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Experimental investigation for heat and mass transfer characteristics of R124-DMAC bubble absorption in a vertical tubular absorber

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ABSTRACT

Experimental investigation for a copper vertical tubular bubble absorber was done with R124 (2-chloro-l,l,l,2,-tetrafluoroethane)-DMAC (N′,N′-dimethylacetamide) as working fluid. The objective of the investigation was to explore key parameters affecting heat and mass transfer characteristics of the bubble absorber and propose new correlations for heat and mass transfer coefficients respectively for the R124-DMAC bubble absorption. The parameters include vapor and solution flow rates, solution inlet temperatures and mass fractions, nozzle orifice diameters and cooling water inlet temperatures. The results showed that to reduce the solution, cooling water inlet temperature and nozzle orifice diameter or to increase vapor and solution flow rate could enhance the heat and mass transfer performance of the absorber. Finally, correlations of Nusselt number and Sherwood number for calculating heat and mass transfer coefficients were proposed, respectively. Both correlations could predict about 90% of the experimental values at a margin of error less than 20%.

1. Introduction

Vapor absorption refrigeration systems (VARSs) are considered as a substitution of the vapor compression refrigeration system because they can be driven by waste heat [1,2]. Vehicle or ship engines will exhaust vast waste heat when they operate. If the waste heat can be recovered to drive VARS to meet cold energy demands for vehicles or ships, the energy consumption of those will be decreased. The conventional VARS with a falling-film type of absorber cannot normally work under vehicle or ship operation conditions, like slanting, swinging, jolting, speeding up and slowing down. However, the bubble absorber has been found to be available under the unstable conditions, since refrigerant vapor is always wrapped by solution during the absorption process [3,4]. In addition, the bubble type absorber is also considered to have better performances than the falling-film type absorber [5,6]. Therefore, the bubble absorber has a bright application prospect in the field of waste heat refrigeration technology for vehicles or ships, and some scholars have researched on bubble absorption characteristics.

For the traditional ammonia-water bubble absorption process, Kang et al. [7] studied the effect of key parameters, namely the orifice diameter, liquid mass fraction and vapor velocity, on the bubble absorption process in a cubic test section in which bubble behaviors were unconstrained. And an experimental correlation of mass transfer coefficient for the bubble absorption process was developed. Meanwhile, the heat and mass transfer performance of bubble absorption processes in plate-type absorbers were also studied by other scholars [8–12]. Research results showed that the key parameters affecting heat and mass transfer of bubble absorption performance were refrigerant vapor and absorption solution flow rates, absorption solution temperature and mass fraction, absorption pressure, cooling-water temperature and flow rate as well as nozzle orifice diameter and number. Increases of the vapor and solution flow rates, absorption pressure or cooling-water flow rate had positive effects on the absorber performance. However, increases of solution temperature and mass fraction had negative effects on the absorber performance. For the increase of cooling-water temperature, it could either negative [9] or positive [12,13] affect the solution heat transfer coefficient. A low cooling-water temperature at the absorber inlet would cause a high absorption thermal load and a high logarithmic mean temperature difference (LMTD) [12]. The negative or positive effect was dependent on the increase in the LMTD which was higher or lower than that of the absorption thermal load. In addition to those, the heat and mass transfer performance in the vertical tubular bubble absorber were also investigated by experiments and modeled analyses [13–16]. Generally, three kinds of flow patterns, churn, slug and bubble flow patterns would be formed in the absorber because

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Nomenclature

Abbreviation

COP	coefficient of performance
DMAC	N′,N′-dimethylacetamide
DMEDEG	diethylene glycol dimethyl ether
DMETEG	dimethylether tetraethylene glycol
DMEU	dimethylethylene urea
DMF	dimethylformamide
DMPU	dimethylpropylenurea
DMU	N,N′-dimethylurea
HCFCs	hydrochlorofluorocarbons
HFCs	hydrofluorocarbons
LMTD	logarithmic mean temperature difference
MCL	N-methyl ε-caprolactam
NMP	N-methyl-2-prrolidone
R124	2-chloro-l,l,l,2,-tetrafluoroethane
R125	pentafluoroethane
R134a	1,1,1,2-tetrafluoroethane
R22	monochlorodifluoromethane
R32	difluoromethane
VARS	vapor absorption refrigeration system
A	cross-section area, m^{2}
c_p	specific heat, J kg^{-1} K^{-1}
d_o	orifice diameter, m
D	inner diameter of inner tube, m
D_o	outer diameter of inner tube, m
D'	inner diameter of outer tube, m
D_c	diffusion coefficient, m^{2} s^{-1}
h	enthalpy, J kg^{-1}
K_{La}	volumetric mass transfer coefficient, kg m^{-3} s^{-1}
K	overall heat transfer coefficient, W m^{-2} K^{-1}
L	effective length of absorption tube, m
m	mass flow rate, kg s^{-1}
Nu	Nusselt number
P	pressure, MPa
Pr	Prandtl number
q_v	volumetric flow rate, m^{3} s^{-1}
Q	the absorber thermal load, W
Re	Reynolds number
s	standard deviation
Sc	Schmidt number
Sh	Sherwood number
t	temperature, °C
Δt	log mean temperature difference, °C
$\bar{t}$	average temperature, °C
u	uncertainty
x	mass fraction, kg kg^{-1}
Δx	log mean mass fraction difference, kg kg^{-1}
x^{*}	equilibrium mass fraction, kg kg^{-1}

Greek symbols

α	convective heat transfer coefficient, W m^{-2} K^{-1}
δ	thickness of inner tube, m
ρ	density, kg m^{-3}
μ	dynamic viscosity, Pa s
λ	thermal conductivity, W m^{-1} K^{-1}

Subscripts

c	cooling water
g	vapor
l	solution
in	inlet
o	orifice
out	outlet
w	tube wall

the bubbles were constrained by tube wall. The effect of key parameters on heat and mass transfer coefficients in the vertical tubular bubble absorber was similar to that in the plate-type absorber.

However, for ammonia-water mixture in which ammonia is used as refrigerant, the ammonia toxicity, flammability and high working pressure cooled by air restricted its application in vehicles or ships [13,17,18]. Fortunately, some organic working fluids might be applied to replace ammonia-water mixture in vehicles or ships. Nevertheless, up to now, only a few researches about heat and mass transfer in bubble absorption process using organic working fluids had been done, which brought much uncertainty to bubble absorber design and application with organic working fluids.

Mariappan et al. [19] designed a water cooled plate type bubble absorber which was applied to investigate R134a-DMAC bubble absorption process in it. The heat and mass transfer characteristics along the length of absorber were obtained by using thermo-physical properties experimental correlations. Sujatha et al. [20,21] carried out experiments and developed a numerical model for a vertical tubular bubble absorber with R22-DMF as working fluid. They compared the heat and mass transfer coefficients between the experimental data and numerical model results and found that the results were consistent well. Suresh and Mani [22,23] visualized the R134a-DMF bubble absorption process in a vertical glass tubular absorber. By visual bubble experiment, they discussed vapor, solution and cooling water flow rates, solution inlet mass fraction, pressure and temperature affected characteristics of heat and mass transfer during bubble absorption process. Finally correlations of mass transfer coefficient for R134a-DMF bubble absorption process were proposed.

Table 1 listed heat and mass transfer studies for bubble absorption with organic working fluids by experiments.

Though a few researches on bubble absorption processes with organic working fluids were done, other organic working fluids in which R32, R124, R134a, R125 are used as refrigerants and DMAC, DMETEG, DMEDEG, DMEU, DMPU, DMF, DMU, MCL or NMP are used as absorbents [24–28] still needs to be explored because they are suitable to be applied in vehicle or ship fields. In accordance with the technical requirements of waste heat refrigeration system for vehicles, the R124-DMAC organic working pair is thought to be more suitable. Under air cooling conditions, the R124-DMAC organic working pair has relatively low condensation pressure, low generation temperature, low solution circulation ratio and high coefficient of performance (COP) [25,26]. By using R124-DMAC as working fluids, Xu et al. [4,29] proposed an absorption-compression hybrid refrigeration cycle driven by exhaust gases and power from vehicle engines to reduce the fuel oil consumption for vehicle refrigeration systems, in which a bubble absorber cooled by air was applied.

Recently, the authors have done some work about visualizing bubble behaviors (as shown in Fig. 1, the bubble behavior was tracked form churn flow to bubble flow) for R124-DMAC in a glass vertical tubular absorber [3,30–32]. However, because of the weak thermal conductive of the glass absorber, the heat and mass trans-