International Journal of Heat and Mass Transfer 108 (2017) 220–231

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Flow boiling heat transfer characteristics and pressure drop of ammonia-lithium nitrate solution in a smooth horizontal tube

Jingkai Jiang [a], Guogeng He [a], Yilin Liu [b], Yue Liu [c], Dehua Cai [a,*]

[a] School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
[b] State Key Laboratory of Coal Combustion, Huazhong University of Science and Technology, Wuhan 430074, China
[c] China-EU Institute for Clean and Renewable Energy, Huazhong University of Science and Technology, Wuhan 430074, China

ARTICLE INFO

Article history:
Received 26 August 2016
Received in revised form 1 November 2016
Accepted 4 December 2016

Keywords:
Ammonia/lithium nitrate solution
Horizontal tube
Flow boiling heat transfer
Pressure drop

ABSTRACT

This paper presents experimental results of flow boiling heat transfer coefficient of ammonia/lithium nitrate solution in a smooth horizontal tube with diameter of 10 mm. The test conditions are selected based on practical working conditions of absorption refrigeration system with ammonia/lithium nitrate solution. The ammonia concentration of the solution at the inlet of test section is around 45.5 wt%. The mass flow rate and boiling temperature of the solution are in the ranges of 20–55 kg/h and 76.7–93.2 °C, respectively. The effects of the heat flux, mass flux and exit vapor quality has been investigated. The maximum flow boiling heat transfer coefficient reaches 2100 $W \cdot m^{-2} K^{-1}$. Results show that heat fluxes have significant influence on boiling heat transfer coefficients (HTCs). Nucleate boiling is found to be predominant during the tests. The experimental results are also compared with the available flow boiling heat transfer coefficients of $NH_3/LiNO_3$ solution and predicting correlations in literature. Kandlikar's correlation is appropriate to characterize the experimental boiling heat transfer coefficients with a mean deviation of ±12.56%. Pressure drops in the solution side are also measured under different working conditions. The results of the present study will be of great significance to the design and optimization of generators in the absorption refrigeration units using ammonia/lithium nitrate solution.

1. Introduction

For transportation facilities like vehicles or ships, exhaust gas carries significant amount of heat, as much as 35% of the thermal energy generated from combustion in the engine [1]. One of the promising way to recover the waste heat is to employ the absorption refrigeration system. This will in whole or part replace the traditional vapor compression refrigeration (VCR) usually installed on vehicles or ships. Compared with VCR, absorption refrigeration not only reduces the total energy consumption, but also eliminates the refrigerant leakage problem which does contribute to global warming [2,3].

Up to now, much research has been done on utilizing the waste gas heat from engines by employing absorption refrigeration system with traditional working pairs. Ramanathan and Gunasekaran [4] conducted simulation on exhaust gas-driven absorption refrigeration system using water-lithium bromide pair. Koehler et al. [5], Rêgo et al. [6] and Manzela et al. [7] presented experimental studies of exhaust gas-driven absorption refrigeration systems with ammonia-water pair. Compared with the traditional working fluids, ammonia/salt absorption refrigeration cycles are considered to be the most possible ones for practical application in small capacity refrigeration units [8]. Ammonia/salt refrigeration cycles are able to provide cooling capacity with temperature below 0 °C without vacuum problems. In addition, rectifiers are not needed in ammonia/salt absorption refrigeration cycles. The latest experimental evaluations on the ammonia/salt absorption refrigeration system, from Cai et al. [9], Moreno-Quintanar et al. [10] and Zamora et al. [11], indicated its feasibility for practical application.

When applied in exhaust-gas driven absorption chillers, ammonia/salt solution highlights its advantages in some actual application situations. The refrigeration units with small cooling capacity are appropriate for the automobiles like long-distance trucks which are usually driven on high ways with a small number of passengers. Energy carried by high temperature exhaust-gas from engines are sufficient to drive absorption systems with ammonia/salt solution. Additionally, advantages of ammonia/salt solution suits well for fishing ships. Almost all the fishing ships need refrigeration system to produce ice for preserving the catch. Táboas et al. [12] theoretically demonstrated that, in fishing ships, the minimum evaporation temperatures of refrigeration cycles

* Corresponding author.
E-mail address: 490316551@qq.com (D. Cai).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.12.004
0017-9310/

Nomenclature

Bo	boiling number
Co	convection number
d	diameter of inner tube, mm
d_e	equivalent diameter, mm
D	diameter of outer tube, mm
Fr	Froude number
G	mass flux, $kg \cdot s^{-1}\ m^{-2}$
Gr	Grashof number
h	convective heat transfer coefficient, $W \cdot m^{-2}\ K^{-1}$
HTC	heat transfer coefficient, $W \cdot m^{-2}\ K^{-1}$
i	specific enthalpy, $kJ \cdot kg^{-1}$
L	length, m
L_{ef}	effective length, mm
m	mass flow rate, $kg \cdot s^{-1}$
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
Re	Reynolds number
RTD	resistance temperature detector
T	temperature, K or °C
w	mass concentration of solution, %
x	vapor quality

Greek symbols

δ	wall thickness, mm
Δt_m	Logarithmic mean temperature difference, K or °C
λ	heat conductivity, $W \cdot m^{-1}\ K^{-1}$
μ	dynamic viscosity, $Pa \cdot s$
ρ	density, $kg \cdot m^{-3}$

Subscript

B	boiling region
g	gas phase
h	heating water
i	inlet
in	inner wall
l	liquid phase
m	mean
NH_3	ammonia
o	outlet
out	outer wall
s	solution
steel	steel
sub	subcooled reigion
TP	two phase
v	vapor

with $NH_3/LiNO_3$ solution can achieve −18.8 °C when the activation temperature is set to 85 °C and that the $NH_3/LiNO_3$ fluid mixtures have higher values of COP when compared with NH_3/H_2O fluid mixture. Hence, ammonia/salt absorption refrigeration systems driven by exhaust gas have high potential for practical application in vehicles or fishing ships.

In practical application, finned tube heat exchangers are widely adopted to recover exhaust heat, which can serve as the generators in the exhaust-gas driven absorption chillers due to the large heat transfer area [13,14]. To achieve an optimal design of the finned tube heat exchanger (the generator in the absorption system), it is necessary to have a better knowledge of the flow boiling heat transfer coefficients (HTC) of the working fluids inside tubes. According to previous literature, some scholars have started to measure the boiling HTCs of ammonia/salt solutions in different heat transfer structures. For inside tubes, Rivera and Best [15] published experimental data on flow boiling HTC of ammonia-lithium nitrate mixture in a vertical tube with ammonia concentration of 38–48 wt%. It was reported that the HTC of $NH_3/LiNO_3$ mixture was two to three times lower than that of NH_3/H_2O mixture. This is the only open publication about the flow boiling HTC of ammonia/salt solution inside tubes. For plate heat exchangers (PHE), Zacarias et al. [16] and Táboas et al. [17] experimentally studied the HTCs and pressure drops of ammonia-lithium nitrate solution. The operating conditions in these two studies had some differences on mass flux, heat flux, generating pressure and solution concentration. Due to these different operating conditions, the boiling HTC of $NH_3/LiNO_3$ solution and the dominant boiling mechanism in these two experiments were quite different. In [16], nucleate boiling appeared to be the dominant factor. In [17], convective boiling most influenced the flow boiling HTC. For pools, Sathyabhama and Ashok Babu [18] investigated the nucleate pool boiling heat transfer of ammonia-water-lithium nitrate mixture with low ammonia mass fraction from 0 to 0.3. It indicated that the HTC decreased with an increase in the ammonia mass fraction. In short, to the knowledge of the authors, only a few studies were carried out on the flow boiling HTC of ammonia/salt solutions and no publications were found to provide that in horizontal tubes.

The gas-liquid heat exchangers made of smooth stainless steel tubes with external fins are quite common in the market, which can be directly applied in ammonia-salt absorption refrigeration system as generators. In this work, the flow boiling heat transfer coefficient and pressure drop in a smooth horizontal tube are experimentally evaluated for ammonia/lithium nitrite solution, which will be of great help to the design and optimization of the exhaust-gas-driven generator in the absorption refrigeration systems with ammonia/lithium nitrate solution. Variations of the flow boiling HTC with heat flux, mass flux and exit vapor quality are presented.

2. Experimental facility and procedure

2.1. Experimental facility

An experimental facility was constructed to measure the boiling HTC of $NH_3/LiNO_3$ solution in smooth horizontal tubes. Also, the pressure drop across the smooth tube can be measured. The schematic and the photograph of the experimental facility are shown in Figs. 1 and 2, respectively. The experimental facility can be divided into three parts: the solution absorption loop, the cooling water loop and heating water loop.

The main components of the solution absorption loop are: ammonia absorber, solution subcooler, pipeline heater, test section (generator), solution precooler and solution cooler. In this loop, $NH_3/LiNO_3$ solution was pumped from the bottom of the absorber into the pipeline heater after filtered and cooled and then entered the test section. The solution subcooler and the pipeline heater were utilized to adjust the subcooling temperature before entering the test section. The pipeline heater was automatically regulated based on the solution inlet temperature of the test section via a PID controller. The mass flow rate of the tested mixture was