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NH_3 in-tube condensation heat transfer and pressure drop in a smooth tube

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ABSTRACT

This paper presents an overview of the issues and new results for in-tube condensation of ammonia in horizontal round tubes. A new empirical correlation is presented based on measured NH_3 in-tube condensation heat transfer and pressure drop by Komandiwirya et al. [Komandiwirya, H.B., Hrnjak, P.S., Newell, T.A., 2005. An experimental investigation of pressure drop and heat transfer in an in-tube condensation system of ammonia with and without miscible oil in smooth and enhanced tubes. ACRC CR-54, University of Illinois at Urbana-Champaign] in an 8.1 mm aluminum tube at a saturation temperature of 35 °C, and for a mass flux range of 20–270 kg m^{-2} s^{-1}. Most correlations overpredict these measured NH_3 heat transfer coefficients, up to 300%. The reasons are attributed to difference in thermophysical properties of ammonia compared to other refrigerants used in generation and validation of the correlations. Based on the conventional correlations, thermophysical properties of ammonia, and measured heat transfer coefficients, a new correlation was developed which can predict most of the measured values within ±20%. Measured NH_3 pressure drop is shown and discussed. Two separated flow models are shown to predict the pressure drop relatively well at pressure drop higher than 1 kPa m^{-1}, while a homogeneous model yields acceptable values at pressure drop less than 1 kPa m^{-1}. The pressure drop mechanism and prediction accuracy are explained though the use of flow patterns.

Condensation et transfert de chaleur et chute de pression de NH_3 à l'intérieur d'un tube lisse

Mots clés : Échangeur de chaleur ; Condenseur ; Tube horizontal ; Ammoniac ; Enquête ; Expérimentation ; Transfert de chaleur ; Chute de pression ; Corrélation

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Nomenclature

C_p	specific heat ($J\,kg^{-1}\,K^{-1}$)
D	tube diameter (m)
dP/dz	pressure drop per unit length ($kPa\,m^{-1}$)
g	acceleration of gravity ($m\,s^{-2}$)
G	mass flux ($kg\,m^{-2}\,s^{-1}$)
h	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
h_{lv}	latent heat of vaporization ($J\,kg^{-1}$)
HTC	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
Pr_l	Prandtl number for liquid phase $Pr = \mu_l C_p l/k_l$
T	temperature (K or °C)
u	mean velocity of a phase
x	vapor quality

Greek symbols

α	void fraction
δ	liquid film thickness
θ	angle for a tube surface where stratified liquid does not flow at a stratified flow region (rad)
μ	viscosity ($N\,s\,m^{-2}$)
ρ	density ($kg\,m^{-3}$)
σ	surface tension ($N\,m^{-1}$)

Subscripts

forced	forced convection condensation
free	free convective condensation
in-tube	in-tube condensation
l	liquid
lo	liquid only
sat	saturation
v	vapor
vo	vapor only
w	tube wall

1. Introduction

Ammonia (NH_3) has been used as a working fluid in refrigeration systems since 1850s. Even though NH_3 has toxicity and an offensive odor, it is an environment friendly refrigerant with zero ODP (ozone depletion potential) and zero GWP (global warming potential). For low temperature applications such as −40 °C, a two-stage NH_3 refrigeration system and a CO_2/NH_3 cascade system are widely used. In both systems, NH_3 is a working fluid in the high-temperature side of the systems as shown in Fig. 1, and heat is rejected to the environment during NH_3 in-tube condensation. For system design engineers, prediction of NH_3 in-tube condensation heat transfer and pressure drop in tubes at saturation temperatures close to 40 °C is a critical issue. However, most well known correlations for in-tube condensation heat transfer coefficients were generated without NH_3 data. Numerous questions of adequacy of these correlations were raised because of observed differences between estimated and calculated heat exchanger performances. The reasons are speculated to be due to the thermophysical properties of ammonia which are very different from those fluids used for experimental validation. Because of these differences, extrapolation may not be suitable.

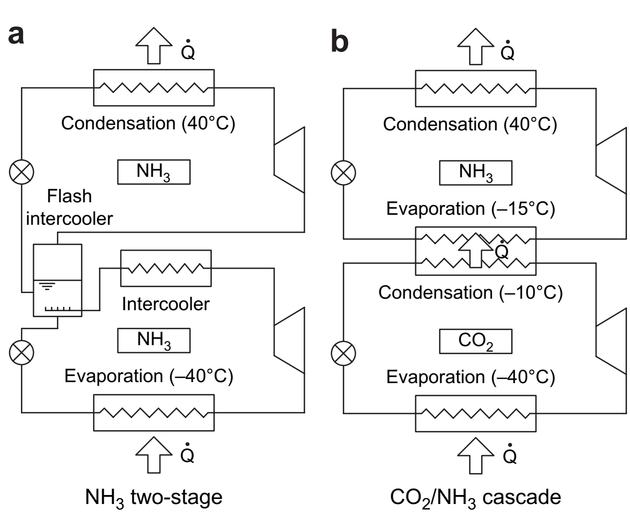

Fig. 1 – Schematic diagrams for a (a) NH_3 two-stage and (b) CO_2/NH_3 cascade system.

Even though the NH_3 in-tube condensation in tubes about 40 °C is an interesting research topic, experimental data for this temperature range are rarely presented in open literature. The NH_3 condensation in microchannel heat exchangers was studied by Litch and Hrnjak (1999). Recently, ASHRAE funded work in heat transfer and pressure drop was performed by Vollrath et al. (2003) and Komandiwirya et al. (2005) at the temperatures near 35 °C. In this study, the experimental data for an 8.1 mm aluminum smooth tube presented by Komandiwirya et al. (2005) are summarized and explained. Their experimental data for in-tube condensation heat transfer and pressure drop are compared with predicted values of general correlations and comparison results are analyzed using thermophysical properties of NH_3. Based on the measured NH_3 heat transfer coefficients, a developed correlation is proposed.

2. NH_3 in-tube condensation heat transfer in a tube

2.1. *Experimental results for NH_3 in-tube condensation heat transfer*

Fig. 2 presents NH_3 in-tube condensation heat transfer coefficients measured by Komandiwirya et al. (2005). The heat transfer coefficients are almost independent of mass fluxes and vapor quality at the mass fluxes lower than 80 $kg\,m^{-2}\,s^{-1}$. For mass fluxes of 120 $kg\,m^{-2}\,s^{-1}$ and higher, heat transfer coefficient is a strong function of vapor quality and mass flux. This dissimilar heat transfer trend at different mass flux conditions can be explained by the relation between the heat transfer mechanism and the flow patterns. It is a widely