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International Journal of Refrigeration 29 (2006) 1043–1052
REVUE INTERNATIONALE DU FROID
INTERNATIONAL JOURNAL OF
refrigeration
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Simulation study of a hybrid absorber–heat exchanger using hollow fiber membrane module for the ammonia–water absorption cycle

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Received 16 September 2005; received in revised form 30 January 2006; accepted 6 February 2006
Available online 5 June 2006

Abstract

An innovative hybrid hollow fiber membrane absorber and heat exchanger (HFMAE) made of both porous and nonporous fibers is proposed and studied via mathematical simulation. The porous fibers allow both heat and mass transfers between absorption solution phase and vapor phase, while the nonporous fibers allow heat transfer between absorption solution phase and cooling fluid phase only. The application of HFMAE on an ammonia–water absorption heat pump system as a solution-cooled absorber is analyzed and compared to a plate heat exchanger falling film type absorber (PHEFFA). The substantially higher amount of absorption obtained by the HFMAE is made possible by the vast mass transfer interfacial area per unit device volume provided. The most dominant factor affecting the absorption performance of the HFMAE is the absorption solution phase mass transfer coefficient. The application of HFMAE as the solution-cooled absorber and the water-cooled absorber in a typical ammonia–water absorption chiller allows the increase of COP by 14.8% and the reduction of the overall system exergy loss by 26.7%.

Keywords: Absorption system; Ammonia-water; Absorber; Design; Heat exchanger; Membrane; Fibre; Porous medium; Modeling; Simulation; Performance

Simulation d'un absorbeur/échangeur de chaleur hybride utilisant un module à membrane à fibre creuse dans un cycle à absorption ammoniac/eau

Mots clés : Système à absorption ; Ammoniac-eau ; Absorbeur ; Conception ; Échangeur de chaleur ; Membrane ; Fibre ; Milieu poreux ; Modélisation ; Simulation ; Performance

1. Introduction

The significance of ammonia–water absorption heat pump will increase due to the features of: (1) the

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0140-7007/$35.00
doi:10.1016/j.ijrefrig.2006.02.002

Nomenclature

A	Interfacial area, m^2
C_p	Heat capacity, $W\,K^{-1}$
d	Diameter of fiber, m
D	Diffusivity, $m\,s^{-1}$
h	Heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
H	Molar enthalpy, $J\,mol^{-1}$
$\overline{H}$	Partial molar enthalpy, $J\,mol^{-1}$
k_g	Gas phase mass transfer coefficient, $m\,s^{-1}$
k_l	Liquid phase mass transfer coefficient, $m\,s^{-1}$
K	Thermal conductivity, $W\,m^{-1}\,K^{-1}$
M	Molar flow rate, $mol\,s^{-1}$
N	Molar flux per segment, $mol\,s^{-1}$
n	Segment n
Nu	Nusselt number, hd/K
Pr	Prandtl number, $C_p\mu/K$
Q	Heat flux per segment, W
Re	Reynolds number, $d\rho v/\mu$
Sc	Schmidt number, $\mu/\rho D$
Sh	Sherwood number, kd/D
U	Overall heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
x	Liquid phase molar fraction of ammonia
y	Gas phase molar fraction of ammonia
δ	Fiber thickness, m
ε	Fiber porosity
μ	Viscosity, $g\,cm^{-1}\,s^{-1}$
ρ	Density, $mol\,m^{-3}$
σ	Ratio of fluxes, $N_{NH_3}/(N_{NH_3}+N_{H_2O})$
τ	Pore tortuosity

Subscripts

aabs	Air-cooled absorber
ana	Analyzer
BG	Bulk gas
BL	Bulk liquid
CL	Cooling fluid
gen	Generator
GM	Gas–membrane interface
i	Component i
int	Gas–liquid interface
LC	Liquid–cooling fluid interface
M	Membrane
MH	Membrane for heat transfer
ML	Membrane–liquid interface
MM	Membrane for mass transfer
rec	Rectifier
sabs	Solution-cooled absorber
shx	Solution heat exchanger
wabs	Water-cooled absorber

capability of utilizing low-temperature heat sources, and (2) the use of a refrigerant which will not cause the ozone depletion problem. The performance of the cycle is highly related to the heat and mass transfers of major components, including absorber and generator [1]. Absorber is the component which has been extensively investigated [2–6]. Besides the generally adopted falling film type device, bubble type device, has been investigated by Kang et al. [6,7].

Hollow fiber membrane contactors made of non-selective, porous membranes have been widely accepted as effective gas–liquid or liquid–liquid devices [8]. The major advantages include: (1) large, undisturbed, known and constant interfacial area available in small volume, (2) independent gas and liquid velocities which avoid flooding, loading, turn down ratio problems from two-phase flows, and (3) straightforward scale-up. Heat exchangers made of various nonporous polymers, such as high temperature nylon, polypropylene and cross-lined polypropylene, have been investigated [9–11]. The experimental results of Zarkadas and Sirkar [11] indicated that the extremely large surface area/volume ratio makes polymeric hollow fiber heat exchangers more efficient than metal heat exchangers for lower temperature applications.

This paper proposes an innovative hollow fiber membrane type device for applications to the ammonia–water absorption heat pump systems. The performance of this hybrid hollow fiber membrane absorber and heat exchanger (HFMAE) as the absorber of a typical ammonia–water chiller is studied via theoretical modeling and simulation. The heat transfer and mass transfer characteristics of this absorber are analyzed and compared to that of a plate heat exchanger falling film type absorber (PHEFFA). The performance of an ammonia–water absorption chiller employing HFMAE is analyzed and compared to the literature's results.

2. Ammonia–water absorption cycle and absorber devices

The configuration of an absorption heat pump cycle can be quite complex if extensive heat exchanges are implemented among various streams within the cycle. A typical example is the generator–absorber heat exchange (GAX) cycle [12]. In this paper, a literature reported [13] and analyzed [14] ammonia–water chiller is adopted for the study. The system diagram of the chiller is illustrated in Fig. 1. Chua et al. [14] analyzed the chiller via developing a mathematical model. The system operation conditions reported in that paper are adopted in this study. The high and low operation pressures are set at 2070 kPa and 480 kPa, respectively. Heat integrations are implemented in the refrigerant heat exchanger, rectifier, solution heat exchanger and solution-cooled heat exchanger. In Chua et al. [14], the