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Performances of grooved plates falling film absorber

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This study presents a new plate-type falling film absorber design, consisting in a vertical grooved falling film absorber. The grooves are designed to obtain good absorber plate wettability, even at a low solution flow rate, resulting in a laminar solution flow regime. Using experimental and numerical tools, the vapor absorption on a LiBr falling film solution is characterized for different operating conditions. The impact of absorber length, cooling water inlet temperature, absorber water vapor pressure, solution inlet temperature, LiBr mass fraction and flow rate is investigated. Experimentally, a high absorption rate is achieved: as high as $7 \cdot 10^{-3}$ kg s^{-1} m^{-2}. Moreover, a 1D stationary model of water vapor absorption in a laminar vertical falling film is introduced and validated. Numerical investigations allow defining the absorber effectiveness for a wide range of operating conditions.

1. Introduction

Absorption systems have been used for cooling applications for more than a century. Today, absorption technology emerges in different areas, especially for refrigeration [1], heat pumping [2] or thermal storage [3,4] applications. In spite of high investment costs and limited efficiency, the increase in the cost of electricity and environmental problems have made this heat-operated cycle more attractive for both residential and industrial applications.

Absorption machines operate with a binary working fluid: a sorbent/sorbate couple. Among the most promising couples for the absorption cycle are the ammonia/water and water/lithium bromide (H_2O/LiBr) combinations [4]. This paper focuses on the H_2O/LiBr working pair, which presents the advantage of being environmentally friendly and does not present a hazard to human health. However, it must be operated at low pressure (a few kPa), making the process performance highly sensitive to leakage [5].

In these machines, the absorber, in which the exothermal absorption phenomenon and coupled heat and mass transfers occur, is one of the main components. It is known to be the least efficient of all the subcomponents of the absorption system, mainly due to the low mass diffusion coefficient of water into the LiBr solution [6]. Moreover, the heat released by the absorption phenomenon at the solution interface leads to an equilibrium condition displacement that limits the phenomenon. Therefore, the absorber is usually the bulkiest and most costly exchanger of the absorption machine. Moreover, its design has a significant impact on the size, cost and performance of system [7].

Among existing absorber technologies, the falling film exchanger is an effective technology for the absorber. It generates a significant exchange surface between the sorbate (water vapor) and the absorbent (LiBr solution) and facilitates the heat transfer from the falling film to the exchanger's cold surface. However, one of the drawbacks of falling film exchangers is the maldistribution of the film on the exchanger surface, which affects flow uniformity at low Reynolds numbers [8]. This well-known phenomenon has encouraged the development of dry patches on the plate and increased the liquid film thickness on the wetted areas [7,9,10]. The non-wetted areas do not participate in the absorption process, thus decreasing the useful absorber surface and the absorption rate. Heat transfers in wetted areas are also lower compared to the perfect wetted situation, due to the greater thickness of the film.

The comprehension and improvement of the vapor absorption rate into falling film absorber has been the subject of several numerical and experimental studies. The non-wetted areas can be reduced by increasing the flow rate [11], which affects the machine's efficiency [12], by reducing the absorber length or by using chemical and physical surface treatments to increase the absorber surface hydrophilicity and thus its wettability. Furthermore, several absorber falling film configurations have been investigated. The horizontal and vertical tube falling film exchangers are the most commonly implemented and studied [9,13–17]. However, in order to develop compact absorbers, alternative configurations have been

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Nomenclature

e	thickness, m
Cp	thermal capacity, J kg^{-1} K^{-1}
g	acceleration due to gravity, m s^{-2}
h	specific enthalpy, J kg^{-1}
$\tilde{h}_{s,H_2O}$	partial enthalpy of liquid water in LiBr solution, J kg^{-1}
l	width, m
L_{cap}	capillary length, m
L_{th}	thermal establishment length, m
L_{dif}	diffusive establishment length, m
$\dot{m}$	mass flow rate, kg s^{-1}
p	pressure, Pa
P	power, W
Pr	Prandtl number,
$\dot{Q}$	heat exchanged with the HTF, W
R	thermal resistance, K m^2 W^{-1}
Re	Reynolds number,
T	temperature, K
ΔT_{cool}	subcooling temperature of the HTF, K
x	LiBr mass fraction, %wt
Δz	discretization height of the exchanger, m

Greek symbols

α	convective heat transfer coefficient, W m^{-2}
β	mass transfer coefficient, m s^{-1}
λ	thermal conductivity, W m^{-1} K^{-1}
μ	viscosity, kg m^{-1} s^{-1}
ρ	density, kg m^{-3}
σ	Boltzman constant, m^2 kg s^{-2} K^{-1}

Indices/exponent

abs	absorbed/absorber
ad	adiabatic mode
cd	condenser
cool	cooling mode
des	desorbed/desorber
eq	equilibrium
ev	evaporator
film	film
H_2O	liquid water
htf	heat transfer fluid
i	inlet
iso	Isothermal mode
int	interface
lin	linear
max	maximum
o	outlet
s	LiBr solution
v	vapor
w	wall

studied, but few studies are available on plate type falling film absorbers. Due to the possibility of accumulating a large number of plates in a small volume, this compact, inexpensive exchanger configuration is attractive, especially for small-capacity absorption machines [13,18–20]. Furthermore, other studies have examined controlling the thermohydraulic characteristics of the LiBr solution falling film. Promising results were obtained using a hydrophobic membrane to limit the solution film's thickness [6,21–23]. Another approach consists in macroscopically texturing the absorber plate surface. Mortazavi et al. [7] developed a 3D absorber surface structure integrating fin components in a vertical flat plate. This absorber design provided thin films and uniformly wet absorber surfaces. Thus, absorption rates up to twice as high as on conventional falling film absorbers were obtained.

In this paper, a new plate-type falling film absorber design is presented: a vertical grooved falling film absorber. The grooves are designed to obtain good wettability of the absorber plate, even at low solution flow rates, leading to a laminar solution flow regime. The operation and performance of this absorber are investigated using experimental and numerical tools developed for this purpose. In the first part of this paper, the vapor absorption rate of the exchanger is characterized experimentally for different operating conditions and compared to numerical results. In the second part, its performance is numerically studied for a wide range of operating conditions.

2. Experimental set-up and protocol

2.1. Absorber design

The absorber studied is composed of two welded stainless steel vertical plates within which a heat transfer fluid flows. The plates are 3 mm thick, 100 mm wide. Two absorber lengths – 300 mm and 500 mm – are studied in this paper (Fig. 1). The solution film flows on the external sides of the plates (considering experimental constraints, the results presented in the present paper were obtained with a single wetted side of the exchanger by the solution). The external surface on which the solution flows is grooved. The vertical grooves are 4 mm wide (l_s in Fig. 1c) and mm deep. The fins separating the grooves are 2 mm wide. Therefore, the effective wet width of the heat exchangers is 60 mm.

The widths were chosen to ensure the entire wetting of the base of the grooves. Considering the contact angle between the LiBr solution and the stainless-steel plate close to 90° [7] and the capillary length of the LiBr solution in the standard condition of use ($x_i = 60$ %wt; $T_{s,i} = 30$ °C; $L_{cap} = \sqrt{\frac{\sigma}{\rho g}} \approx 2,25\ mm$), the ability of different groove widths to ensure good surface wettability was compared. The width range studied was between 0.5 and 8 mm, and the film Reynolds numbers lower than 400 (laminar flow). Stainless steel is known to be a low wetting substrate for aqueous solutions such as LiBr/H_2O solutions (the contact angle is typically between 80 and 90°). Tests show that when the groove width is lower than the capillary length, gas is entrapped at the wedge of the grooves and liquid is progressively expelled from the grooves due to a surface tension effect (the solution then preferably flows outside of the grooves). Surface tension effects become negligible when groove width becomes greater than the capillary length, allowing the liquid to wet the base of the grooves. When the grooves are too wide compared to the capillary length ($l_s > 2\ L_{cap}$), the solution never wets the entire base of the grooves for the flow rate range studied. Grooves 4 mm wide ensure satisfactory wetting of the base of the grooves and were therefore chosen for the further design of the absorber. Consequently, grooved plates present the advantage of ensuring significantly greater wetting of the exchange surface compared to flat plate configuration, especially at a low flow rate, as with absorbers. This absorber technology is simple and easy to implement using traditional machining techniques. It is a promising technology for absorption processes. Moreover, the