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Heat and mass transfer characteristics of a constrained thin-film ammonia–water bubble absorber

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ABSTRACT

A study of absorption of ammonia vapour bubbles into a constrained thin-film of ammonia–water solution is presented. A large-aspect-ratio microchannel constrains the thickness of the weak solution film and ammonia vapour bubbles are injected from a porous wall. A counter flowing coolant in a minichannel removes the generated heat of absorption. Experiments and a simple one-dimensional numerical model are used to characterize the absorber performance at a nominal system pressure of 6.2 bar absolute. Effect of varying the mass flow rate of the weak solution, vapour flow rate, solution inlet temperature, and coolant inlet temperature on absorption heat and mass transfer rates and exit subcooling are discussed. Two absorber channel geometries, each of 600 μm nominal depth, are considered: 1) a smooth-wall channel, and 2) a stepped-wall channel that has 2-mm deep trenches across the width of a channel wall. Results indicate that the reduction in coolant inlet temperature significantly enhances the mass transfer rates in both absorber geometries. While the stepped-wall geometry exhibits higher mass transfer rates at lower coolant inlet temperatures of 30 °C and 40 °C, the smooth-wall channel shows higher mass transfer rates at the highest coolant inlet temperature of 58 °C. Both absorption limited and residence time limited conditions are observed with variation of weak solution flow rate at fixed vapour flow rates.

Absorbeur à bulles à ammoniac-eau aux pellicules minces limitées : caractéristiques du transfert de chaleur et de masse

Mots clés : Absorbeur ; Microcanal ; Bulle ; Ammoniac ; Eau

1. Introduction

High electric power rates and environmental concerns have stimulated a renewed interest in the development of smaller and more efficient vapour absorption refrigeration and air-conditioning systems (Herold et al., 1996). Among absorption systems, the use of ammonia as the refrigerant is beneficial because of its favorable refrigerant thermodynamic properties

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Nomenclature

A	heat exchange area, interfacial mass exchange area (m^2)
c_p	specific heat at constant pressure (J kg^{-1} K^{-1})
f	circulation ratio (unitless)
g_m	mass transfer conductance (kg m^{-2} s^{-1})
H	microchannel depth (m)
h	specific enthalpy of fluid stream (kJ kg^{-1})
$\dot{m}$	mass flow rate (kg s^{-1}, g min^{-1})
NTU	heat transfer unit (unitless)
P	pressure (Pa)
$\dot{q}$	heat rate (W)
Re	Reynolds number (unitless)
Re_v	Reynolds number for vapour; $2\dot{m}_v/\mu_v(W+H)$ (unitless)
$\dot{s}$	source rate (W)
T	temperature (K)
U	overall heat transfer coefficient (W m^{-2} K^{-1})
W	width of the microchannel (m)
X	mass concentration (unitless)

Greek

Δ	differential quantity
ΔT_{lm}	log-mean temperature difference (K)
$\Delta T_{sub,Exit}$	exit subcooling temperature (K)
ΔX_{lm}	log-mean mass concentration difference (unitless)
ε	heat transfer effectiveness (unitless)
ε_d	modified heat transfer effectiveness (unitless)

Subscripts

abs	absorber
c	coolant
g	gas
h	hot
i	inlet
in	inlet
max	maximum
min	minimum
out	outlet, exit
plate	across porous plate
s	solution
sat	saturation
smth	smooth wall
ss	strong solution, stainless steel
stp	stepped wall
sub	subcooling
v	vapour (anhydrous ammonia gas)
ws	weak solution

as well as its zero ozone depletion and global warming potential (Trott and Welch, 2000). The focus of the present study is on the absorber, a critical component of the system in terms of size and performance. Typically, two main types of absorbers are in use for ammonia–water systems: the falling film absorber and the bubble absorber. Falling film absorbers have the advantage of high heat transfer coefficient when using microchannel cooling tubes and low vapour pressure drop across the absorber. However, liquid distribution presents a significant challenge. In the bubble absorber, the area for mass transfer is large; however heat transfer in the solution needs to be enhanced. Also, in the bubble absorber, vapour distribution is of importance. Bubble absorbers offer advantages of compactness compared with falling film absorbers and of orientation/gravity independence. On the downside, the pressure drop needed to bubble the vapour into the solution is typically more significant compared with the falling film absorbers.

This paper presents the heat and mass transfer characteristics of a constrained thin-film ammonia–water bubble absorber under a typical cycle operating pressure. In literature, several investigators have experimentally and numerically studied bubble absorption heat and mass transfer performances on ammonia–water system. These studies have shown absorption to be dependent on different geometrical arrangements and flow conditions, each of which are discussed below.

1.1. *Absorber geometrical arrangements*

Vapour distribution and bubble dynamics have been shown to significantly impact the bubble absorber performance. Cerezo et al. (2009) used a corrugated plate heat exchanger in the bubble absorber mode. Their test section consisted of three parallel channels. Coolant flowed inside the outer channels of the absorber while the weak solution flowed in counter flow in the central channel. Vapour bubbles were injected at the inlet of the weak solution through a 1.7-mm-orifice. The maximum heat transfer coefficient and mass transfer conductance reported were 5400 W/m^2 K and 0.0063 kg/m^2 s, respectively, for an effective heat transfer area of 0.1 m^2.

Kim et al. (2003a,b) studied a bubble absorber that consisted of a long, vertical Pyrex glass tube. The weak solution flowed downwards in the tube while vapour bubbles, in counter flow, rose from the bottom of the tube. Low solution flow rates (16.7 g/min–58 g/min), typical of a generator–absorber–heat exchanger cycle, were tested. The Pyrex test section permitted visual studies of the flow without cooling. Coolant jackets were used around the tube for the non-visual studies. Observations of Kim et al. (2003a) confirmed a frost (churn) flow pattern near the entrance of the vapour, followed by a slug flow pattern with well-shaped Taylor bubbles throughout the rest of the absorber. No dry patches occurred on the walls of the test section, even at the lowest solution flow rate. For the 10 mm tube inner diameter, absorption lengths required were as high as 1.2 m for a vapour flow rate of 20 g/min. In a follow-up paper, Kim et al. (2003b) captured the effect of vapour dynamics by measuring a higher heat transfer coefficient in the frost region of the absorber compared to the slug flow region.

Jenks and Narayanan (2008) investigated absorption in a microchannel with vapour injection from one of the walls, see Fig. 1. The coolant was in counter flow to the solution and the injected vapour bubbles flowed along with the solution. Three different surface geometries and three different smooth-wall channel depths for a plate-type microchannel