically studied natural convection during condensation and evaporation in annuli with both the inner and the outer surfaces heated. Their main conclusion was that the latent heat greatly increased the heat transfer coefficients compared to single phase flows.

Wang et al. [9] analyzed turbulent downward gas/condensing vapor flow inside an annulus using an analytical model developed using available correlations for interfacial shear stress. The model was compared against experimental data for steam–air flows through annuli by Stewart et al. [10] and Kasprzak and Podpora [11]. The obtained heat transfer coefficient proved to be greatly dependent on Reynolds number and ratio between inner and outer diameter. Relatively large tube ratios significantly enhanced condensation rates.

Bandhauer et al. [12] did experiments with R-134a, R-123 and R-12 inside micro-channels with $0.506 < d < 1.524$ mm under different operating conditions. The measured heat transfer data showed large differences from the models developed for larger channels mainly because the flow regime and interfacial shear force played a more significant role.

Park et al. [13] experimented with R-1234ze inside a multiport extruded tube with a hydraulic diameter of 1.45 mm for each square channel. They found trends of decreasing heat transfer coefficient with decreasing mass flux, vapor quality and increasing saturation temperature. The heat transfer coefficient was unaffected by entrance conditions or condensation heat flux.

The condensation of R-152a inside circular 1.152 mm diameter and square 0.952 mm hydraulic diameter mini-channels has been investigated experimentally by Liu et al. [14]. Both pressure drop and heat transfer coefficients were shown to increase with mass flux and vapor quality. Similarly to what is reported by Park et al. [13], the heat transfer coefficient decreased with increasing saturation temperature. For single phase flows the heat transfer coefficient agreed with the correlations proposed by Gnielinksi [15].

Cavallini et al. [16] performed a comprehensive experimental study on the condensation of refrigerants. Different models were applied to the experimental data together with their own model. They suggested that the disagreement between experimental and calculated values are the result of liquid entrainment. Based on this criterion, they recommended a heat transfer model for condensation in mini-channels which takes into account the effect of the entrainment rate of droplets from the liquid film. The agreement between the data for R-134a, R-410A, and R-236ea in an l.4 mm-inner diameter mini-channel and predictions from their model was satisfactory. The general trend was increasing heat transfer coefficient with increasing mass flux and vapor quality.

Koyama et al. [17] indicated that the shear stress plays an important role in determining the heat transfer coefficient. They proposed a correlation that takes into account the effect of both forced and free convection where the forced convection term is calculated based on the frictional pressure drop.

Wang et al. [18] showed that at low mass fluxes or vapor quality a stratified flow pattern prevails where the heat transfer is governed by conduction across the film. At higher mass fluxes or quality the pattern changes to annular flow in which forced convection is the dominating heat transfer mode. Their model is able to take flow transitions into account.

Garimella et al. [19] measured two-phase pressure drop in five circular channels ranging in hydraulic diameter from 0.5 mm to