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Flow boiling heat transfer characteristics and pressure drop of R290/oil solution in smooth horizontal tubes

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ABSTRACT

R290/oil solution is a potential working pair of absorption refrigeration systems. This paper presents experimental results of flow boiling heat transfer coefficients of R290/oil solution in smooth horizontal tubes with inner diameters of 4, 6 and 8 mm. The R290 mass concentration of the solution at the inlet of the test section is about 15%. Mass flux, heat flux and boiling temperature are in the ranges of 221–387 kg/m^2 s, 14–27 kW/m^2 and 59–71 °C, respectively. The effects of mass flux, heat flux, exit vapor quality, boiling temperature and inner diameter on flow boiling heat transfer coefficients have been investigated. Results show that when compared with other operating parameters, the variation of the solution properties triggered by boiling temperature has the most obvious influence on boiling heat transfer coefficient. And the decrease of inner diameter of the test section will be beneficial to the flow boiling heat transfer. The present experimental results are also compared with experimental data from other literature as well as predicted values of various existing correlations. It is found that the correlation of Gungor and Winterton has the highest precision, with a mean deviation of ±15.75%. Pressure drops of the solution side are also measured under different test conditions. The results of the present study will be of great help to the application of R290/oil solution and the design and optimization of finned tube heat exchangers (generators) in absorption refrigeration systems.

1. Introduction

Nowadays due to the rising energy consumption and environmental challenges especially caused by the conventional vapor compression refrigeration, absorption refrigeration techniques have attracted increasing attention in both residential and industrial applications. Compared with vapor compression refrigeration, absorption refrigeration can not only reduce the energy consumption, but also eliminate the refrigerant leakage problem which intensifies the greenhouse effect and ozone depletion [1,2].

When it comes to the field of absorption refrigeration, perfect absorption working pairs have been being searched without a pause, for the reason that the existing research does not fulfill all the requirements from various applications. Conventional absorption refrigeration systems always use NH_3/H_2O or $H_2O/LiBr$ as working pairs. However, practical systems with these two working pairs have obvious disadvantages, such as the need of rectifier for the NH_3/H_2O absorption system and the inability of offering cooling capacities below 0 °C for the $H_2O/LiBr$ absorption system [3].

In recent years, NH_3/salt mixtures have promoted the researchers' increasing interests for their outstanding advantages compared with the traditional ones [4–6]. Whereas, NH_3/salt absorption refrigeration systems have the risk of crystallization and the working pairs are corrosive to copper. Some other kinds of working pairs, for example, R22-E181, R134a-E181 [7], R124-organic absorbents [8], also have been studied by the researchers. But the refrigerants of these mixtures have high global warming potential or ozone depletion potential, which is of great harm to the environment.

On the other hand, many researches have been done on utilizing R290 as refrigerant in the field of vapor compression refrigeration [9]. The solubility of R290 with refrigeration oil is high enough so that R290/oil solution can be used as working pairs of absorption refrigeration. Unlike absorption refrigeration systems using other working pairs, R290/oil absorption refrigeration systems are able to operate normally at evaporating temperature below 0 °C without the rectifier and have no risk of crystallization. Besides, the working pairs are noncorrosive to general metallic materials. R290 is a natural refrigerant that has very low global warming potential and zero ozone depletion potential. Up to now, research about applying R290/oil solution in absorption refrigeration is

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Nomenclature

Bo	boiling number
Co	convection number
c_p	specific heat capacity, J kg^{-1} K^{-1}
d	diameter of inner tube, mm
d_e	equivalent diameter, mm
D	diameter of outer tube, mm
Fr	Froude number
G	mass flux, kg s^{-1} m^{-2}
Gr	Grashof number
h	heat transfer coefficient, W m^{-2} K^{-1}
h_f	latent heat, kJ kg^{-1}
HTC	heat transfer coefficient, W m^{-2} K^{-1}
L	length, m
L_{ef}	effective length, mm
m	mass flow rate, kg s^{-1}
P	pressure, kPa
Pr	Prandtl number
q	heat flux, W m^{-2}
q_v	volume flow rate, m^3 s^{-1}
Q	heat flow rate, kW
r	radius of inner tube, mm
Re	Reynolds number
RTD	resistance temperature detector
s	liquid specific gravity at 15.56 °C, kg m^{-3}
S_{he}	heat exchange square, m^2
T	temperature, K or °C
V	volume, m^3
x	vapor quality

Greek symbols

δ	wall thickness, mm
ε	specific area of heat transfer, m^{-1}
Δt_m	logarithmic mean temperature difference, K or °C
λ	heat conductivity, W m^{-1} K^{-1}
μ	dynamic viscosity, Pa s
ν	kinematic viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}
ω	mass concentration of solution, %

Subscripts

B	boiling region
crit	critical
g	gas phase
h	heating water
i	inlet
in	inner wall
l	liquid phase
m	mean
man	manufacturer
o	outlet
oil	oil
out	outer wall
s	solution
r	refrigerant, R290
steel	steel
sub	subcooled region
TP	two phase
v	vapor
w	wall

limited. Dadah et al. [3] studied a solar absorption air conditioning system using R290/AB3000 refrigeration oil. The results showed that the system operated well at specific operating condition and COP of the system was as high as 1. Fukuta et al. [10] theoretically and experimentally investigated the performance of a compression/absorption hybrid refrigeration cycle using R290/mineral oil as working pairs. The calculation results showed that COP of the cycle was high and the cycle was feasible. The experimental results showed that absorption efficiency was a key factor that influenced the performance of the system. According to these limited research, it can be concluded that R290/oil mixtures are satisfactory to be used in absorption refrigeration systems.

In practical absorption refrigeration systems, finned tube heat exchangers are widely used as the generators to recover exhaust heat for its large heat transfer area [11,12]. To design the finned tube heat exchanger (the generator) optimally, it is necessary for researching the flow boiling heat transfer coefficient (HTC) of the working pairs inside horizontal tubes. Some scholars have measured the boiling HTCs of various working pairs in different heat transfer structures. For HTCs of absorption working pair inside horizontal tubes, Jiang et al. [13] published experimental data on flow boiling heat transfer of $NH_3/LiNO_3$ solution in a smooth horizontal tube with mass flow rate ranging from 20 kg/h to 55 kg/h and boiling temperature ranging from 76.7 °C to 93.2 °C. The results showed that nucleate boiling was predominant during the tests. Further, a correlation used to predict the boiling HTCs of the NH_3/salt solution was proposed by Jiang et al. [14] based on more than 600 groups of experimental data. The correlation was appropriate to predict the experimental data with a mean deviation less than ±10%. Rivera and Best [15] published experimental data on flow boiling HTCs of ammonia-lithium nitrate mixture in a vertical tube with ammonia concentration of 38–48 wt%. It was reported that the average HTCs of $NH_3/LiNO_3$ mixture were two to three times lower than that of NH_3/H_2O mixture.

For plate heat exchangers, Táboas et al. [16] experimentally investigated flow boiling heat transfer coefficients and the pressure drop of ammonia/water mixture in a plate heat exchanger with heat flux range of 20–50 kW/m^2, mass flux range of 70–140 kg/m^2 s, mean vapor quality range of 0.0–0.22 and pressure range of 7–14 bar for ammonia concentration between 0.42 and 0.62. The authors reported that the boiling HTCs were highly dependent on the mass flux and the pressure drop was mainly influenced by the mass flux and vapor quality. Besides, Táboas et al. [17] published experimental data on flow boiling HTC and pressure drop of ammonia/lithium nitrate and ammonia/(lithium nitrate + water) in a plate heat exchanger. The results showed that convective boiling was predominant and the addition of water had effects on the flow boiling heat transfer. Zacarías et al. [18] also carried out study on the HTCs and pressure drops of ammonia-lithium nitrate solution. However, the working conditions of Zacarías et al. had some differences with that of Táboas [17] on mass flux, heat flux, generating pressure and solution concentration. Thus, the experimental results of Zacarias et al. showed that nucleate boiling appeared to be the dominant factor, which was different with the results of Táboas.

According to the previous literature, R290/oil solution is a potential working pairs for absorption refrigeration due to its appropriate thermophysical properties and the advantages of environmental-friendly features. Although there have been lots of researches about flow boiling heat transfer coefficients of pure