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Numerical investigation of ammonia falling film absorption outside vertical tube with nanofluids

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ABSTRACT

In the last years the ammonia-water refrigeration cycle has been gradually improved by using nanofluid technology. In this work, a numerical model for the absorption of ammonia on a falling film was developed for different ammonia-water mixtures containing nanoparticles and dispersants. The variation of both falling film thickness and physical properties of the mixture were considered to find the best fitting model. Results show that when absorption pressure decreases or when initial concentration of mixture increases, the relative intensity of effect on absorption rate is weakened by the variation of thermal conductivity but enhanced by the variation of mass transfer coefficients and flow resistance, while the variation of mixture's viscosity exhibits very low effect. When the results are compared to similar experimental data for the ammonia falling film absorption with nanofluids, it was found that the heat and mass transfer are mainly affected by the film drag reduction and its physical properties. The numerical model obtained can be used for calculating the absorption rate of ammonia-water-nanofluid mixtures with acceptable accuracy, since 87% of relative errors are lower than 20%.

1. Introduction

Ammonia water absorption refrigerators have recaptured scientists' attention due to the phenomenon of global warming and ozone depletion. However, the performance of the absorption cycle needs to be improved because it is lower than the performance of the vapor compression refrigeration system. Since the size and performance of the absorber can significantly impact on the system's overall performance, the latest research have focused on the absorption enhancement unit. Generally, there are three methods to enhance the efficiency of heat and mass transfer of absorbers: the mechanical treatment, the chemical treatment, and nanotechnology [1].

A nanofluid is defined as a liquid suspension of particles whose diameter are smaller than 100 nm. As a result of the limitation of heat transfer in a working fluid, solid particles are dispersed throughout it to improve its thermal properties as well as its heat transfer coefficient. In recent years, nanofluids have been gradually used as engineering fluids because of their superior performance on stability [2,3], thermal conduction [4–6], thermal convection [7–10] and boiling heat transfer [11–16]. Recently, the nanofluids applied in ammonia water absorption refrigeration system have involved Cu, CuO [17], CNTs [18], Ag [19], Fe_2O_3, $ZnFe_2O_4$ [20], Al_2O_3 [21], and even nano emulsifier [22]. The performances of those kinds of nanofluids on absorbing ammonia were investigated for bubble or falling film absorption, and the results are satisfactory.

According to the research results of Kang et al. [23], the mass transfer coefficients has greater effect on system's performance running in bubble mode than that in falling film mode. Besides this, the heat transfer coefficients have more significant effects on heat exchanger size (absorption rate) in the falling film mode than in the bubble mode. The fluid flow and heat transfer aspects of nanofluids have been studied by many researchers. However, the researches on absorption process of ammonia by nanofluids are relatively deficient. A few existing literatures are mainly focused on the experimental studies with a predominating portion of bubble absorption type. A latest theoretical study on ammonia bubble absorption of nanofluids has been just found [18]. Nevertheless, to the authors' best knowledge, the theoretical study on ammonia falling film absorption of nanofluids has not been found. For this reason, there is a great need of theoretical research on

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Nomenclature

u	film velocity in the direction of falling, $m \cdot s^{-1}$
v	film velocity in the direction of film thickness, $m \cdot s^{-1}$
g	gravity acceleration, $m \cdot s^{-2}$
C_p	constant-pressure specific heat, $kJ \cdot kg^{-1} \cdot K^{-1}$
D_m	diffusion coefficient, $m^2 \cdot s$
T	temperature, °C
P	absorption pressure, MPa
K	mass transfer coefficient
m_{ab}	absorption amount in the interface of the control volume in unit time, $kg \cdot s^{-1}$
Δh_{ab}	heat of absorbing unit mass of ammonia gas, $kJ \cdot kg^{-1}$
M	gross absorption in unit time, $g \cdot s^{-1}$
S	mass transfer interface area of falling film, m^2
Re	Reynolds number
Sc	Schmidt number

Greek letters

ρ	density, $kg \cdot m^{-3}$
Γ	flow rate, $m^3 \cdot s^{-1}$
ξ	mass concentration of fluid, %
δ	film thickness, mm
λ	thermal conductivity, $W \cdot (m \cdot K)^{-1}$
η	dynamic viscosity, $Pa \cdot s$
τ	effective flow time in absorption, s
ν	kinematic viscosity, $m^2 \cdot s^{-1}$

Super/subscripts

i	vapor–liquid interface
in	inlet of falling film
w	cooling water
r	relative
n	nanofluid
f	basefluid
ff	falling film
s	solutions in containers and distributor
a	Fig. (a)
b	Fig. (b)
c	Fig. (c)

Abbreviations

AS	absolute slope of the fitting straight line about absorption rate
RS	relative slop, defined by the ratio of absolute slope to the absorption rate when λ_r (or η_r, K_r, τ_r) = 1

ammonia-water falling film absorption with nanofluid and hereby obtain the main variables of ammonia-water nanofluid falling film absorption. In this work, a numerical model for an ammonia-water-nanoparticles falling film absorption outside vertical tube was developed. The variation of falling film thickness along the tube and the changes in physical properties of ammonia-water mixture was considered when adding nanoparticles and dispersants. The influence of physical properties of nanofluids over the efficiency of ammonia-water absorption is studied in detail. Finally, the numerical results were compared with experimental data. It is expected that this study brings some basic ideas that help to understand how mixture's physical properties affect on the heat and mass transfer coefficients in the absorption process and also to establish some theoretical foundation for further research on the application of nanofluids.

2. Model descriptions

The physical model and mathematical model introduced herein are similar to our previous studies on numerical model of falling film absorption with ammonia-water affected by a magnetic field [24]. The difference in this work is that the magnetic field is replaced by a nanofluid, considering the changes in the mixture's flow and its physical properties when nanoparticles and dispersants are added. The detailed description about the physical model and mathematical model are presented at the end of this section.

2.1. Physical model

In conventional water-cooled absorption cooling devices, the solution flow takes place on the external surface of horizontal tubes in conventional falling film configuration of the absorber. However, wettability of the falling film affects the heat and mass transfer performance greatly. In order to observe, check and adjust the wettability of the falling film all through the experiment, the shell of the main body of the absorber is made up of transparent acrylic glass. Therefore, to observe the conditions of solution film distribution in real-time through the transparent shell of the absorber all through the experiment, the configuration selected for the absorber is that of falling film on the external surface of a vertical tube in our previous experimental study [20]. And in this paper, the combined and follow-up theoretical study also adopts this selection.

The process of ammonia falling film absorption outside vertical tube with nanofluids is shown in Fig. 1. The absorber unit consists of the top shell and the falling film tube. The ammonia water (or nanofluid) solution enters the absorber from the top and then it forms a film in the distributor, and finally it falls along the exterior surface of the heat-transfer tube. Ammonia gas enters to the absorber from the bottom and is evenly distributed in the absorber. Thus absorption heat is generated as a result of the absorption of ammonia vapor by the solution. Cooling water enters from the bottom of

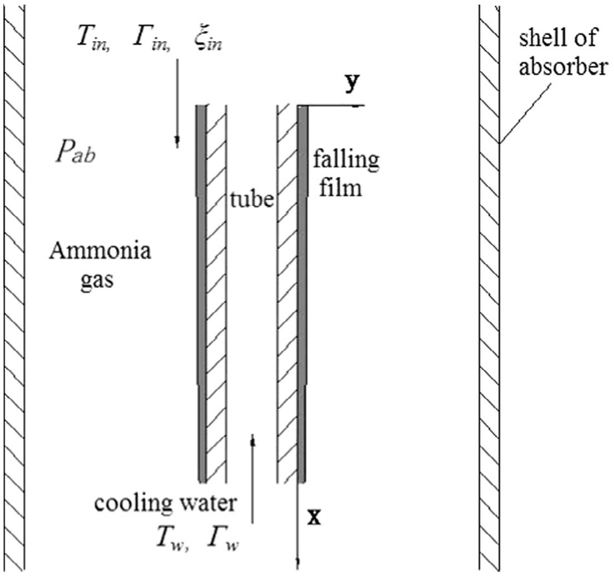

Fig. 1. Sketch of ammonia-water nanofluid falling film absorption.