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Characterization of the droplet formation phase for the H_2O—LiBr absorber: An analytical and experimental analysis☆

Fabrizio Cola[a], Jonathan Hey[b], Alessandro Romagnoli[a,*]

[a] Nanyang Technological University, 50 Nanayag Ave, Singapore 639798, Singapore
[b] Singapore Institute of Manufacturing Technology (SIMTech), 2 Fusionopolis Way, Singapore 138634, Singapore

HIGHLIGHTS

- An analytical tool to study the vapor absorption for a forming droplet is proposed.
- Rhomboidal geometry is the optimal choice to maximize absorption interface area.
- Most of the solution does not absorb vapor, even if using smaller droplets.
- Droplet size reduction and solution sub-cooling can improve the absorption rate.

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ABSTRACT

The poor heat and mass transfer occurring in the H_2O—LiBr absorber is one of the main limitations towards reducing the size of absorption chillers. Previous research shows that, as droplets form at the base of the absorber pipes, considerably large mass transfer coefficients can be obtained. However, modeling this phase of droplet formation has not been fully explored, as most of the research focuses on the film flow process preceding the droplet formation. The present study focuses on two aspects. Firstly, the dynamics of the droplet formation is investigated, with a focus on the effect of the solid surface shape on the droplet formation. A model to describe the droplet profile geometry was developed using the Euler-Lagrange equation and validated against experimental tests. Several pin geometries were tested and the results have shown that a 120° rhomboidal geometry is more suitable to increase the liquid-vapor interface area, while lowering the risk of droplet coalescence. Secondly, an analytical heat and mass transfer model based on the Fourier Series method has been developed to study the influence of pin size on the absorption process in an adiabatic absorber. The results show that the optimum width of the 120° rhomboidal pin is found at 6 mm, which maximizes the water absorbed during the droplet formation phase, without excessive use of material. The common assumption that treats the forming droplet as a half sphere fails to capture changes in the pin-droplet interaction which adversely affects the model accuracy. The proposed model shows that for pin widths smaller than 6 mm, the absorption process is impaired by the lower surface area exposed to the water vapor, resulting in up to 67% less mass absorbed obtainable and a decrease in the cooling power obtainable.

In more practical terms, a rated 3 kW of cooling power is used as a case study with a 6 mm pin which reduces the absorber volume by 30% with respect to an absorber with 3 mm wide pins. This shows that by treating the droplet formation phase with a more physically-sound geometrical domain can improve the accuracy of the absorption models and can be easily implemented with any programming language to help in the design optimization of the absorber.

1. Introduction

Absorption refrigeration is one of the main technologies for effective low-grade heat recovery [1], due to direct heat-to-cool conversion [2]. The LiBr—H_2O absorption chiller is known to be effective especially for low heat temperatures [3], although the solution is more prone to crystallization [4]. Implementation of absorption refrigeration has been proven to be feasible for data center cooling by Ebrahimi et al. [5],

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* Corresponding author.
E-mail address: a.romagnoli@ntu.edu.sg (A. Romagnoli).

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Nomenclature

Roman symbols

B	curvature radius (non-dimensional)
$Bo = \rho g r^2/\sigma$	Bond number
C	concentration (mol/m^3)
D	mass diffusivity (m^2/s)
G	gravitational acceleration (m/s^2)
H_{lv}	latent heat of vaporization (J/kg)
i	counter index
k	thermal conductivity (W/m K)
N_{or}	number of orifices
$Oh = \mu/(\rho r \sigma)^{1/2}$	Ohnesorge number
P	pressure (Pa)
q	heat flux (W/m^2)
R	radius (non-dimensional)
r	radius (m)
S	arc length (non-dimensional)
T	temperature (K)
t	time (s)
V	volume (non-dimensional)
$We = \rho r u^2/\sigma$	Weber number
Z	height (non-dimensional)
z	height (m)

Greek symbols

β	contact point angle
λ	Taylor wavelength
ρ	density (kg/m^3)
σ	surface tension (N/m^2)
θ	angle (rad)
μ	dynamic viscosity (Pa s)
δ	deviation

Subscripts

abs	absorbed
cr	critical
d	droplet
i	initial
eq	equilibrium
exp	experimental
form o	formation boundary
oth	boundary theoretical
th	theoretical
tot	total

whose system predicts a payback time of 4–5 months when the chiller is directly implemented on chip. This system was however only analytically studied. Air conditioning and dehumidification are possible applications of this chiller [6,7] as well as trigeneration which is theoretically possible [8,9]. In reality, the large footprint of absorption machines hinders their applications in fields, such as domestic and automotive air-conditioning. A few attempts have been made at developing a small-scale chiller, such as the device of Determan and Garimella [10]. The main obstacle faced here is the size of the absorbers [11]. Extensive research has been focused on improving the absorber performance and consequently reducing its size. Raisul Islam et al. [12] used film inverting segments on a tubular absorber and showed a maximum increase of 100% in the absorbed mass flux, which could be further improved with the addition of more inverting segments. Mortazavi et al. [13] used flat fins on a plate absorber to improve the film distribution; the reduced average film thickness caused the increase in the absorption rate by up to two times with respect to conventional falling film absorbers. The use of a hydrophobic membrane was analyzed by Ali [14] who analytically designed an absorber having a surface to volume ratio of $130\,m^2/m^3$ which claims to overcome the worsening of the mass absorption due to the presence of the membrane. A herringbone microstructure was then applied by Bigham et al. [15] to the membrane absorber; the mixing provided by the microstructure introduced an advective contribution that increased the absorption rate by a factor of 2.5.

The possibility of using an adiabatic absorber was also investigated, since this allows for more diverse strategies for the solution flow distribution. The efficacy of column flow-based adiabatic absorbers has been assessed by Li et al. [16], who highlighted the advantage of requiring no additional energy to operate this device. The use of flat fan sheets of solution by use of a vee-jet nozzle has been studied by Palacios et al. [17]. The high level of deformation of the vapor-liquid interface caused the mass transfer coefficient to be one order of magnitude larger than for conventional falling film absorbers; the authors concluded that the absorber size could be reduced by a factor of five by using this configuration. González-Gil et al. [18] produced a direct air-cooled absorber using the flat fan sheet configuration. A cooling capacity of 4.5 kW was achieved for a single effect absorption cycle with a reduced risk of crystallization, obtained due to the low solution temperatures made possible by the new design. Application of this type of absorber to a solar powered chiller could satisfy 65% of the seasonal cooling demand for the research group lab [19].

In both the falling column and the flat fan sheet case an increase in the contact area between the refrigerant vapor and the solution is observed, but this comes at the cost of reduced solution mixing which works against the maximization of vapor absorption. As a result, only the initial part of the absorber is effective in providing a high absorption rate, whose value decays rapidly as the liquid-vapor interface reaches thermodynamic equilibrium with the surrounding vapor.

In-depth analysis of standard falling film absorbers (composed by a series of cooled pipes and a falling film of solution) has demonstrated that the phase during which the solution droplets form at the tube base is particularly effective from the point of view of the heat and mass transfer. This has been proven by Subramaniam and Garimella [20,21], who performed a numerical analysis of the different phases the solution undergoes in a tubular absorber. Their work is the continuation of previous analytical work done by Jeong and Garimella [22] who showed that during the droplet formation phase, the mass transfer coefficient was one order of magnitude larger than that occurring during pure falling film phase and droplet free fall phase. Furthermore, the droplet formation proved more effective than falling film for higher mass flow rates, by means of a higher rate of forming droplets. As the wetting ratio decreases, the droplet formation contributes relatively more than the falling film; however, the absorption rate of both phases increases with the wetting ratio, as the higher sub-cooling gained during the falling film phase creates a higher concentration gradient for the absorption in the following droplet formation phase. Similar results were obtained in the model by Ben Hafsia et al. [23], who showed that the absorbed vapor mass flow rate for the combined droplet formation and falling phase was three times larger than that for the falling film (at least in the first tube rows).

In the analytical studies available in the literature, the droplet formation has always been modelled assuming a hemispherical shape of the droplet. In the work done by Jeong and Garimella [22] the hemispherical droplet is considered to have constant volume and surface area, while in Ben Hafsia et al. [23], the volume and surface area of the hemisphere are a function of time. An average mass transfer coefficient based on penetration theory was employed in [22,23] and in the work