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# Absorption characteristics of falling film LiBr (lithium bromide) solution over a finned structure

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# ABSTRACT

In this study, an absorber design suitable for the plate-and-frame absorber configuration is introduced. The design utilizes a fin structure installed on a vertical flat plate to produce a uniform solution film and minimize its thickness and to continuously interrupt the boundary layer. Using numerical models supported by experiments employing dye visualization, the suitable fin spacing and size and surface wettability are determined. The solution flow thickness is measured using the laser confocal displacement measurement technique. The new surface structure is tested in an experimental absorption system. A significantly high absorption rate  $(6 \times 10^{-3} \text{ kg/m}^2 \text{s at a pressure potential of 700 Pa})$  is achieved in comparison with the conventional absorption systems. The effect of absorber water vapor pressure, solution flow rate, solution inlet concentration, cooling water inlet temperature and solution inlet temperature on the absorption rate is investigated. The proposed design provides a potential framework for development of highly compact absorption refrigeration systems.

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### 1. Introduction

VCSs (Vapor compression systems) are the most widely used cooling systems in refrigeration, air conditioning and heat pump applications. Despite the advantages that have made their application widespread, VCSs consume significant electrical energy, and account for a large portion of energy consumption in buildings. In addition, the growing worldwide concern over the adverse environmental impacts of the refrigerants used in these systems, such as ozone depletion effect, has prompted the development of more eco-friendly alternative technologies. Unlike VCSs, ARSs (absorption refrigeration systems) primarily utilize low-grade thermal energy, and use eco-friendly refrigerants such as water. These systems are often used in large-scale applications where a thermal energy source (e.g. a boiler) or excess heat from a process is available. However, ARSs are not economically competitive with the VCSs in small-scale applications due to their high initial cost. ARSs can play a significant role in our future energy economy, if highperformance, inexpensive, and robust systems could be developed.

One of the main components of an ARS that has a significant impact on its size, cost and performance is the absorber heat

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http://dx.doi.org/10.1016/j.energy.2015.04.074 0360-5442/Published by Elsevier Ltd. exchanger. In an absorber, the refrigerant molecules are absorbed into an absorbent in an exothermic process, as they release heat when change phase from vapor to liquid. Additional heat is also generated due to interactions between the refrigerant and absorbent molecules. The generated heat must be removed from the absorbent to perpetuate the absorption process. In the existing systems, the falling film technology is utilized to generate significant vapor—absorbent interface and to facilitate heat removal from the absorbent as it falls on a cold surface. Since heat is generated at the vapor—solution interface and must transfer through the solution film to reach the cold surface, the liquid film thickness plays a major role in the absorption process. A thick solution film also exhibits significant mass transfer resistance as the refrigerant molecules diffuse through the solution.

Enhancement of the absorption rate and development of scalable absorber configurations have been the subject of numerous studies. The falling film absorption process over a vertical wall [1], horizontal [2–5] and vertical tube banks [6–8] and helical coiled tube configuration [9,10] has been studied both numerically and experimentally to better understand physics of the falling film process and to explore enhancement opportunities. Falling film over a horizontal tube bank is the arrangement commonly implemented in the existing large-scale systems. However, in efforts to develop compact absorbers, alternative configurations have been explored [11–16]. Most recently, the efficacy of the membrane-

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based absorption process and its scalability have been demonstrated [15,16]. Nasr and Moghaddam [15] reported absorption rates 2.5 times higher than that of the conventional falling film absorbers. Bigham et al. [16] numerically showed that further enhancement in the membrane-based absorption process can be achieved through generation of vortices within the flow through implementation of micro-scale features on the flow channel wall. The vortices change the mass transfer mode within the solution from diffusive to advective.

In this study, we introduce an alternative absorber design suitable for the plate-and-frame absorber configuration. The design utilizes a 3D surface structure installed on a vertical flat plate. The structure is designed to produce a uniform solution film and minimize its thickness and to continuously interrupt the boundary layer. The solution flow thickness over the structure is determined using the laser confocal displacement measurement technique. The new surface structure is tested in an experimental absorption system. The effects of various operating parameters such as water vapor pressure, solution flow rate, solution inlet concentration, cooling water inlet temperature and solution inlet temperature on the absorption rate are studied.

# 2. Concept

One of the drawbacks of the conventional falling film technology is maldistribution of the absorbent film over the cooled surface. Maldistribution forms undesirable flow patterns with a high liquid accumulation at some areas while leaving other areas non-wetted [5]. The non-wetted areas do not participate in the absorption process and result in a significant reduction in the effective absorption surface area. Increasing the flow rate shrinks the nonwetted areas leading to a more effective implementation of the available surface area [3]. It has been shown that the absorption rate continuously increases with the solution flow rate until the surface is fully wetted. The fully wetted state is reached at a relatively high solution flow rate (i.e. about 2–4 kg/min m) and results in a high solution film thickness [3,10]. It has been argued [1] that increasing the solution flow rate beyond the fully wetted state, does not lead to further enhancement of the absorption rate due to heat transfer limitations.

To overcome difficulties associated with a thick solution film, we present a simple solution of patterning the cooling surface with spatially ordered fins. This new geometry, as it will be fully discussed later in this section, shifts the fully wetted state to a significantly lower solution flow rate at which the absorption process in not thermally limited. As a result, as it will be shown in the results section, the absorption rate continues to increase beyond the fully wetted state. We illustrate this concept with the help of Fig. 1, where the effect of a staggered array of rectangular fins on the flow pattern and the resulting contact area between the fluid and the cooling surface (or simply the substrate) is shown. Fig. 1 shows that the rivulet flow regime (characterized by distinct flow streams as shown in Fig. 1a) exhibited by a liquid falling over a flat vertical wall is transformed into the continuous film regime when the wall is patterned with surface features (Fig. 1b). However, the array of structures should be carefully designed to yield the desired flow characteristics. For example, the fin elements in the grid should be located close enough to each other to have the expected effect of structures on the flow, but far enough to ensure that capillary force does not dominate the flow. Through preliminary experimental and numerical studies, it is determined that at low values of fins spatial separation, the capillary force leads to filling of the surface structure and formation of a thick liquid film on the wall while at higher values of separation, the effect of the structures is diminished and individual flow streams are formed. This indicates



**Fig. 1.** Flow distribution comparison over a) flat and b) patterned surfaces. Water is colored lightly with a red dye for better observation of the flow pattern. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

that, at a given flow rate, there is an optimum value for the spatial distance that favors the formation of a thin and continuous liquid film over the surfaces. Hence, in order to optimize the design, a numerical simulation is conducted. The focus of the simulation is on the flow dynamics of the problem with the objective of selecting geometrical and flow parameters that ensure a uniform flow distribution.

The simulations are carried out with the pressure-based finite volume scheme using the commercial CFD package FLUENT [17]. To track the liquid and vapor volume fractions in each cell of the entire computational domain, a volume-conserved technique, VOF (Volume of Fluid) method [18–20], is employed. In this method, a convection equation is used to calculate the liquid volume fraction,  $\alpha_l$ , as:

$$\frac{\partial}{\partial t}(\alpha_l \rho_l) + \overrightarrow{\mathbf{v}} \cdot \nabla(\alpha_l \rho_l) = \mathbf{0} \tag{1}$$

where  $\rho_1$  is the liquid density. Since the volume fraction values do not uniquely identify the interface between the phases, an interface reconstruction scheme needs to be revoked. In the present study, the piecewise linear geometric reconstruction scheme [21,22] available in FLUENT [17] is employed to update the volume fraction values in each cell. Pressure–velocity coupling is achieved using the SIMPLE algorithm. An important factor that impacts the capillary force acting at the meniscus formed between the fins is the surface wettability, which can be characterized by the contact angle defined at the triple line, where the three phases meet. The contact angle can influence the flow pattern and thus the interfacial contact areas.

A set of numerical simulations has been conducted to investigate the contact angle influence on the flow pattern. Fig. 2 shows the flow patterns predicted by the numerical model for aqueous LiBr solution (55 wt% LiBr) in a section of the fin array for different contact angles and flow rates. A close inspection of Fig. 2 reveals that by decreasing the contact angle from 70° to 30° at a constant flow rate (cf. Fig. 2a and b), the flow pattern switches from a

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Fig. 2. Flow patterns at different contact angles and flow rates.

discontinuous drop mode, in which most of the fluid accumulates around the fin structures, to a discontinuous rivulet mode (with multiple flow streams). There appears to be a threshold flow rate to fully wetted regime above which the individual flow streams coalesce to form a continuous falling liquid film. As the contact angle decreases, the fully wetted regime occurs at a lower flow rate resulting in a thinner film. For instance, at a contact angle of 70°, no continuous film is observed at the same flow rate (cf. Fig. 2a and c). Decreasing the contact angle to 30° shifts the transition to a flow rate of about 0.5 kg/min m (cf. Fig. 2b and d), which is significantly lower, compared to that of conventional falling films.

### 3. Experimental absorption studies

### 3.1. Absorber design and fabrication

Fig. 3 shows a photograph of the absorber heat exchanger unit. In this section, we provide details of the final fin structure. At this point, it is important to remark that the fins assembled in the unit is an offset-strip fin [23], which is rather easier to fabricate (e.g. via sheet metal forming techniques) compared to the machined patterned surface shown in Fig. 1b. But, as the simulation results (cf. Fig. 2) show, for the flow rates considered in the present study, the liquid does not flow over the fins. Therefore, the front faces of the offset-strip fin do not have any participation as far as the flow dynamics are concerned. Consequently, no significant change in the flow characteristics is to be expected between the rectangular fin array (Fig. 1b) and the equivalent offset-strip fin (Fig. 3b); we chose the latter for its ease of manufacturing. For the purpose of comparison, we also mention that in the present case the fin structure is



Fig. 3. a) Absorber heat-exchanger and b) Lanced offset fin geometry.

rotated by  $90^{\circ}$  with respect to the flow direction as opposed to the configuration adopted in a typical heat exchanger.

The fin array is bonded onto the bottom face of a rectangular cavity machined in the absorber plate. It should be noted that in the case of the rectangular fin array (Fig. 1b), the base surface is flat, while in the case of the offset-strip fin (Fig. 3b) structure, the base surface elevation varies by approximately 150  $\mu$ m (i.e. the fin thickness). However, this nonuniformity is significantly smaller than the overall fin spacing and the liquid film is expected to follow the surface contour. A solution distributor containing six cylindrical through holes with a diameter and a length of 1 mm and 6.35 mm, respectively, is also bonded to the bottom of the cavity at the absorber inlet. The overall dimensions of the absorber are  $152 \times 304 \text{ mm}^2$  with an active area (i.e. the finned area) of  $38 \times 170 \text{ mm}^2$ . A glass window on the front wall of the absorber allows optical access to the fin structure for performing the solution film thickness measurements. The geometrical details of the fin are provided in Fig. 3. The fin is made of copper sheets of thickness 0.15 mm, with a lanced length, fin height and pitch of 6.35 mm, 6.35 mm and 11.6 mm, respectively.

As shown in the previous section, the wetting characteristics of the fin structure has a significant effect on distribution and uniformity of the solution film; the more wetting the surface is, the better the fluid spreading behavior will be. Hence, fins were surface treated both physically and chemically to make them as hydrophilic as possible. Fins were first sandblasted with fine aluminum oxide particles to form microscale surface roughness followed by 5 h of surface oxidation/hydroxylation in boiling water. As a result, the LiBr solution contact angle on the fin surface reduced from 90° to  $30^\circ$ , as shown in Fig. 4.

# 3.2. Solution film thickness measurement setup

To measure the solution film thickness, a surface scanning laser confocal displacement meter (LT9030M, Keyence) is utilized (cf.

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Fig. 4. Results of hydrophilic surface treatment of the fin structure.

Fig. 5). This technique has also been used by other researchers for liquid film thickness measurements [24,25]. In this test, the solution is pumped into the absorber from an inlet port at the top of the absorber and collected from an outlet port at the bottom of the absorber. The operation principle of the confocal displacement



Fig. 5. a) Solution film thickness measurement test setup. b) A diagram showing principle of laser confocal displacement measurement.

measurement method is illustrated in Fig. 5b. In this method, the objective lens of the system is vibrated at high frequency by a tuning fork. The laser beam passes through the objective lens and is then focused on the target surface. The reflected beam is then directed through a pinhole to the light-receiving element. When the focus is obtained on the target surface, the light-receiving element detects the highest intensity. The position of the target surface can be determined by measuring the exact position of the objective lens. The resolution of our laser confocal displacement unit is 0.1  $\mu$ m, and it is capable of measuring film thicknesses ranging from 50  $\mu$ m up to 1 mm.

# 3.3. Absorption experiment setup and test procedure

A detailed description of the absorption test setup used in this study can be found elsewhere [15]; however, it is briefly described here for completeness. As shown in Fig. 6a, the test loop consists of two flow lines: the solution line and the refrigerant (water) line. The solution line consists of an absorber, a desorber, a micro gear pump (HNP Mikrosysteme, Germany), a filter, a solution reservoir, a Coriolis mass flow meter (Bronkhorst USA) and two heat exchangers. The weak solution leaving the absorber is pumped through a filter into a preheater and then into the desorber. In the desorber, heat is applied to the weak solution by a thin film heater (Omega Engineering, CT), resulting in desorption of water from the solution. The desorbed water vapor flows into the condenser. The now strong solution flows through a heat exchanger where it is cooled to a preset temperature, and then into the mass flow meter. It is finally returned to the absorber and flows through the absorber where it comes in contact with the water vapor and absorption takes place.

The refrigerant line consists of the condenser and the evaporator, and also a flow meter (Micro Motion, CO) and a water reservoir. The water vapor coming from the desorber flows into the condenser where it liquefies. The condensed water passes through a flow meter and then into the evaporator. In the evaporator, the water is heated and evaporated using a flexible heater attached to the back wall of the evaporator. The water vapor flows into the absorber, where it is absorbed by the strong solution.

A schematic diagram of the absorber is shown in Fig. 6b. The strong solution enters the absorber from the top and passes through the solution distributer, and then through the fin structure. The water vapor enters the absorber through its vapor inlet port, and is then absorbed by the solution. The now weak solution exits the absorber through the solution outlet port. A water chiller provides cooling water to an array of microchannels (4 mm wide and 0.4 mm deep) machined on the backside of the absorber to remove the heat of absorption.

Lithium bromide solution (55% LiBr by weight) inhibited by lithium molvbdate (Leverton-Clarke Ltd, UK) and degassed and deionized water are fed into the solution and water lines, respectively. To begin the experiment, the pump is turned on and the desired flow rate is adjusted. The water chiller is also turned on, and the absorber cooling water temperature and flow rate are set. The valve between the evaporator and absorber is then opened, allowing the absorption process to begin. Consequently, the solution inlet temperature to the absorber and desorber heat exchangers were adjusted. Once the desired temperatures are reached, the desorber and evaporator heaters are powered. Changes in temperatures, pressures and mass flow rates are monitored. The system is assumed to have reached steady state when variations in the absorber pressure and the solution density are less than 10 Pa and 5 kg/m<sup>3</sup>, respectively, for a minimum duration of 30 min. The absorption rate can be directly obtained from the reading of the refrigerant (water) line flow meter.

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Fig. 6. a) Schematic diagram of the experimental setup and b) Schematic diagram of the cross section of the absorber heat exchanger.

### 3.4. Experimental uncertainty

The range and uncertainty of the key operating conditions used in this parametric study namely solution and refrigerant flow rates, pressure, density, and temperatures are summarized in Table 1.

## 4. Results and discussions

### 4.1. Solution thickness

As discussed earlier, the solution film thickness has a significant influence on the absorption rate. The absorption process can be thermally limited at high solution flow rates due to formation of a thick solution film. It has been shown that a solution film with a thickness of a few hundred microns does not thermally limit the absorption process [15,26]. To determine the range of film thicknesses for this study, thickness measurement has been performed at different solution flow rates and the results are provided in Fig. 7. The measurements are conducted over multiple points along a horizontal line between two consecutive fin rows (shown as line A-B in Fig. 3a) and the results are averaged. The figure also presents the film thickness of two other absorber configurations previously reported in the literature [15,27]. As shown, the solution film thickness remains within a few hundred microns over the tested flow rate range.

### 4.2. Absorption rate

The driving force for the absorption process is the difference between the water vapor pressure in the LiBr solution ( $P_{s,w}$ ) and the absorber vapor phase pressure ( $P_v$ ). Any change in temperature and concentration of the solution phase results in changes in the pressure potential and hence the absorption rate. Fig. 8 presents

#### Table 1

Range and uncertainty of parameters.

Parameter	Nominal	Range	Experimental error	Uncertainty
Solution flow rate	0.55 kg/min m	0.44–1.22 kg/min m	±0.008 kg/min m	±1.0%
Absorption rate	N.A	40–120 g/h	±0.8 g/h	±1.0%
Water vapor pressure	1.2 kPa	0.8–1.4 kPa	±5.5 Pa	±0.5%
Inlet solution concentration	57 wt% LiBr	54–59 wt% LiBr	±0.17 wt% LiBr	±0.3%
Inlet solution density	1627 kg/m <sup>3</sup>	1570–1660 kg/m <sup>3</sup>	$\pm 5 \text{ kg/m}^3$	±0.3%
Solution inlet temperature	25 °C	30–38 °C	±0.3 °C	±0.9%
Cooling water inlet temperature	25 °C	25–35 °C	±0.3 °C	±1.0%

variations of the absorption rate as a function of pressure potential for the present study as well as two membrane-based [14,15], a vertical tube [7], three horizontal tube [2,4,5] and a vertical wall [1] absorber configurations. The solution water vapor pressure used in the calculation ( $P_{s,w}$ ) is the average of the solution water vapor pressure (calculated using the corresponding solution temperature and concentration [15]) at the absorber inlet and exit. The water vapor pressure in the vapor phase ( $P_v$ ) is the measured vapor



Fig. 7. Solution film thickness as a function of flow rate.

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Fig. 8. Variation of absorption rate as a function of water vapor pressure potential.

pressure. The absorption rate achieved in this study is significantly higher than that of prior studies at a substantially lower pressure potential and solution flow rate (0.55 kg/min m).

In subsequent tests, the effect of the absorber vapor pressure, solution flow rate, solution inlet concentration and temperature, and cooling water inlet temperature on the absorber performance is experimentally investigated and compared with different absorber designs reported in the literature. It should be noted that the solution inlet conditions reported in different studies vary and account for some difference between the results.

The effect of the absorber vapor pressure on the absorption rate is shown in Fig. 9. Vapor pressure inside the absorber is increased from 0.8 kPa to 1.4 kPa by increasing the evaporator temperature.



Fig. 9. Variation of absorption rate as a function of vapor pressure.

Other test parameters were kept constant at the nominal values listed in Table 1. As can be seen, the absorption rate increases almost linearly with the vapor pressure. As the vapor pressure inside the absorber increases, the equilibrium concentration of water at the interface increases which leads to a higher mass transfer driving potential and absorption rate. A 2.5-fold increase in the absorption rate is observed as the absorber pressure increased from 0.8 to 1.4 kPa.

The solution flow rate is another important factor that impacts the absorption rate as well as the system performance. To evaluate the effect of solution flow rate on the absorber performance, tests were conducted at different flow rates ranging from 0.44 to 1.22 kg/ min m, while other test parameters were held at their nominal values (cf. Table 1). In Fig. 10, absorption results are compared with those of other absorber designs available in the literature. Since the variation in the flow rate is significant in different studies, the abscissa is displayed on a logarithmic scale. As it can be seen from the inset figure (plotted on a linear scale), the absorption rate almost linearly increases with the solution flow rate. However, in other studies, the absorption rate is low at low solution flow rates because of non-uniformity of the solution film. This non-uniformity results in formation of dry regions that do not participate in the absorption process. The absorption rate continuously increases with the solution flow rate until the surface is fully wetted. After this stage, as seen in the graph, the absorption rate curve reaches a plateau.

The reasons for a steady increase in the absorption rate achieved here could be described through analysis of the solution flow thermohydraulics. As the solution flow rate increases, the solution film thickness as well as the solution average velocity increases. Since the thermal resistance between the solution-vapor interface, at which the water vapor heat of phase change is released (cf. Fig. 11), and the cooling surface is a function of  $\delta/k$  ( $\delta$  is the solution film thickness and k is the solution thermal conductivity), increasing the solution film thickness increases the thermal resistance and inhibits [10] cooling of the solution-vapor interface resulting in higher water pressure in the solution phase. A higher water pressure decreases the pressure potential and the absorption rate. On the other hand, as the flow rate increases, the solution inside the absorber is replenished faster with the strong solution leading to an increase in the pressure potential and consequently the absorption rate. Since the film thickness range in the current study (cf. Fig. 7) is only a few hundred microns, the thermal resistance does not significantly impact the absorption process. As a result, the effect of solution velocity increase on the absorption rate is dominant and the absorption rate increases with the flow rate within the studied flow rate range.

In addition, increasing the solution flow rate changes the solution exit condition. Therefore, the average solution water vapor pressure and consequently the available pressure potential changes. In order to isolate the effect of changes in solution flow rate, the absorption coefficient ( $K_m$ ) which is the absorption rate divided by the pressure potential is calculated. The pressure potential for each data point is calculated by subtracting the average solution water pressure between the inlet and exit flows from the absorber vapor pressure. As shown in Fig. 12, the absorption coefficient linearly increases with the solution flow rate. Using this data it can be argued that enhancement in the absorption rate is due to heat and mass transfer enhancement within the solution film.

The effect of solution inlet concentration on the absorption rate is shown in Fig. 13. The absorption rate linearly increases with the solution inlet concentration. Almost similar trend has been observed for a coil absorber [10], a vertical wall absorber [1], and a vertical tube absorber [6]. As the solution concentration increases, the solution water vapor pressure decreases, and therefore the

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Fig. 10. Variation of absorption rate as a function of flow rate for the present study as well as those from the literature. The inset figure presents the data on a linear scale.



Cooling surface

**Fig. 11.** Illustration of temperature gradient established within the solution film due to heat release at the vapor—solution interface.

pressure potential and the absorption rate increases. However, it should be noted that operation of the system at higher concentrations requires more control measures since it increases the risk of LiBr crystallization. Crystallization occurs when the concentration of the solution exceeds the solubility limit of LiBr salt in the solution.

Similar to the trend observed in the previous experimental and numerical studies [1-3,7,9,10], the absorption rate decreases linearly with increasing the cooling water inlet temperature, as shown in Fig. 14. The higher cooling water temperature increases the bulk solution temperature, which results in a rise in the solution vapor pressure [15] that in turn reduces the pressure potential and consequently the absorption rate. The absorption rate decreases by 45% as the cooling water temperature increases from 30 °C to 37.5 °C.



Fig. 12. Variation of absorption coefficient as a function of solution flow rate.



**Fig. 13.** Variation of absorption rate as a function of solution inlet concentration in the present study and comparison with the literature data.

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**Fig. 14.** Variation of absorption rate as a function of cooling water inlet temperature in the present study and comparison with the literature data.

Finally, variations of the absorption rate with the solution inlet temperature is shown in Fig. 15. Similar to the effect of cooling water inlet temperature, the partial water vapor pressure of the solution increases with the solution inlet temperature resulting in a decline in the pressure potential and the absorption rate. However, the variation of the absorption rate is not significant due to effective cooling of the solution in the current configuration [28–30].

### 5. Conclusions

Absorption characteristics of water vapor into the aqueous LiBr solution in a falling film absorber were experimentally



**Fig. 15.** Variation of absorption rate as a function of solution inlet temperature in the present study and comparison with the literature data.

investigated. A new absorber design with surface topological features was used to obtain a uniform flow distribution. Using a numerical model, the geometry and surface wettability of the structures were tuned to optimize the design of the structure to achieve a continuous thin liquid film. Based on the final design, an absorber with a suitable geometry and surface properties was fabricated and tested. Film thickness measurements and flow pattern experiments confirmed that the solution film remains thin and more uniformly wets the cooling surface at a significantly lower solution flow rate compared to the existing designs. Absorption rate measurements were conducted and the results were compared with the absorption data reported in the literature for various absorber designs. The proposed design offers promising absorption rates (up to two times higher) compared to the conventional falling film absorbers. The sensitivity of the absorption rate to operating conditions was also investigated. The determined results can be used to find the optimum operating conditions of an absorber.

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# References

- Karami S, Farhanieh B. A numerical study on the absorption of water vapor into a film of aqueous LiBr falling along a vertical plate. Heat Mass Transf 2009;46:197–207. http://dx.doi.org/10.1007/s00231-009-0557-y.
- [2] Islam MR. Absorption process of a falling film on a tubular absorber: an experimental and numerical study. Appl Therm Eng 2008;28:1386–94. http:// dx.doi.org/10.1016/j.applthermaleng.2007.10.004.
- [3] Raisul Islam M, Wijeysundera N, Ho J. Performance study of a falling-film absorber with a film-inverting configuration. Int J Refrig 2003;26:909–17. http://dx.doi.org/10.1016/S0140-7007(03)00078-1.
- [4] Seol SS, Lee SY. Experimental study of film flow and heat/mass transfer in LiBr-H<sub>2</sub>O solution flowing over a cooled horizontal tube. Int Commun Heat Mass Transf 2005;32:445-53. http://dx.doi.org/10.1016/j.icheatmasstransf er.2004.07.007.
- [5] Sun J, Fu L, Zhang S, Hou W. A mathematical model with experiments of single effect absorption heat pump using LiBr-H<sub>2</sub>O. Appl Therm Eng 2010;30: 2753-62. http://dx.doi.org/10.1016/j.applthermaleng.2010.07.032.
- [6] Fu Lin SJ, Shigang Z. Experimental study on vertical vapor absorption into LiBr solution with and without additive. Appl Therm Eng 2011;31:2850–4. http:// dx.doi.org/10.1016/j.applthermaleng.2011.05.010.
- [7] Medrano M, Bourouis M, Coronas A. Absorption of water vapour in the falling film of water-lithium bromide inside a vertical tube at air-cooling thermal conditions. Int J Therm Sci 2002;41:891-8. http://dx.doi.org/10.1016/S1290-0729(02)01383-2.
- [8] Matsuda A, Choi K, Hada K, Kawamura T. Effect of pressure and concentration on performance of a vertical falling-film type of absorber and generator using lithium bromide aqueous solutions. Int J Refrig 1994;17:538–42. http:// dx.doi.org/10.1016/0140-7007(94)90030-2.
- [9] Yoon J-I, Kwon O-K, Bansal PK, Moon C-G, Lee H-S. Heat and mass transfer characteristics of a small helical absorber. Appl Therm Eng 2006;26:186–92. http://dx.doi.org/10.1016/j.applthermaleng.2005.05.009.
- [10] Kaynakli O. The first and second law analysis of a lithium bromide/water coil absorber. Energy 2008;33:804–16. http://dx.doi.org/10.1016/j.energy.20 08.01.009.
- [11] Cerezo J, Bourouis M, Vallès M, Coronas A, Best R. Experimental study of an ammonia–water bubble absorber using a plate heat exchanger for absorption refrigeration machines. Appl Therm Eng 2009;29:1005–11. http://dx.doi.org/ 10.1016/j.applthermaleng.2008.05.012.
- [12] Warnakulasuriya FSK, Worek WM. Drop formation of swirl-jet nozzles with high viscous solution in vacuum-new absorbent in spray absorption refrigeration. Int J Heat Mass Transf 2008;51:3362–8. http://dx.doi.org/10.1016/ j.ijheatmasstransfer.2007.11.015.
- [13] Palacios E, Izquierdo M, Marcos JD, Lizarte R. Evaluation of mass absorption in LiBr flat-fan sheets. Appl Energy 2009;86:2574–82. http://dx.doi.org/10.1016/ j.apenergy.2009.04.033.
- [14] Ali AHH. Design of a compact absorber with a hydrophobic membrane contactor at the liquid-vapor interface for lithium bromide-water absorption chillers. Appl Energy 2010;87:1112–21. http://dx.doi.org/10.1016/j.apene rgy.2009.05.018.
- [15] Nasr Isfahani R, Moghaddam S. Absorption characteristics of lithium bromide (LiBr) solution constrained by superhydrophobic nanofibrous structures. Int J

#### M. Mortazavi et al. / Energy xxx (2015) 1-9

Heat Mass Transf 2013;63:82–90. http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.03.053.

- [16] Bigham S, Yu D, Chugh D, Moghaddam S. Moving beyond the limits of mass transport in liquid absorbent microfilms through the implementation of surface-induced vortices. Energy 2014;65:621–30. http://dx.doi.org/10.1016/ j.energy.2013.11.068.
- [17] User's guide for ANSYS FLUENT 12. Fluent Inc; 2009.
- [18] Hirt C, Nichols B. Volume of fluid (VOF) method for the dynamics of free boundaries. J Comput Phys 1981;39:201–25. http://dx.doi.org/10.1016/0021-9991(81)90145-5.
- [19] Rider WJ, Kothe DB. Stretching and tearing interface tracking methods. In: AIAA 12th comput. fluid dyn. Conf; 1995. p. 806–10.
- [20] Pilliod JE, Puckett EG. Second-order accurate volume-of-fluid algorithms for tracking material interfaces. J Comput Phys 2004;199:465–502. http:// dx.doi.org/10.1016/j.jcp.2003.12.023.
- [21] Li J. Piecewise linear interface calculation. Technical report, Comptes Rendus de l Academie des Sciences Serie II. Fascicule B-Mecanique; 1995.
- [22] Gueyffier D, Li J, Nadim A, Scardovelli R, Zaleski S. Volume-of-fluid interface tracking with smoothed surface stress methods for three-dimensional flows. J Comput Phys 1999;152:423–56. http://dx.doi.org/10.1006/jcph.1998.6168.
- [23] Webb RL, Kim N-H. Principles of enhanced heat transfer. New York: Wiley; 1994.
- [24] Han Y, Shikazono N, Kasagi N. Measurement of liquid film thickness in a micro parallel channel with interferometer and laser focus displacement meter. Int J

Multiph Flow 2011;37:36–45. http://dx.doi.org/10.1016/j.ijmultiphase flow.2010.08.010.

- [25] Hazuku T, Fukamachi N, Takamasa T, Hibiki T, Ishii M. Measurement of liquid film in microchannels using a laser focus displacement meter. Exp Fluids 2005;38:780–8. http://dx.doi.org/10.1007/s00348-005-0973-9.
- [26] Yu D, Chung J, Moghaddam S. Parametric study of water vapor absorption into a constrained thin film of lithium bromide solution. Int J Heat Mass Transf 2012;55:5687–95. http://dx.doi.org/10.1016/j.ijheatmasstransfer.201 2.05.064.
- [27] Jeong S, Garimella S. Falling-film and droplet mode heat and mass transfer in a horizontal tube LiBr/water absorber. Int J Heat Mass Transf 2002;45:1445–58. http://dx.doi.org/10.1016/S0017-9310(01)00262-9.
- [28] Yoon J-I, Phan TT, Moon C-G, Lee H-S, Jeong S-K. Heat and mass transfer characteristics of a horizontal tube falling film absorber with small diameter tubes. Heat Mass Transf 2007;44:437–44. http://dx.doi.org/10.1007/s00231-007-0261-8.
- [29] Miller WA, Keyhani M. The correlation of simultaneous heat and mass transfer experimental data for aqueous lithium bromide vertical falling film absorption. J Sol Energy Eng 2001;123:30. http://dx.doi.org/10.1115/1.1349550.
- [30] Tsuda H, Perez-Blanco H. An experimental study of a vibrating screen as means of absorption enhancement. Int J Heat Mass Transf 2001;44:4087–94. http://dx.doi.org/10.1016/S0017-9310(01)00038-2.