Effect of Surfactants on the Flow Patterns of Horizontal Tube Bundles with a Falling Film

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The influence of two alcoholic surfactants on the flow patterns of falling film tube bundles is investigated. The flow patterns are measured in a single-stage absorption chiller in the absence of surfactants. The surface tension of H_2O/aqueous LiBr solution with different concentrations of 1-octanol and 2-ethylhexanol is measured at low pressure in a saturated atmosphere. Small quantities of surfactants in the aqueous solution do not have an influence on the flow patterns of the condenser and evaporator, while a shift from droplet to jet mode is predicted in the absorber and generator at the typical working condition of an absorption chiller.

Keywords: Absorption chillers, Flow patterns, Lithium bromide, Low pressure, Surfactants

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1 Introduction

Absorption chillers provide a cooling supply with negligible electrical power consumption compared to traditional vapor compression chillers, since they are driven by low-temperature waste heat. Nevertheless, their large size and high costs make them not yet competitive and, thus, they have to be further optimized. The heat exchangers of an absorption chiller with the working pair water/aqueous lithium bromide are usually designed as horizontal tube bundles with a falling film because of their good heat transfer coefficients at low pressure. To increase the heat and mass transfer of the absorber, which has been widely recognized as the limiting component of such chillers, small quantities of alcoholic surfactants are added to the aqueous lithium bromide solution. As a consequence, its surface tension is reduced and local gradients of surface tension at the vapor-liquid interface are established, which in turns trigger the Marangoni convection. Thus, the pattern of the liquid film is destabilized [1] and the heat and mass transfer of the absorber is enhanced, possibly due to a better wetting of the tubes, increased interfacial area and interfacial mixing [2]. This, in turn, leads to an augmentation of the cooling capacity and coefficient of performance of the absorption chiller [3].

Recently, it has been shown that these surfactants are also present in the vapor phase at low pressure and are effective in reducing the surface tension of water when delivered to the liquid interface only through the vapor phase [4]. In an absorption chiller working with water as refrigerant and aqueous lithium bromide as sorbent solution, the operative pressure varies between ca. 10 and 60 mbar [5]. Thus, the surfactant initially added to the aqueous lithium bromide solution in the absorber is also expected to be present in small concentrations in the other components and to also reduce the surface tension of the falling film in the generator, condenser, and evaporator. As a consequence, the flow patterns of the other tube bundles of the chillers may be also influenced by the addition of surfactants. A comprehensive knowledge of the flow regimes of each heat exchanger is fundamental for the choice of the most suitable heat transfer correlation for a precise and accurate design of the component. As a consequence, the working point of the overall cycle can be adjusted to increase the efficiency of the chiller.

The goal of this work is to investigate the influence of two different alcoholic surfactants on the flow regimes of tube bundles with a falling film. The flow regimes in the heat exchangers of a single-stage absorption chiller are measured without surfactants in the solution and compared to the flow pattern map of Hu and Jacobi [6], since it agrees well with flow patterns observed with aqueous lithium bromide [7–9]. The surface tension of water and aqueous lithium bromide solution with concentrations of 1-octanol (1-O) and 2-ethylhexanol (2-EH) ranging from 0 to 1000 ppm is measured at low pressure without inert gases, thus representing the real operating conditions of the absorption chiller. The influence of the surface tension reduction on the Kapitza number (*Ka*) and on the flow regimes of the absorber, generator, condenser, and evaporator is then discussed quantitatively.

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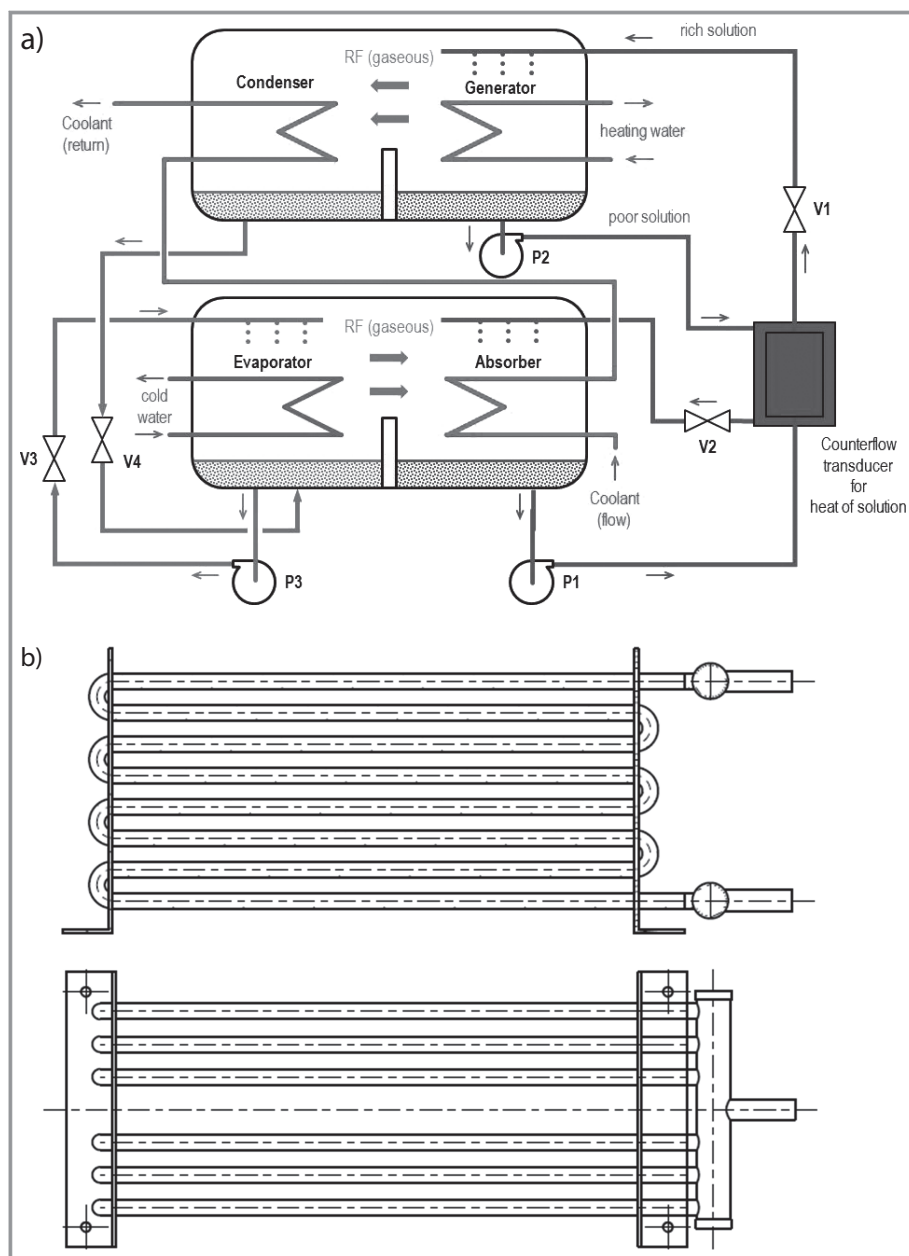
2 Experimental Setup and Procedure

2.1 Absorption Chiller

A schematic of the single-stage absorption chiller used in this work is reported in Fig. 1. The chiller has a nominal cooling capacity of 5 kW and is made out of two stainless steel vacuum vessels, where the evaporator and absorber are incorporated in the bottom one and the condenser and generator in the upper one, respectively. All heat exchangers are designed as horizontal copper tube bundles (d_o = 12 mm, s = 12 mm, L = 400 mm) with multiple rows and columns except for the solution heat exchanger, which is a compact plate heat exchanger. The vessels are equipped with four gauge glasses on one side (one in front of each tube bundle), so that the flow patterns which occur during the measurements can be recorded by means of a high speed camera. A more detailed description of the setup can be found in [5].

In this investigation, the Reynolds number (*Re*) of the falling film in the absorber and generator is varied between 10 and 35, while the inlet temperature of the hot, cooling, and cold water is kept constant at 85, 27 and 15 °C, respectively. The concentration of the aqueous lithium bromide solution varies between 58 and 60 wt % at the inlet of the generator and absorber, respectively.

2.2 Surface Tension Measurement

The surface tension of water and aqueous lithium bromide solution (60 wt %) with surfactants is measured according to the pendant drop method, where the shape of a small drop is fitted to the Young-Laplace equation and the surface tension is then iteratively calculated [10]. The measurements are carried out at low pressure in a saturated atmosphere into a vacuum cell (Fig. 2). The cell is made out of two concentric stainless steel tubes. Thermic oil flows in the gap between them and tempers the cell at the desired temperature and pressure. Two gauge glasses are installed on each side of the cell, so that pictures of the droplets can be taken by a high speed camera and further analyzed. Prior to the measurement, the cell is evacuated to remove any inert gases and filled with the aqueous surfactant solution. Further information about the test rig and the procedure is reported in Lonardi and Luke [4].

The surfactants used in this work are 2-ethylhexanol and 1-octanol, which are two isomers. 1-Octanol has a linear structure, while 2-ethylhexanol presents a more complex branched structure. These additives are added to the aqueous solutions in eight
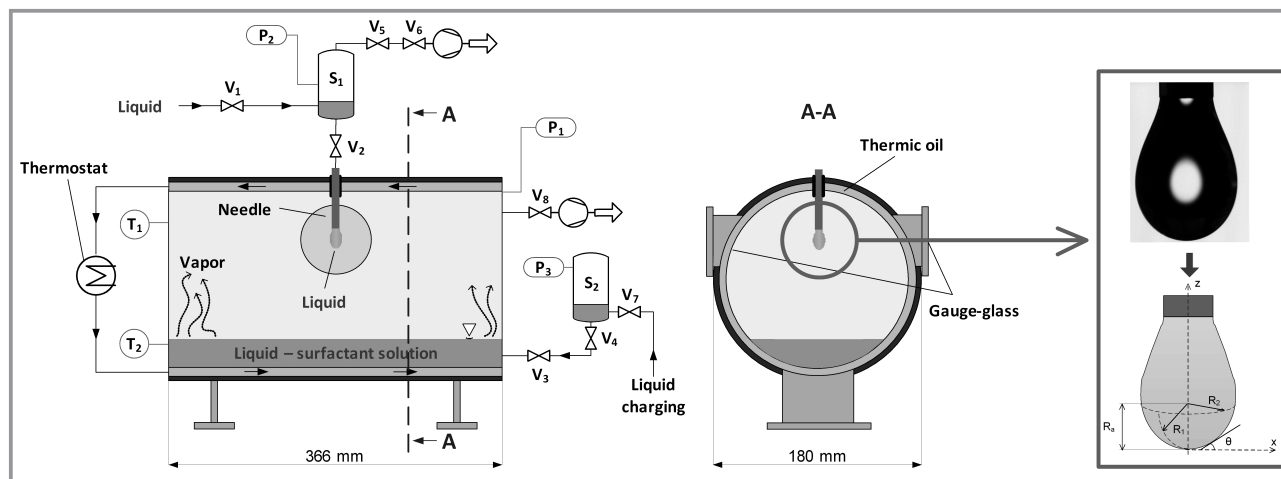

Figure 1. (a) Schematic of the single-stage absorption chiller [7] and (b) technical drawing of the absorber tube bundle [5]. RF, refrigerant.

Figure 2. Schematic of the vacuum cell for the surface tension measurement [4].

different concentrations between 0 and 1000 ppm. The surface tension of water is measured at p = 30 mbar and T = 23 °C, while the one of aqueous lithium bromide is measured at p = 10 mbar and T = 43 °C, both being saturation conditions.

It has to be noted that the droplets generated at the tip of the needle in the current investigations are constituted by pure water and aqueous lithium bromide solution without any surfactant. Indeed, the surfactant is added only to the solution at the bottom of the cell prior to the surface tension measurement. Thus, because of the low pressure and its volatility, the surfactant is delivered and adsorbed at the drop interface only through the vapor phase. This particular configuration of the measuring procedure was successfully used in a previous work to prove the validity of the vapor surfactant theory at low pressure [4]. This theory states that surfactants are effective in reducing the surface tension of a liquid also when delivered to the vapor-liquid interface only through the vapor phase [11]. Moreover, the exact concentration of the surfactant in the liquid drops cannot be estimated accurately in the current setup if the surfactant is added directly to the liquid which generates the drops. Indeed, in this case, a small amount of the surfactant would diffuse to the vapor phase once the liquid-surfactant solution reaches the phase separator 1 (Fig. 2) and the exact concentration of the surfactant in the drops formed hereafter cannot be known accurately.

2.3 Data Reduction

The flow pattern maps for a film falling over a tube bundle are usually represented by plotting the Reynolds number over the Kapitza number. The Reynolds number of the falling film is calculated as:

$$Re = \frac{4\Gamma}{\mu} \tag{1}$$

where Γ (kg m^{-1}s^{-1}) is the specific flow rate of water (condenser and evaporator) or aqueous lithium bromide solution (absorber and generator) and μ (Pa s) is the dynamic viscosity of the liquid film. The Kapitza number is expressed according to Eq. (2):

$$Ka = \frac{\sigma^3 \rho}{\mu^4 g} \tag{2}$$

where σ (N m^{-1}) is the surface tension of the liquid, ρ (kg m^{-3}) the density of the liquid, and g (m s^{-2}) the gravitational acceleration. The values of the surface tension used in the Kapitza number are the ones measured in the vacuum cell, while the dynamic viscosity and density for the aqueous lithium bromide solution are obtained by the experimental data collected by Patek and Klomfar [12]. It has to be noted that the surfactants are assumed not to have an influence on other properties of the liquid, such as viscosity or density, since the maximum concentration considered in this work is very low (1000 ppm = 0.1 wt %).

3 Results

3.1 Surface Tension

The surface tension of the aqueous solutions with 2-EH and 1-O is shown in Fig. 3 as a function of the surfactant concentration in the cell. As expected, the surface tension decreases with increasing surfactant concentration until a minimum value, the so-called plateau value, is reached. The surfactant, which is initially present only in the solution at the bottom of the cell (Fig. 2), diffuses into the vapor phase and adsorbs at the droplet interface, thus reducing its surface tension. In the case of water, 1-O leads to the highest surface tension reduction (σ = 37.13 mN m^{-1}), while the highest decrease of surface tension of the aqueous lithium bromide solution is obtained by means of 2-EH
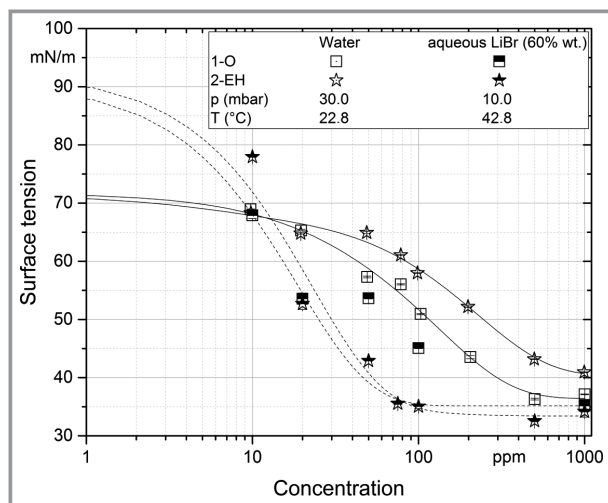
Figure 3. Surface tension of water and aqueous LiBr over concentration of surfactant in the cell.
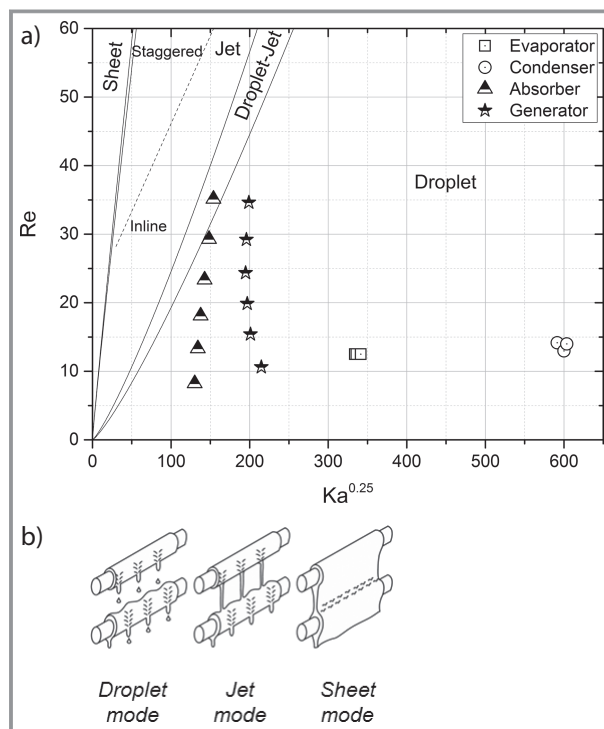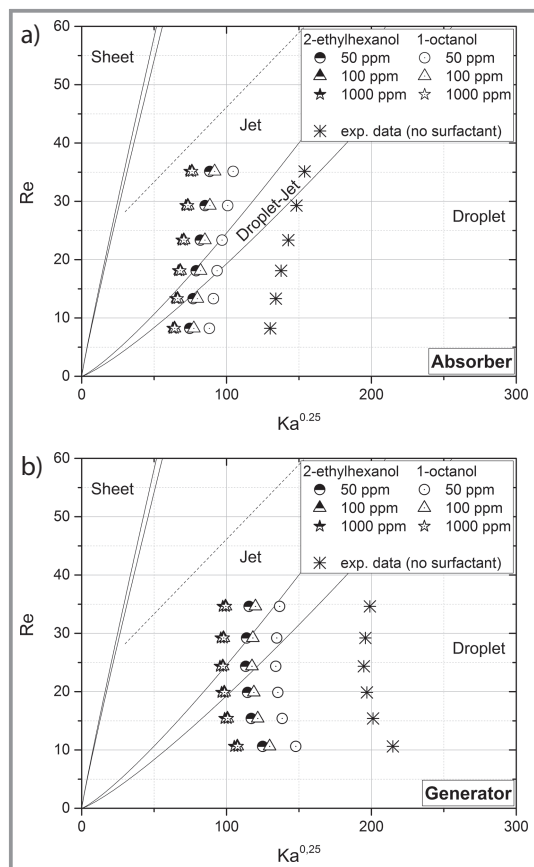

Figure 4. (a) Experimental flow patterns of the tube bundles (without surfactants) according to the map of Hu and Jacobi [6] and (b) flow regimes in a tube bundle [5].

(σ = 32.56 mN m^{-1} at C = 500 ppm), even though 1-O leads to similar values of surface tension at the highest concentration. A lower surface tension results in smaller droplets (Tab. 1), which are in turns expected to influence the flow pattern of the falling film.

3.2 Flow Patterns

According to Hu and Jacobi [6], the flow patterns of a film falling over a tube column are the droplet mode, jet mode, and sheet mode (Fig. 4). At low *Re*, the liquid is departing from the upper to the lower tube in the form of droplets. As the solution flow rate increases, droplets first coalesce into jets and, then, jets come together to form sheets. The experimental results of the measurement series conducted in the absorption chiller are plotted in Fig. 4 as Reynolds number over Kapitza number. The Reynolds number of the absorber and generator varies between 10 and 35, while the ones of the evaporator and the condenser are considerably lower

and almost constant. This is because the water flow rate (refrigerant) is consistently lower than the one of the aqueous lithium bromide solution. Contrary, the Kapitza numbers calculated in the evaporator and condenser are higher because of the lower viscosity of water compared to aqueous lithium bromide (see Eq. (2)).

The flow patterns observed in the four tube bundles are mainly droplets, whereas jets are observed in the absorber and generator at the highest *Re* investigated. This is well predicted by the flow map of Hu and Jacobi [6], even though they conducted their investigations with water, glycol, oil and alcohol. In the present study, jets are already observed in the absorber and generator at low *Re* numbers because of the narrow inter-tube distance of the tube bundles (12 mm), which leads to an earlier coalescence of the droplets.
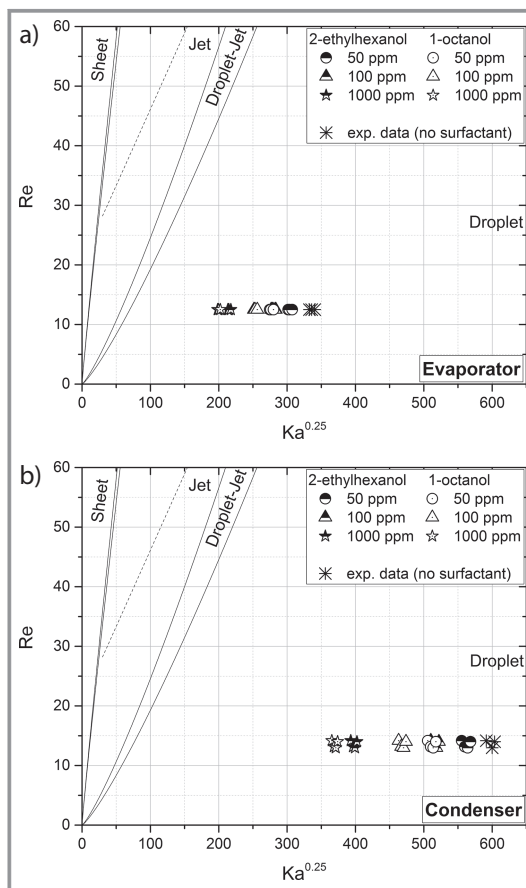
The flow patterns predicted in the absorber and generator by adding surfactant to the aqueous lithium bromide solution are plotted in Figs. 5 and 6, respectively. As mentioned before, the *Re* numbers are the same reported in Fig. 5 (measured without surfactants), while the new *Ka* number is calculated with the surface tension values measured and reported in Fig. 3. The presence of small quantities of 2-EH (50 ppm) already

Table 1. Droplets of water and aqueous LiBr with different concentrations of 2-ethylhexanol.

2-EH conc. [ppm]	0	50	100	500	1000
Water					
Aqueous LiBr (60 wt %)					

Figure 5. Predicted flow patterns (a) in the absorber and (b) in the generator in the presence of surfactants.

Figure 6. Predicted flow patterns (a) in the condenser and (b) in the evaporator in the presence of surfactants.

leads to a shift from droplet to jet regime in the absorber when $Re > 20$. At the highest concentrations of 1-O and 2-EH (1000 ppm), the jet mode is already predicted at $Re = 15$. This is in good agreement with the results of Cavallini et al. [9], who experimentally investigated the flow patterns of aqueous lithium bromide solution with 90 ppm of 2-EH falling over a single column of tubes. Indeed, they always observed jets in the falling film and a sheet flow was only established when $Re > 110$.

In the generator, a shift from droplets to full jets is only predicted at high surfactant concentrations and $Re > 30$. Thus, assuming that the surfactant concentration in the absorber is the same as in the generator, the surfactants may lead to a shift in the jet mode in the absorber but not influence the droplet mode in the generator at low Re number and low surfactant concentration. The presence of small quantities of surfactants in the aqueous lithium bromide solution is also expected to lead to the onset of the Marangoni convection in the liquid film and, thus, to destabilize the film as observed in a previous study [13]. As a consequence, jets which are formed due to the reduced surface tension may also break into small droplets between two adjacent tubes. Moreover, splashing between tubes at high Re and high surfactant concentrations may as well occur if the Marangoni

convection is very strong, so that the falling film departing from the upper tubes does not reach the lower ones, but is rather diverted outside the tube bundle. Thus, the wetting of the tubes could also be reduced in this case and the heat and mass transfer consequently decreased. These complex phenomena cannot be described and predicted well by the flow patterns maps and have to be investigated experimentally.

Fig. 6 illustrates the predicted flow patterns in the condenser and generator influenced by the presence of surfactants. Even when assuming that all the surfactant (originally added into the aqueous lithium bromide solution) evaporates in the generator and, thus, is delivered with water vapor first to the condenser and then to the evaporator, no change in the flow regime is predicted. Thus, due to the low Re number and high Ka number, which characterizes the falling film of these two heat exchangers, only droplets are expected between the tubes, also in the presence of surfactants.

4 Conclusions

The influence of two alcoholic surfactants on the flow patterns of copper tube bundles with a falling film is

investigated. The flow regimes of the condenser, evaporator, absorber, and generator are investigated experimentally in a test rig of a single-stage absorption chiller and compared with the flow pattern map of Hu and Jacobi [6]. The surface tension of water and aqueous lithium bromide with two surfactants in eight different concentrations is measured at low pressure and used to predict the flow pattern variation in each component.

The results of this work show how small quantities of surfactants are effective in reducing the surface tension of water and aqueous lithium bromide solution even when delivered to the liquid interface through the vapor phase. The flow patterns of the tube bundles of an absorption chiller at typical working condition are mainly droplets, and jets are observed in the absorber and generator at high Reynolds number. The addition of small quantities of surfactant in the solution leads to a shift from droplet to jet mode in the absorber and generator, depending on the concentration, while it has no influence on the flow patterns of the condenser and evaporator. According to the most recent correlation for the heat transfer in the absorber [14], a shift from droplet to jet mode results in a slight decrease in the heat transfer coefficient. On the other side, the presence of surfactants in the aqueous lithium bromide solution also leads to the onset of the Marangoni convection on the liquid film on the tubes. This is a complex mechanism which is expected to have an influence both on the coupled heat and mass transfer and on the flow patterns of the falling film but cannot be predicted by the flow pattern maps and needs to be experimentally investigated.

In this framework, the influence of surfactants on the coupled heat and mass transfer in the absorber and generator and on the variation of the flow patterns should be also experimentally investigated in further studies to take into account these two opposite effects and, therefore, to choose the most appropriate correlation for a more precise design of the generator and absorber of an absorption chiller.

Symbols

C	[kg kg^{-1}]	concentration
d_O	[m]	outer diameter
g	[m s^{-2}]	gravitational acceleration
Ka	[–]	Kapitza number
L	[m]	length
p	[bar]	pressure
R_1	[m]	radius
R_2	[m]	radius
R_a	[m]	radius
Re	[–]	Reynolds number
s	[m]	spacing
T	[°C]	temperature

Greek letters

Γ	[kg m^{-1}s^{-1}]	specific solution flow rate
θ	[°]	angle
μ	[Pa s]	dynamic viscosity
ρ	[kg m^{-3}]	density
σ	[N m^{-1}]	surface tension

Abbreviations

2-EH	2-ethylhexanol
1-O	1-octanol
RF	refrigerant

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