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Experimental investigation of flow boiling heat transfer characteristics in smooth horizontal tubes using NH_3/NaSCN solution as working fluid

Dehua Cai [a], Yue Liu [b,c], Xiao Liang [a], Jingkai Jiang [d], Mingjing Fan [e], Guogeng He [a,*]

[a] School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
[b] China-EU Institute for Clean and Renewable Energy, Huazhong University of Science and Technology, Wuhan 430074, China
[c] Shenzhen Huazhong University of Science and Technology Research Institute, Shenzhen 518000, China
[d] Department of Mechanical Engineering, University of Minnesota, Minneapolis, MN 55455, United States
[e] Overseas Development Department, Qingdao Haier Air-conditioner Gen. Corp., Ltd, Qingdao 2660101, China

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ABSTRACT

Ammonia-sodium thiocyanate (NH_3-NaSCN) solution is an efficient absorption refrigeration working pair. This paper presents the experimental results of the flow boiling heat transfer coefficients (HTCs) of ammonia-sodium thiocyanate solution in horizontal tubes with three different inner diameters (4, 6 and 8 mm). The experimental measurements were conducted with different heat fluxes, mass fluxes, boiling temperatures and vapor qualities to determine their impact on the flow boiling heat transfer coefficients of the tested working pair. Comparison of NH_3-NaSCN and NH_3-$LiNO_3$ solution has been performed and higher flow boiling HTCs of NH_3-NaSCN solution than that of NH_3-$LiNO_3$ solution are obtained under similar working conditions. The results also indicate that the heat flux has the most significant influence on the flow boiling HTCs. The updated flow boiling HTCs prediction correlation for ammonia-salt working pair proposed by the authors' previous work has been validated by the present experimental results. The present study help to extend the basic researching results of NH_3-NaSCN working pair, which is of great significance to the design and optimization of generators in the absorption refrigeration units, and will ultimately be beneficial to energy saving for refrigeration area.

1. Introduction

Absorption refrigeration system has attracted increasing research interest in recent years. Compared with the conventional vapor compression refrigeration system, absorption refrigeration systems reduce large amount of total electric energy consumed by human society as the absorption system can be directly driven by thermal energy instead of electric energy. Besides, working substances used by absorption refrigeration cycles trend to be natural refrigerants, which cause zero Ozone Depletion problem and slight Global Warming Effect. Recently, energy resources depletion and the environmental disruption are the most concerned topics all over the world, The excellent energy saving and environmental-friendly features lead the absorption refrigeration technology to a competitive refrigeration technology [1,2].

Among the different working pairs in the absorption refrigeration system, the NH_3-H_2O and H_2O-LiBr solution are the most adopted working pairs and have been put into commercial use over the last decades. However, there are still some drawbacks of these two working pairs. The H_2O-LiBr system cannot provide cooling capacity at evaporating temperature below 0 °C due to the freezing feature of refrigerant water. The NH_3-H_2O system needs an extra rectifier at the outlet of the generator for refrigerant purification in the absorption system, which complicates the system and raises the cost. These aspects lead to negative effects on its commercial use and practical application especially in small capacity application. To overcome those problems, ammonia-salt working pairs (NH_3-$LiNO_3$ and NH_3-NaSCN) were proposed. Many studies have been conducted in ammonia-salt absorption refrigeration cycles since these working pairs were proposed. Recently, ammonia-salts working pairs are considered to be the most possible ones for practical application in small capacity absorption refrigeration units [1]. When compared with the LiBr-H_2O system, ammonia-salt absorption refrigeration cycle can be driven by a lower temperature heat source and obtain much lower evaporating temperature, which greatly extend its application field. Another aspect, ammonia-salt absorption refrigeration cycle does not need a rectifier to rectify the refrigerant vapor leaving the generator, which helps to miniaturize the system and reduce the system cost. In

* Corresponding author.
E-mail address: gghe@mail.hust.edu.cn (G. He).

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Nomenclature

Bo	boiling number
Co	convection number
d	diameter of inner tube, m or mm
d_e	hydraulic diameter of annulus, m or 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
f_{ann}	friction factor of an annulus
F_{ann}	factor to take into account the dependence on d_i/d_o

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 region
TP	two phase
v	vapor
w	wall

addition, ammonia-salt system can provide cooling capacity in a wide temperature range, the evaporating temperature can be from below 0 °C to above 0 °C. Hence, the ammonia-salt absorption refrigeration system can operate under both air-conditioning and freezing working conditions. Cai et al. [3], Moreno-Quintanar et al. [4] and Zamora et al. [5] have presented their research on the performance evaluation of the ammonia-salt absorption refrigeration system to determine its feasibility for practical applications.

As it is mentioned above, absorption refrigeration can be driven by thermal energy. Low grade energy such as solar energy [6], industrial waste heat energy and exhaust gas heat [7] can be directly utilized in absorption refrigeration systems. For transportation facilities like vehicles and ships, exhaust gas from the engines carries significant amount of available heat energy. Conventionally, up to 35% of the total thermal energy generated from combustion in an automotive gas engine is discharged to the ambient through exhaust gas [8]. These wasted heat energies carried by the engine exhaust gas are always with high quality, the exhaust gas temperature can be as high as 600 °C. Meanwhile, there are a huge holdings of vehicles and ships around the world. So, recovering this amount of waste heat in the exhaust gas and applying to the absorption refrigeration system will help improve the overall energy efficiency of the internal combustion engines. Many scholars have done much research on utilizing the waste gas heat from engines by employing absorption refrigeration system with traditional working pairs. Ramanathan and Gunasekaran [9] conducted simulation on exhaust gas-driven absorption refrigeration system using water-lithium bromide pair as the working solution. Koehler et al. [10] Rego et al. [11] and Manzela et al. [12] presented experimental studies of exhaust gas driven absorption refrigeration systems with ammonia-water pair. When applied absorption chillers driven by exhaust gas, ammonia-salt solutions have many advantages over the ammonia-water and water-lithium bromide solutions in some actual application situations. For the automobile, such as the trucks that are driven for a long distance, the small cooling refrigeration units will provide enough cooing capacity for the drivers and the passengers. And the exhaust-gas heat and temperature from the engine with large heat loads and high temperature are sufficient to drive the absorption refrigeration system with ammonia-salt working pair. Ammonia-salt solutions are suitable not only for the vehicles, but also for the fishing ships. After the fishes are captured, one big problem for the fisher is how to preserve their catches and keep them fresh before landing. Driven by the engine exhaust heat, the ammonia-salt absorption system can work under freezing condition, which provides cooling capacity for preservation purposes of the catches. Táboas et al. [13] theoretically demonstrated that, in fishing ships, the evaporation temperatures of NH_3-$LiNO_3$ absorption refrigeration cycle can be the minimum to −18.8 °C. Besides that, the NH_3-$LiNO_3$ absorption refrigeration system have higher COP than that of NH_3-H_2O absorption system. Hence, absorption refrigeration system with ammonia/salt solutions driven by exhaust gas have high potential for practical application in vehicles and fishing ships respectively for air-conditioning and freezing purposes.

Another important aspect, solar driven absorption refrigeration technology plays an irreplaceable role in renewable energy utilization field. The solar radiation energy collected by solar heat-collecting tubes or parabolic collector can directly drive the absorption refrigeration cycle for air-conditioning, freezing and cooling capacity storage purposes. G. Moreno-Quintanar et al. [4] experimentally evaluated and compared a solar intermittent refrigeration system for ice production operating with the mixtures $NH_3/LiNO_3$ and $NH_3/LiNO_3/H_2O$. Evaporating temperatures as low as -8°C were obtained for a time period of 8 h. Quintanar et al. declared that the coefficient of performance of absorption system with $NH_3/LiNO_3/H_2O$ is 24% higher than that of $NH_3/LiNO_3$. F. Siddiqui et al. [6] analyzed a novel solar driven hybrid storage absorption refrigeration cycle from the exergo-economic point of view and found that the solution pump and generator showed the highest exergetic efficiencies. W. Rivera et al. [14] experimentally evaluated a solar intermittent refrigeration system for ice