Design of a compact absorber with a hydrophobic membrane contactor at the liquid–vapor interface for lithium bromide–water absorption chillers ☆

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ABSTRACT

In this study, design of a compact plates-and-frames absorber possessing a hydrophobic microporous membrane contactor at the aqueous solution–water vapor interface is performed analytically. The absorber is a component of a 5 kW cooling capacity single-effect lithium bromide–water absorption chiller that incorporates a hot water thermally driven generator and a water-cooled absorber and condenser. Good agreement prevailed for the analytically evaluated water vapor mass transfer flux and aqueous solution outlet temperature when compared with measured values at similar operating conditions. At design point conditions, the main design parameters obtained are a membrane contactor area of 6.06 m^2, a ratio of the mass transfer area to absorber net volume (A_m/V_{net}) of 130.1 (m^2/m^3), and ratio of the membrane area (mass transfer area) in this design configuration to the area required for heat transfer is 1.162, respectively. The results clearly indicate that the aqueous solution channel thickness is the most significant design parameter that affects the absorber size compactness; the thinner the thickness of the solution channel, the higher the ratio (A_m/V_{net}). The results also show the countercurrent refrigerant flow with the aqueous solution has positive effects on the absorber size compactness.

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1. Introduction

In the beginning of the refrigeration technology, absorption refrigeration was the most widely used in almost all refrigeration and cooling applications because it utilizes low quality energy. From the end of the 19th century until now, the small capacity, vapor compression systems have been used more than the equivalent absorption systems due to their better performance at lower capital cost. Large-scale cooling capacity absorption chillers have existed for many years. Recently, small-scale absorption chillers with cooling capacity of 10–15 kW are available on the market with net weight not less than 400 kg, and, most of them have shell and tube absorbers. Such absorbers are heavy with large size and sensitive to the orientation. These features limit the use of these chillers for manportable cooling applications or residential buildings cooling in the summer season. In the latter, the chiller can be thermally driven by either domestic hot water network in northern countries or by solar energy everywhere. Therefore, for residential buildings cooling applications, one of the main goals for several researchers is to develop a small-scale cooling capacity and compact size absorption chillier with indoor environmental friendly refrigerant that can compete with vapor compression sys-

tems and driven from either one of the above mentioned thermal sources of hot water at 85 °C. On the other hand, a cooling tower could be used to provide water (coolant) at 25 °C required for waste heat rejection from both the absorber and the condenser of the chiller. Therefore, at such easily furnished operating conditions, and for indoor use, a single-effect lithium bromide–water (LiBr–H$_2$O) absorption chiller is considered to be the most appropriate system.

Among major components of LiBr–H$_2$O absorption chillers is the absorber, which has a direct effect on the size of the chiller as it works under static vacuum pressure accompanied by higher water vapor specific volume. Drost et al. [1] cited that, the development of compact absorbers enables the deployment of small heat-actuated absorption heat pumps for distributed space heating and cooling applications, heat-actuated automotive air conditioning, and manportable cooling. A step toward reducing size and weight of small cooling capacity absorption chillers has been attempted by introducing a novel absorber design in which a polymeric membrane contactor is incorporated at the aqueous LiBr–H$_2$O solution–water vapor (refrigerant) interface. Such a design will be non-sensitive to the orientation with horizontal and can be incorporated into either frames-and-plates or shell and double pipe.

The present study is concerned with using a membrane contactor at aqueous LiBr–H$_2$O solution–water vapor interface in the absorber design. Therefore, the literature survey was focused on membrane utilization in absorption chiller systems. To the author's knowledge, only limited investigations are available in

Nomenclature

$\dot{m}$	mass flow rate (kg s^{-1})	λ	thermal conductivity (W m^{-1} K^{-1})
A	surface area (m^2)	ρ	density (kg m^{-3})
Calc.	calculated value	τ	membrane pore tortuosity
Ch.	flow channel	μ	viscosity (kg m^{-1} s^{-1})
COP	coefficient of performance		
d	diameter (m)	*Subscripts*	
D	mass diffusivity (m^2 s^{-1})	A	absorber
dA	differential area (m^2)	abs	heat of absorption
Exp.	experimental value	air	air
h	enthalpy (J kg^{-1})	C	condenser
J	water vapor mass flux (kg m^{-2} s^{-1})	cw	cooling water (coolant)
k	mass transfer coefficient (m s^{-1})	E	evaporator
L	net absorber height (m)	g	gas within membrane pores
M	molecular weight (kg mol^{-1})	G	generator/desorber
n	number of segments along the absorber	H_2O	water
p	partial water vapor pressure (Pa)	HT	required for heat transfer
P	total pressure (Pa)	in	inlet
Q	heat rate capacity (W)	int	solution–vapor interface
q	heat transfer flux (W m^{-2})	m	membrane
R	the universal gas constant (8314 J mol^{-1} K^{-1})	out	outlet
T	temperature (°C or K)	ov	overall
U	overall heat transfer coefficient (W m^{-2} K^{-1})	p	membrane pore mean value
v	flow velocity (m s^{-1})	s	aqueous lithium bromide solution
V	net absorber volume (m^3)	$sold$	solid membrane material
W	absorber net depth (m)	sup	support layer
X	LiBr mass fraction (%)	v	water vapor (refrigerant)
y	vertical coordinate	w	wall between coolant and solution
z	horizontal coordinate	X	solution heat exchanger
Greek letters		*Superscript*	
δ	thickness (m)	i	segment i
ε	membrane porosity		

the literature concerning use of the membrane contactor in absorption heat pump applications. For LiBr–H$_2$O absorption chillers, Ali and Schwerdt [2] specified the characteristics of the appropriate membrane that can be used in this absorber design. They indicated that this membrane should have high permeability to water vapor, hydrophobic to the aqueous solution with high liquid entry pressure to avoid wettability of the membrane pores and no capillary condensation of water vapor to avoid blocking of the pores. They concluded that for practical use, the membrane should have a thin hydrophobic microporous active layer with a thickness up to 60 μm on a supported layer, mean pore sizes around 0.45 μm and porosity of up to 80%. Srikhirin et al. [3] described in their review an osmotic-membrane absorption cycle in which the rich-refrigerant solution in the absorber and the weak-refrigerant solution in the generator are separated from each other by an osmotic-membrane, which allows only the refrigerant to pass. They cited that, the refrigerant can be transferred from the absorber to the generator by an osmotic diffusion effect through the membrane without any mechanical pump. Yu et al. [4] investigated experimentally this osmotic-membrane absorption cycle before the review cited by Srikhirin et al. [3] in which the membrane-pumping module takes the place of the refrigerant absorber and the solution circulating pump of the aqueous solution. Yu and co-authors concluded that the use of the proposed membrane module in an absorption refrigeration system, where water is employed as the refrigerant, the membrane-pumping module does provide water (refrigerant) flow from the evaporator to the generator against a pressure increase. The thermal transfer cycle obtained from such a modification, however, no longer functions as does that of a heat pump. Interpretation the result of Yu et al. [4]

is found on the results of Su and Riffat [5]. In which they found a very large pressure difference of up to 6000 bars is required in the case of using the osmotic-membrane separation in LiBr/H$_2$O chiller working at usual operating temperature. They cited that this pressure is beyond the operating range of any commercially available osmotic-membrane moreover the need for a very large mechanical pumping power. Schaal et al. [6] investigated experimentally and simulated an absorber for absorption chiller with a single hollow fiber microporous membrane in which ammonia water is used with integrated cooling. They reported that, the experiments with the single hollow fiber together with the simulation results show that porous membranes show promise for use in absorbers in refrigeration technology. Chen et al. [7] carried a simulation study of a proposed hybrid absorber-heat exchanger using a porous hollow fiber microporous membrane module for the ammonia–water absorption cycle. In their model, they considered the ammonia–water concentration across this microporous membrane as the refrigerant driving force. While, Baker [8] indicates that in the case of a microporous membrane and absence of static pressure difference across the membrane the vapor partial pressure difference at the membrane sides is the mass transfer driving force.

Investigations on utilizing membranes for vapor desorption inside the desorber/generator of absorption heat pumps have been considered in more research than its use in the absorber case. Drost et al. [1] studied experimentally and simulated the ultra-thin film channel of an aqueous lithium bromide mixture desorption process using microporous membrane separation. While, Thorud et al. [9] investigated experimentally the performance of vapor extraction from aqueous lithium bromide mixture as a function