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Experimental investigations and an updated correlation of flow boiling heat transfer coefficients for ammonia/lithium nitrate mixture in horizontal tubes

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ABSTRACT

In this work, experiments have been performed to investigate the flow boiling heat transfer coefficients (HTC) of ammonia/lithium nitrate mixture in horizontal smooth tubes with different internal diameters (4 mm, 6 mm). According to the practical working conditions of absorption refrigeration system, the ammonia concentration for the tested ammonia/lithium nitrate mixture was selected as 45.0 wt%, and the boiling temperature of tests were in the range of 78–90 °C. The effects of boiling temperature, heat flux, mass flux and tube size on the flow boiling HTCs were investigated in this article. Results show that higher heat and mass fluxes as well as heat transfer tube with larger diameter tend to exert positive influence on flow boiling HTCs of the present study cases. Based on more than 600 groups of experimental data, a new correlation was proposed to predict the effects of mass flux, heat flux, and tube size on flow boiling HTCs for $NH_3/LiNO_3$ mixture under investigated conditions, with a mean deviation less than ±10%. The new correlation will be of great significance to the design and optimization of generators in the practical absorption refrigeration units using ammonia/lithium nitrate mixture.

1. Introduction

In October of 2016, representatives from nearly 200 nations adopted the Kigali Amendment to reduce the emission of greenhouse gases, specifically hydrofluorocarbons (HFCs). Under such a circumstance, the development of absorption refrigeration technologies gains increasing popularity in the field of refrigeration, for its advantages of saving energy and protecting environment.

Compared with the traditional vapor compression refrigeration, absorption refrigeration is able to make use of waste heat and eliminate the leakage problem of refrigerants with greenhouse effect [1]. According to the literature [2,3], absorption refrigeration is being tried to apply in the fields with low-grade waste thermal energy, such as vehicles or ships. As reported, the exhaust gas from the transportation facilities takes up almost 35% of the total energy generated from fuel combustion in the engine [4]. Hence recovering this large amount of waste heat can be an effective method to reduce energy consumption. However, for these mobile facilities, it is necessary to realize the miniaturization of absorption refrigeration system when considering the practical application requirements. With the distinct advantages over the traditional absorption working pairs, ammonia/salt mixtures contribute to reducing the overall size of absorption chillers, considered to be the most possible ones for practical application in small capacity refrigeration units [5]. And many efforts have been made to achieve this goal. Moreno-Quintanar et al. [6], Cai et al. [7] and Zamora et al. [8] conducted experimental evaluations on small-capacity absorption chillers with ammonia/salt mixtures; Táboas et al. [9] theoretically demonstrated its feasibility for practical application in fishing ships. The state-of-the-art research results not only indicate the possible application of ammonia/salt absorption chillers on practical occasions in mobile facilities, but also encourage further research on relevant fields.

The exhaust heat from engines can be directly recovered by fin and tube heat exchangers. Hence, the fin and tube heat exchangers can be applied as generators of absorption refrigeration units. The most critical components of an absorption cycle are respectively the absorber and generator, working efficiencies of which to a great extent determine the overall performance of the practical cycle. Hence, the improvement and optimization of the components become a heated research direction [10,11]. As described in our

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Nomenclature

Bo	boiling number, $Bo = \frac{q}{h_{fg}G}$
C_g	friction factor for gas, $C_g = 0.046$
C_l	friction factor for liquid, $C_l = 16$
Co	Convection number, $Co = \left(\frac{1-x}{x}\right)^{0.8}\left(\frac{\rho_g}{\rho_l}\right)^{0.5}$
d	diameter of inner tube, mm
d_b	diameter of bubble, m
d_e	equivalent diameter, mm
D	diameter of outer tube, mm
G	mass flux, $kg \cdot s^{-1} m^{-2}$
h	convective heat transfer coefficient, $W \cdot m^{-2} K^{-1}$
h_{fg}	latent heat of vaporization, $kJ \cdot kg^{-1}$
HTC	heat transfer coefficient, $W \cdot m^{-2} K^{-1}$
ID	inner diameter, mm
L_{ef}	effective length, mm
m	mass flow rate, $kg \cdot s^{-1}$
MAD	mean absolution deviation
MRD	mean relative deviation
P	pressure, kPa
Pr	Prandtl number
q	heat flux, $W \cdot m^{-2}$
q_v	volume flow rate, $m^3 \cdot s^{-1}$
Q	heat flow rate, kW
RD	relative deviation
Re	Reynolds number
T	temperature, K or °C
w	ammonia mass concentration of solution, %
We	Weber number, $We = \frac{G^2 d}{\sigma\rho}$
x	vapor quality
X	Lockhart-Martinelli parameter, $Re_l > 1000$, $Re_g > 1000$, $X = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_g}{\rho_l}\right)^{0.5}\left(\frac{\mu_l}{\mu_g}\right)^{0.1}$ $Re_l < 1000$, $Re_g > 1000$, $X = \left(\frac{C_l}{C_g}\right)^{0.5} Re_g^{-0.4}\left(\frac{G_l}{G_g}\right)^{0.5}\left(\frac{\rho_g}{\rho_l}\right)^{0.5}\left(\frac{\mu_l}{\mu_g}\right)^{0.5}$

Greek symbols

α	angle, rad
λ	heat conductivity, $W \cdot m^{-1} K^{-1}$
μ	dynamic viscosity, $Pa \cdot s$
ρ	density, $kg \cdot m^{-3}$
σ	surface tension, $N \cdot m^{-1}$

Subscript

B	boiling region
cv	convective
exp	experimental
g	gas phase
i	internal diameter
l	liquid phase
m	mean
nb	nucleate boiling
o	outlet
pred	predicted
s	solution
sub	subcooled region
tp	two-phase
w	wall

previous work [12], the measurement of the flow boiling heat transfer coefficient (HTC) inside horizontal heat transfer tubes is essential for the optimal design of the fin and tube type generators in the exhaust-gas driven absorption chillers. But there are only two open publications related to the flow boiling heat transfer of ammonia/salt mixtures inside tubes, which will cause much impediment when designing the heat exchanger that serves as the generator. Rivera and Best [13] firstly started an experimental investigation of the flow boiling HTC of ammonia/lithium nitrate mixture in a vertical tube with internal diameter of 16.2 mm. It was found that the HTC of $NH_3/LiNO_3$ mixture was two to three times lower than that of NH_3/H_2O mixture. And the experimental data could be predicted well using the correlation from Mishra et al. Then our previous paper [12] presented the flow boiling HTC of ammonia/lithium nitrate mixture in a smooth horizontal tube with the internal diameter of 8 mm, with all the test conditions based on the practical working condition. The experimental results showed that the maximum flow boiling HTC could reach 2100 $W \cdot m^{-2}$ K^{-1} and that Kandlikar's correlation is appropriate to predict the flow boiling HTCs.

On the basis of the authors' previous work, the present study provides a further discussion on flow boiling HTCs of ammonia/lithium nitrate solution inside horizontal tubes. Compared with the measurement of boiling HTC in other heat transfer structures like plate heat exchangers [14,15], the experimental data of the flow boiling HTC for ammonia/lithium nitrate mixture inside tubes is too scarce to develop a general correlation. Moreover, with the trend of using small tubes and micro-structures in the heat exchanger, the measurement of the flow boiling HTC inside tubes should contain more different structural parameters, for example, different diameters of tubes and tubes with inner fins [16,17]. Therefore, this work experimentally investigated the flow boiling HTCs of ammonia/lithium nitrate mixture in horizontal smooth tubes with different internal diameters. Although the available correlations for flow boiling HTCs predictions are appropriate for pure refrigerants or refrigerant mixtures, relatively high deviations are caused by those correlations in flow boiling HTCs prediction of ammonia/salt solution [12]. A good number of experimental data were obtained by the present study, based on which a new correlation that modified from existing model was proposed to predict the flow boiling HTC of ammonia/lithium nitrate mixture inside horizontal smooth tubes. Variations of the flow boiling HTC with structural and test parameters were also presented in this paper.

2. Experimental facility

A detailed description of the test facility used in this study can be found in the previous work [12]; however, it is briefly described here for completeness. As shown in Fig. 1, the experimental facility can be divided into three parts: the solution absorption loop, the cooling water loop, and heating water loop. The $NH_3/LiNO_3$ mixture was pumped from the absorber into the test section which could be regarded as the generator in this loop. The test section in the experimental facility was composed of horizontal smooth stainless annular tubes, the dimensions of which are summarized in Table 1. In the test section, the $NH_3/LiNO_3$ mixture flowed inside the inner tube. And the heating water from the high-pressured heating water vessel, flowing inside the outer tube, provided heat for the $NH_3/LiNO_3$ mixture in the test section. The function of the solution subcooler and the pipeline heater was to ensure the subcooled temperature of the $NH_3/LiNO_3$ mixture before entering the test section. After the flow boiling process happened in the test section, the gas-liquid mixture went into the absorber wherein