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Numerical and experimental investigation of a vertical *LiBr* falling film absorber considering wave regimes and in presence of mist flow

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ABSTRACT

The absorber represents the most critical component in absorption systems and one of the key issues. In this component complex heat and mass transfer phenomena during the absorption process takes place simultaneously. For this reason the development of mathematical models validated against experimental data always constitutes useful tools for the design and improvement of falling film absorbers. A testing device has been designed and built to reproduce absorption phenomena in vertical $LiBr-H_2O$ falling film absorbers with the primary objective to obtain experimental data. On the other hand, a mathematical model of falling film absorption of H_2O vapour in *LiBr* aqueous solutions has been implemented. Wave regime is considered by including and solving the Free Surface Deflection Equation. The numerical results are validated using the experimental data.

During the development of this work, the authors have paid careful attention to the verification of experimental data. Such verification consists of performing energy and mass balances in the fluid film side. Important discrepancies were found in our experimental data. Therefore, an extensive study was carried out in order to find the source of such errors. The conclusion is that there is a drag of *LiBr* solution in the water vapour which increases with the *Re* number. This mist flow cannot be measured experimentally, but can be evaluated in an indirect way. The mathematical models have been adapted in order to consider the influence of mist flow. On the other hand, in the literature there are not many experimental works related to falling film absorbers which expose enough information to verify the reliability of their experimental data.

1. Introduction

Absorption refrigeration technology has become more attractive in recent years. This is due to both the increasing price of primary energy, and the necessity of a more efficient decentralized energetic model. However, absorption technology has not been extended enough. The main impediment is the high initial investment required. In order to develop low-cost absorption machines of small capacity, the initial investment must be reduced. This is possible if the cooling tower is removed from the system. Therefore, air-cooled absorbers and condensers is a topic of technological interest. This is the reason why we give especial emphasis on studying the absorber under air-cooled conditions.

The absorber is usually the largest element of absorption machines due to its low heat and mass transfer coefficients. This fact determines the design of the whole system. Vertical falling film absorbers are an optimal solution of air-cooled systems [1–4]. In such devices the heat and mass transfer processes are produced simultaneously.

One of the earliest modelling attempts was published by Grigoreva and Nakoyarkov [5]. The authors consider the case of steady absorption in a smooth laminar falling film in an isothermal, impermeable vertical plate. A constant profile is assumed in streamwise velocity. Heat and mass transport are described by solving energy and species equations in two spatial dimension under the following assumptions: i) mass and thermal diffusion are negligible in the stream-wise direction; ii) the transverse velocity is negligible. Using these simplifying assumptions the authors provide a solution by means of Fourier separation variables techniques. Grossman [6] uses essentially the same simplifying assumptions as Grigoreva and Nakoyarkov [5]. However, he uses a parabolic velocity profile and a different boundary condition at the inlet (inlet solution temperature is equal to the wall temperature). Thus, no

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thermal boundary layer develops from the wall). Grossman uses two methods to solve the problem. First, using the Fourier method as in [5], he seeks a series expansion solution. Secondly, he uses a numerical technique based on finite difference method.

On the same line, Brauner et al. [7] presents a solution valid near the inlet region using similar technique as in Ref. [5]. Brauner's contribution is the application of Fick's law of diffusion at the interface without assuming infinite dilution in the liquid film. Andberg [8] is probably one of the first attempts to develop a solution for the horizontal tube case. The hydrodynamic of the falling film is divided into different regions, which are solved individually in the streamwise direction. Boundary layer approximations of the Navier Stokes equations are applied using finite difference techniques. Finally, Kawae et al. [9] develop a finite difference model to laminar similar to [8], but applied to vertical falling-film. The main differences are: i) thermophysical properties are not constant; ii) fully developed parabolic stream-wise velocity profile; iii) transverse velocity equal to zero.

In this work, a systematic research approach based on numerical modelling and experimental validation has been followed. On the one hand, an experimental setup which reproduces vertical falling film absorption, has been designed and built, $LiBr-H_2O$ is used as working fluid. The absorption process is controlled adjusting the following independent variables: solution concentration, solution temperature, cooling water temperature, absorber pressure and solution mass flow. The versatility of the experimental setup allows to manipulate independent variables for producing many experimental data of heat and mass transfer ratios under a wide variety of flows/conditions. The mass and heat absorbed are calculated by performing a mass and energy balances, respectively. An untypical situation has been detected during the experimental data reduction. It has been proved that water vapour drags some $LiBr$ micro drops from the generator to the absorber. This situation generates a kind of mist flow which increases as Re increases. The quantity of mist flow can only be evaluated in an indirect way. It is quantified using the "volumetric fraction" concept. Section 2.3 explains in detail the study in which this conclusion is reached, and the different actions that were taken in order to avoid this undesired situation. In the literature, no author mentions this untypical situation. However, some authors show important inconsistencies in their experimental data ([4,10–12]).

On the other hand, a mathematical model of falling film absorption of H_2O by $LiBr$ aqueous solutions has been implemented. The model is semi-empirical, based on Navier-Stokes equations together with energy and mass species simplified under the boundary layer hypotheses. The coupled equations are solved by means of the finite difference method in a step by step procedure. Another issue to be taken into consideration is the wavy regime in a vertical falling film. Experimental observation shows that wavy regime appears even in low Reynolds number ($Re \approx 20$) [13,14]. It is also well known that wavy regime causes increase of diffusion and mass transfer [15–18]. For this reason, wavy profiles are implemented together with falling film formulation. In the mathematical model, the Free Surface Deflection Equation is solved in each grid step for every Reynolds number, which is recalculated in function of mass absorbed. The mathematical model has been modified in order to consider the mist flow (see section 2.3).

2. Experimental set-up description

The experimental setup and its main components are shown in Fig. 1. The container (V1) is situated at the top of the structure. It has a capacity of approximately 17 L (V1). It works as a generator, and it uses both an immersion heater of 2 kW and a set of Flexible Silicone Rubber Heaters placed directly on the outer surface with a total heating capacity of 4.4 kW. Each one of the heat generation sources is governed by an independent PID control. Therefore, each of them can be operated independently or simultaneously. The difference between using the immersion heater or flexible rubber heaters consists of the heat flux density ($\frac{W}{m^2}$) which provides each of the heaters. The absorber (A) is a single vertical tube, with a 0.022 m outer diameter and 0.018 m inner diameter. In order to visualize the absorption process, the vertical absorber is situated inside a borosilicate glass cover with a 0.315 m diameter and 1.5 m length. Two metal plates coupled with flat O-rings of nitrile-butadiene rubber (NBR) are situated both at the top and bottom of the glass container. The vertical absorber tube passes through the upper metal plates. Therefore in order to assure the sealing between the tube and the plate, an O-ring (NBR) is placed coupled with a flange. The measuring instruments used are as follows: Resistance Temperature Detectors (RTD), Coriolis mass flow-meters and densimeters (C1, C2, C3) and pressure sensors (PS1, PS2). Other components are: gear pumps (P1, P2, P3, P7), peristaltic pump (P6), vacuum pumps (P4,P5), thermal baths (TB1, TB2), plate heat exchanger (HX). There are three different circuits in the experimental apparatus: (i) $LiBr$ aqueous solution, (ii) H_2O vapour and (iii) H_2O coolant. The circuit (i) begins in (V1) where the $LiBr$ aqueous solution is heated, and water vapour is generated. The temperature in (V1) is controlled by (RTD1). The rich solution is pumped from the generator and it passes across a heat exchanger (HX), where points 1 and 2 represent the inlet and the outlet of the plate heat exchanger.

The inlet mass flow and density are measured by (C1), the rich solution enters at the top of the absorber where it is collected in the dispenser which creates the falling film on the outer side of the vertical tube. While the fluid is flowing down, the absorption phenomenon is produced. The bottom dispenser picks up the weak solution which is sent back to the generator using the gear pump (P2). Both mass flow and density of the outlet solution are measured by (C2). The solution passes across (HX), where points 1' and 2' represent the inlet and the outlet of the plate heat exchanger respectively. The water vapour flows from the top of the generator to the absorber. During the generation process, the pump (P7) recirculates the aqueous solution. This is useful in order to maintain a homogeneous temperature inside the generator. Both absorption and generation pressures are measured using the pressure gauges (PS1) and (PS2), respectively. Since concentration is an important factor, it is necessary to adjust it in an accurate way. A peristaltic pump (P6), together with vessels (V2) and (V3), are used to establish concentration. (V3) contains H_2O, while (V2) contains highly concentrated $H_2O-LiBr$ solution. Using the pump (P6) it is possible to increase or decrease the concentration in the generator by adding either H_2O or $H_2O-LiBr$ solution. Both concentration of the rich and the poor solution can be calculated since $c = f(\rho, T)$. Thus, (RTD2) and (RTD5) are used for obtaining concentrations while (RTD3) and (RTD4) are used for calculating an energy balance in the absorber. The coolant circuit is fed directly by the thermal bath (TB2), where the inlet temperature can be adjusted, and the coolant fluid is pumped in counter-flow. On the other hand, an energy balance in the coolant fluid is performed using (RTD6) and (RTD7). The thermal bath (TB1) is used to adjust the inlet temperature of the rich solution. During absorption process, this is a key issue to maintain this temperature under control due to its influence in the absorption process. Finally, the vacuum pumps (P4) and (P5), together with a liquid nitrogen cold trap, are used for removing non-absorbable gases. In order to avoid problems of condensations with RTD measurements for the vapour temperature, the authors have used a thermistor coupled with the optical sensor (HAM) in order to obtain more accurate measurements.