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FALLING FILM EVAPORATION: AN OVERVIEW

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Abstract: *Evaporation and boiling heat transfer occurrence in falling film evaporators are considered in this work. A literature review on the main parameters influencing the heat transfer phenomenon is performed. Many authors have focused either on fluid characteristics such as mass flow rate, flow patterns, or on the geometry of the system such as the intertube spacing, the tube diameter, the tube surface, or the feeder height. The effect of operating conditions, such as temperature difference between wall temperature and saturation temperature, saturation pressure or temperature, heat flux are also taken into account.*

Keywords: *Falling film, evaporation, nucleate boiling, heat transfer*

Nomenclature

g	acceleration of gravity $(m\ s^{-2})$
Ar	Archimedes number $(\rho^2 d^3 g^{-1} \mu_l^{-3})$
r	cavity radius (m)
h_{lv}	enthalpy of evaporation $(kJ\ kg^{-1})$
H	feeder height (m)
h	heat transfer coefficient $(W°C^{-1}m^{-2})$
Ka	Kapitza number $(g\mu_l^4\rho^{-1}\sigma^{-3})$
L	length (m)
Bo	modified boiling number ($qA/h_{lv}\dot{m}$)
Ga	modified Galileo number $(\rho\sigma^3 g^{-1}\mu_l^{-4})$
We	modified Weber number ($\dot{m}^2 D/A\rho\sigma$)
Nu	Nusselt number $(hk^{-1})(\upsilon^2 g)^{1/3}$
Pr	Prandtl number $(Cp\mu k^{-1})$
P	pressure (Pa)
R	radius tube (m)
Re	Reynolds number $(4\Gamma\mu_l^{-1})$
T	temperature $(°C)$
ΔT	temperature difference $(T_w - T_i)$
$T_w - T_s$	temperature superheating $(°C)$
k	thermal conductivity $(kJ\ s^{-1}°C^{-1}m^{-1})$
d	tube diameter (m)
s	tube spacing (m)

Greek letters

$\theta_{contact}$	contact angle between the fluid and the surface
ρ	density $(kg\ m^{-3})$
λ	departure site spacing (m)
μ	dynamic viscosity $(N\ s\ m^{-2})$
δ	film thickness (m)
υ	kinematic viscosity $(m^{-2}s^{-1})$
Γ	mass flow rate per unity of length $(kg\ m^{-1}s^{-1})$ (each side)
σ	surface tension $(kg\ s^{-2})$

Subscripts

i	inlet
l	liquid
s	saturation
s	vapor
w	wall or surface

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1. INTRODUCTION

Heat transfer through falling film (also called spray film) evaporation is an important and commonly used process. It has been widely employed in heat exchange in desalination devices, absorption/desorption-type chillers, OTEC (ocean thermal energy conversion primer), petrochemical, and chemical process industries, just to mention a few industries.

One of the most prominent characteristics of falling film evaporation technology is the low refrigerant charge, which is an attractive feature in the refrigeration industry because of the high costs of HFCs and HCFCs or because of the objective of increased safety in the case of ammonia (Gonzales and Jabardo, 1992).

OTEC pilot plants using this technology to achieve a close temperature approach between the evaporating fluid and the heating fluid, and hence a higher cycle thermal efficiency (Thome, 1998). Falling film evaporators have been used extensively in chemical processing plants due to their minimal fluid residence time and high heat transfer rates with low temperature differences (Yang and Shen, 2008). That advantage is used by the industry food because there are products thermo-sensibles.

Falling film evaporators have the following advantages concerning to flooded evaporators: (1) avoid the elevation of the boiling temperature caused by hydrostatic head in the lower part of evaporator. This effect is important in evaporators of large vertical dimensions, (2) high heat transfer coefficient, which improves the cycle efficiency, (3) low temperature difference between the fluid and the heated surface. It helps to utilize low-grade waste heat and avoids the superheating at the surface tube, increasing de energy efficiency of the system, (4) minimal pressure drop. This is important when the working fluid is a viscous liquid one as it is often the case of petrochemical and chemical process industries, (5) minimize the refrigerant charge, capital e operating costs, (Thome, 1999; Gonzales and Jabardo, 1992) and, (6) mitigate fouling and non-condensable effects (Ruan *et al*, 2008)

In falling film evaporation, the working fluid is distributed by a distributor tube or spray nozzle over the top of tube, forming a thin film of liquid around the tube. Guarantying the distribution and tube alignment is important in the flow uniformity and to avoid the dryout phenomenon. Heat transfer process in falling film evaporators takes place when the fluid is flowing downwards on the heated tube. Its mechanism can be produced by convective evaporation when there is a direct evaporation at the liquid-vapor interface or by boiling nucleate when there are bubbles formation at the heating tube wall. However, it is possible to find those simultaneous processes in an evaporation film.

There are several parameters affecting the heat and mass transfer in falling film evaporator. Chen and Jebson (1997) proposed some variables:

1. Evaporation temperature;
3. Mass flow rate of the liquid feed;
4. Inlet temperature of the liquid feed;
6. Tube length of heating;
7. Tube diameter;
8. Tube characteristics (material, wall thickness, and type of treatment applied to tube).

Thome (1999) carried out a review of falling film evaporation on single tubes and tube bundles. He emphasized studies on the new alternative refrigerants by that time along with ammonia. He documented experimental, empirical and analytical studies published prior 1994 to 1999. His work described chronologically several studies, covering a broad range of variables and geometries for falling film evaporation: vertical and horizontal tubes, oil effects, plain and numerous enhanced tubes, intertube film flow regimens, etc. Later, Ribatski and Jacobi (2005) organized a critical review of the literature but excluding vertical tube arrangements and desalination systems. This work is important because it collected different studies and analyzed heat transfer coefficient as a function of independent parameters such as heat flux, flow rate, film temperature, tube diameter and liquid feeder configuration on the falling film evaporation for single plain tubes. In addition, they made a differentiation between nucleate boiling and convective heat transfer.

The present article provides a literature review of falling film evaporation, and some of these are presented in the Table 1. Next, the present work performs a briefly discussion of different parameters such as mass flow, intertube spacing and flow patterns, tube diameter, temperature difference between wall temperature and saturation temperature (temperature superheating), saturation temperature, heat flux, surface and perimeter of the tube, feeding used for falling film evaporation.

2. NUCLEATE BOILING AND CONVECTIVE HEAT TRANSFER

The mechanism of heat transfer is fundamental for studying the behavior of heat transfer. Thus, the condition of operations, surfaces and geometries defines the heat transfer phenomenon. Fully established nucleate boiling is expected at a higher heat flux level. When nucleation is present, the heat flux exceeds the likely operating heat flux range of falling film evaporator. Nucleate boiling will not occur before the film flow is heated to a substantial superheat after passing through a certain length of preheating zone. Once nucleation is initiated it will go if there is a superheat zone associated.

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Table 1. Summary of experimental studies in falling film evaporation

Author	Tube	#	Material	q" [kW/m²]	Fluid	Temp. [°C]	Press. [kPa]	Γ [kg/s.m]	*Re* *Pr*	Dimensions Ext. Diam. [mm]	Dimensions Length [mm]
(SARAVACOS *et al*, 1970)	Vert.	1	Steel Stainless	---	Water Apple juice	32-94	Sat. Press	---	150-2450 5.62-90	39.9	2286
(CHUN; SEBAN, 1971)	Vert.	1	Steel Stainless	2.3-8.2	Water	28-100	3.86-100.2	0.0059-0.1323	320-21000 1.77-5.7	28.78	292.1
(FLETCHER et al., 1974)	Horiz.	1	90-10 Copper-Nickel	23.5-63.1	Distilled water	49-127	10.1-244.3	0.02-0.0379	134-254 ---	25.4 50.8	254
(FLETCHER et al., 1975)	Horiz.	1	90-10 Copper-Nickel	23.5-63.1	Sea water 3.45 % Sol. (weight)	49-127	10.1-244.3	0.0318-0.042	---	25.4 50.8	431.8
(MITROVIC, 1986)	Horiz.	1	Copper	18.4	Isopropyl alcohol Distilled water	25	101.3	0.1-0.26	80-280 ---	18	184
(CHYU; BERGLES, 1987)	Horiz.	1	Copper	10-208	Water	98	99	0.0072-0.72	100-10000 ---	25.4	152
(ROGERS; GOINDI, 1989)	Horiz.	1	Aluminum	---	Water	27	Sat. Press	up 0.25	up 2000 ---	132	457
(PARKEN et al., 1990)	Horiz.	1	Brass	30-80	Water	49 127	12 246	0.135-0.366	1000-7000 1.3-3.6	25.4 50.8	152
(HU, X.; JACOBI, A.M., 1996)-Part A	Horiz.	1	Brass	---	Water Ethylene glycol Water- glycol Oil Alcohol	20	101.3	up 0.22	up 580 ---	9.5 12.7 15.9 19.0 22.2	229
(HU, X.; JACOBI, A.M., 1996)-Part B	Horiz.	1	Brass	up 115	Water Ethylene glycol Water-ethylene glycol	20-40	101.3	up 0.72	up 1900 5.5-18	15.88 19.05 22.22	203.2
(PUTILIN et al., 1996)	Horiz.	1	Constantan Brass Copper Aluminum	10-75	Water	40-100	101.3	0.08-0.12-0.25-0.36-0.40	50-1200 ---	30 38	205
(CHEN; JEBSON, 1997)	Vert.	1	Steel Stainless	---	Water + Solution sugar (10%)	50-90	Sat. Press.	0.00667-0.010-0.0133-0.0167-0.020-0.0233	250-3000 ---	32	1200 1600 2000
(ALHUSSEINI; CHEN, 1998)	Vert.	1	Steel Stainless SS321	7.8-19.5	Water Propylene glycol	38.5-103.5	6.8-99.9	0.00877-1.104	124-15600 1.7-47	38.1	3050
(LIU et al., 2002)	Horiz.	3	Copper	40-60	Water	98	101.3	0.03239-0.3599	450-5000 1.75-7.02	13 20 30	130 200 300

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Table 1. Summary of experimental studies in falling film evaporation (continuation)

Author	Tube	#	Material	q" [kW/m²]	Fluid	Temp. [°C]	Press. [kPa]	Γ [kg/s.m]	*Re* *Pr*	Dimensions	
										Ext. Diam. [mm]	Length [mm]
(SALVAGNINI ; TAQUEDA, 2004)	Vert.	1	Glass	---	Water	98	101.3	0.00036-0.00337	9-84 1.75	51	1500
(XU et al., 2004)	Horiz.	1	Copper	---	Deionized water	50	Sat. Press.	0.03-0.32	200-2500 ---	25 40	---
(PAVLENKO et al., 2008)	Flat Plate	1	Constantan	5-30	Liquid nitrogen	-195,8	101.3	---	90-1690 ---	32	75
(RIBATSKI, 2006)	Horiz.	3	Steel Stainless	---	Water Ethylene glycol	27	Atm	up 0.18	---	11 20 40 80	---
(AWAD; NEGED, 2008)	Horiz.	3x 3	Steel Stainless	5-25	Water	---	40-100	0.06-0.14	275-675 ---	12.7 25.4 38.1 50.8	500
(RUAN et al., 2008)	Horiz.	3	Brass	---	Water Ethylene glycol	---	Atm	up 0.3	up 600 ---	25.4	300
(YANG; SHEN, 2008)	Horiz.	2	Aluminum bronze	---	Pure water Sea water	50	12.345	0.013-0.062	---	14	500
(JOHANSSON et al., 2009)	Vert.	1	Steel Stainless	4.3-10.4	Water Black liquor Up 40% dry solid content	92-110	Atm	---	300-3800 ---	60	4500
(WANG, Q. et al., 2010)	Vert.	1	Brass	---	Distilled water	28	Sat. Press	0.042-0.144	---	19	500
(LI et al., 2011)	Horiz.	6x 2	CAB-Tube Korodense (Copper alloys) Smooth	22.5	Water	11-18	0.85 a 1.15	0.000024-0.00027	10 a 110	15.88	700
(CHIEN; TSAI, 2011)	Horiz.	3	Copper	4.5-48.5	R-245fa R-245[a]	5 20	Sat. Press	0.012-0.04	187-372 6.26-7.15	19	70
(CHRISTIANS; THOME, 2012)	Horiz.	3	Copper	20-60	R-134a R-236fa	5	Sat. Press	0.02-0.3	up 2000 ---	19.05	554
(SHAHZAD et al., 2012)	Horiz.	4x 12	Steel Stainless	7.9-19.4	Sea water (15-90)x10^3 ppm	5.9-23	0.92-2.81	---	---	16	1990
(SNAJDAREK et al, 2012)	Horiz.	4	Copper	up 4.5	Water	---	60-96.2	up 0.2	---	12	---

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Chun and Seban (1971) used the Eq. (1) for find the liquid superheating, $T_w - T_s$, needed for a bubble to grow. They used as a cavity radius of $9.906x10^{-6}m.$

$$T_w - T_s = (2T_s^2 R\sigma)/rP \tag{1}$$

In contrast, the convective heat transfer there are not bubbles in the film, because the energy supplied to system only is used to evaporation in the liquid-vapor interface. Thus, when the tubes are heated, the heat is conducted from the surface to the interface by the film, where the vapor does not direct contact with the surface tube.

3. HEAT TRANSFER

3.1 Liquid mass flow

When there are variations of mass flow, some conditions may change the behavior of the heat transfer coefficient. With the increment of the liquid load, in one hand, the average thickness of liquid film will also increase, which is not favorable for an increase in heat transfer when the heat transfer is given for the laminar region. On the other hand, the velocity of liquid flow outside the tube increases, which amplifies the fluctuation of liquid film, which helps to improve convective heat transfer. Chyu and Bergles (1987) developed a study of falling film evaporation using water. They concluded that the overall heat transfer coefficient increases with the increase of the Reynolds number corresponding to turbulent flow. Schwartzberg (1988) apud Chen (1997) concluded that for Re <500, the heat transfer coefficient was proportional to the Reynolds number. For 500 < Re < 1600, the heat transfer coefficient decreases slightly, whereas for Re >1600, an increase the Reynolds number implies a slight rise of the heat transfer. Hu and Jacobi (1996); Putilin *et al* (1996); Xu *et al* (2004) found that a increasing of the Reynolds number implies an increasing of the overall heat transfer, but Hu and Jacobi (1996) explained that as result of the momemtum changes in the impingement zone. Paramalingam *et al* (2000) found that for high Reynolds number the overall heat transfer coefficient is independent of the mass flow. But, when the mass flow decreases could induce a breakdown of the film, which could cause a decreasing of the mass flow evaporator rate. The problem in this point is the fully wet, and hence the decreasing of the effective area of evaporation. However, Liu *et al* (2002) found for 450<Re>5000, the effect of the Reynolds number on the heat transfer coefficient is insignificant, and hence that is not an effective method to improve the overall heat transfer coefficient.

Alhusseini and Chen (1998) studied the falling film evaporation of single component liquids. They found that there is a dependency between the mass flow and the heat transfer coefficient. Thus, the heat transfer coefficient has a minimum value in the transition region. Therefore, for laminar region the heat transfer decreased as the Reynodls number incresed. In contrast, for turbulent region the heat transfer improved when the Reynolds number incresed. However, this behaivor was most evident for high Prandtl numbers. Yang and Shen (2008) found Nusselt numbers decreasing with increasing Reynolds number for laminar films at low Reynolds numbers. At higher Reynolds numbers, turbulent transport dominates yielding to increasing Nusselt number. Ruan *et al* (2008) studied distilled water falling over horizontal round tubes and found that if liquid feeding mass flow rate increases, the heat transfer coefficient increases nonlinearly: the heat transfer coefficient increases sharply with Γ when Γ is small (Γ < 0.1 kg/m.s), and the increase in heat transfer coefficient becomes less significant when Γ is further increased. Snajdarek *et al* (2012) found that the heat transfer coefficient increases with the mass flow rate of the spreading water. The experiment was carried out in a low-pressure environment formed in the heat exchanger chamber by vacuum pump which showed that the heat transfer coefficient was closely related to the mass flow rate.

When the falling film evaporation is controlled by nucleating the overall heat transfer coefficient in boiling is very high and independent of the Reynolds number (Chyu and Bergles, 1987). Chen and Jebson (1997) observed that the heat transfer coefficient was enhanced by increasing the Reynolds number because at higher Reynolds number, the turbulence increased and the thickness of the laminar sublayer decreased. In addition, they investigated that the heat transfer coefficient is affected by Prandtl number due to the effect of viscosity.

3.2 Intertube spacing and flow pattern

Tube spacing could change the thickness of liquid film but these changes can be negligible on the heat transfer coefficient Liu *et al* (2002). Hu and Jacobi (1996) found dependence between the tube spacing and the flow pattern. They observed changes with some alterations of the tube spacing, however, there is a weak dependency on tube spacing in the jet mode.

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In falling film evaporation there are two important phenomenons to study: hydrodynamics and thermal developing. The best hydrodynamic behavior improves the conditions thermal development. Hence, these two parameters must be coupled. Hebert (2009) affirms that the hydrodynamics of the liquid film appears to be the key parameter.

There are three flow patterns to characterize the fluid; sheet mode, jet mode and droplet mode as showing in the Fig. 1. When the film flow rate is low, the liquid flows on the tube in the droplet mode. If the flow rate increases, the transition from droplets to circular jets is given. With a further increase in the flow rate, the jets merge into a liquid sheet (Hu and Jacobi, 1995). The flow and heat transfer characteristics are different for each of the falling film modes

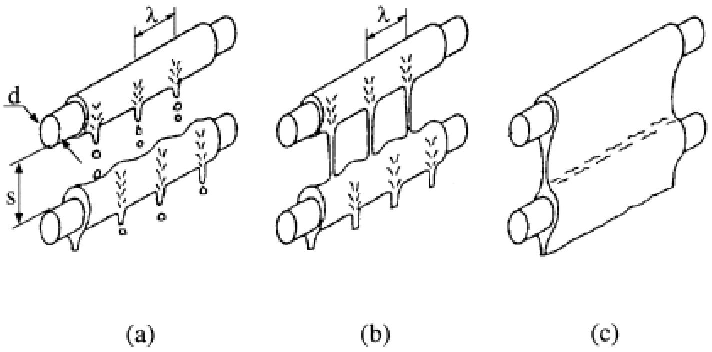

Figure 1. The falling film modes (a) droplet mode (b) jet mode (c) sheet mode (Mitrovic, 1986)

Other characteristic in the patter flow is the departure site spacing. Hu and Jacobi (1996) found that the departure site spacing depends on flow rate and decreases for an increasing in Re; this dependence is higher for fluids with a large $Ga^{1/4}$. Thus, when inertia effects dominates, the flow turns to the sheet mode. When gravity or surface tension dominates flow turns to a droplet pattern. The formation of jets is apparently related to a complicated competition between these effects and viscous forces. They found correlations for these flow patterns;

$$\begin{aligned} &\text{Sheet mode} \longrightarrow Nu = 2.194 Re^{0.28} Pr^{0.14} Ar^{-0.20} (s/d)^{0.07} \\ &\text{Jet mode} \longrightarrow Nu = 1.378 Re^{0.42} Pr^{0.26} Ar^{-0.23} (s/d)^{0.08} \\ &\text{Droplet mode} \longrightarrow Nu = 0.113 Re^{0.85} Pr^{0.85} Ar^{-0.27} (s/d)^{0.04} \end{aligned} \tag{2}$$

In convective heat transfer, Chyu and Bergles (1987) observed in turbulent region that liquid is fed in sheet pattern, when the dimensionless number (H/d) was equal to unity or the equivalent to $H = 3$ mm , thus, when the configurations is above of that value, there are a formation of columns, and then droplets. Hu and Jacobi (1996) showed the average heat transfer coefficient has a strongly dependence with low Reynolds numbers. For jet mode, the dependency is less pronounced. However, in the sheet mode the dependency still exists for water. The sheet mode flow is not influenced by the modes of liquid feeding or the tube spacings. Thus, in evaporators the tube spacing can be neglected (Liu *et al*, 2002). In addition, Li *et al* (2011) concluded that as the Reynolds number increases, the heat transfer coefficients will increase to a peak value and then gradually decrease. Mitrovic (2005) suggested empirical correlations as transition criterion of flow mode. That can be represented by the Eq. (3). The C_f are 0.34, 0.92 and 1.08 for droplets-columns, columns-columns sheet and columns sheet-sheet, respectively.

$$Re_{transition} = C_f Ka^{1/4} \tag{3}$$

Ribaski (2006) found that in the falling film evaporation flow contraction can exist along the tube bundle and consequently the wet surface area is diminished. That film flow contraction was explained by two phenomenon. The first is due to tube spacing, and controlled by the gravity and surface tension effects. The second is related to the diameter tube, and controlled by the inertial forces, viscous and surface tension effects. He concluded the film flow contraction increases with the increasing of the tube spacing for high number Reynolds (sheet pattern). However, there is a little dependence between the tube spacing and the film flow contraction for column and droplet pattern. The longitudinal film flow contraction increases with the increasing diameter and spacing tube.

In nucleate boiling falling film evaporation, Christians and Thome (2012) showed that although the inter-tube flow pattern may be different, the flow structure over the tubes is very similar. Thus, the flow structure does not greatly affect the heat transfer.

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The study of breakdown of the film is a fundamental parameter to improve the efficiency of the falling film evaporation system, because the breakdown can cause problems as the fouling of the tubes. That affects the efficiency and hence the evaporation rate of the system. Puzyrewski and Zuroski (1969) found the influence of surface tension, viscosity, and density of liquids on the phenomenon of disintegration of a liquid sheet. Ponter *et al* (1967) (Paramalingam *et al*, 2000) found a correlation to guarantee the minimal flow rate to cover the all tube surface in vertical falling film evaporation. Thus, the desinger should project the evaporator with a superior flow rate of the next correlation.

$$\Gamma_{\text{minimum}} = 1.69\left(\frac{\mu\rho}{g}\right)^{1/5}\left[\sigma\left(1-cos\theta_{\text{contact}}\right)\right]^{3/5} \tag{4}$$

When there is a reduction on the Re, the breakdown can occur. However, that minimal mass flow rate is not only dependent of the Reynolds. Hence, the density, viscosity, superficial tension and contact angle between liquid and vapor are variables to study the breakdown.

Pavlenko *et al* (2008) analyzed the breakdown for falling wavy liquid nitrogen film evaporation in flat plate. They affirmed that exist an equilibrium heat flux point to avoid the breakdown caused by the displacement of wet zones in film liquid flow due to thermal mechanism. Thus, at small Reynolds numbers and relatively small heat fluxes (convective), the breakdown occur due to appearance of local dry spots and rapid propagation of interphase boundary. However, at high heat flux (nucleation), the breakdown is caused by the rapid growth of vapor bubbles, which causes dispersion and expulsion of a large number of fine droplets.

3.3 Tube diameter

Tube diameter changes the conditions to develop hydrodynamic and thermal boundary layers. Sarma and Saibabu (1992) showed that for a mass flow in laminar region and heat flux constant (non-isothermal conditions), increasing the diameter reduces the film thickness. Hence, the thermal resistance decreases and the overall heat transfer coefficient increases. Hu and Jacobi (1996) found that for convective heat transfer, the heat transfer coefficient was larger for smaller tubes over the entire experimental range of Reynolds numbers (Re>1900) because for small tubes, there is a fully developed boundary layer occupying a larger fraction of the total heat transfer area. Liu *et al* (2002) found that the effect of the tube diameter on the heat transfer is insignificant in low and moderate Reynolds number (lower than 2000), but the heat transfer coefficient for Reynolds number above 2000, is influenced by the tube diameter, improving the coefficient in smaller diameters. When the diameter decreases the fluctuations on the film are more important, increasing the convection heat transfer outside the tube Xu *et al* (2004). On the other hand, for the tubes with greatest tube diameter, the film is most stable due to the effect of Marangoni (Rogers and Goindi, 1989).

In nucleate boiling falling film evaporation the tube diameter influences the heat transfer. When exists a decreasing in the tube diameter carry out an increasing the overall heat transfer coefficient (Fletcher *et al* 1974; 1975). Van der Mast (1976) found that the heat transfer coefficient for the inlet-section is considerably higher than further down the tube. It is probably due to the high turbulence at the impingement zone. Jambunathan *et al* (1992), found an empirical correlations for heat transfer for single circular jet impingement. They noticed the local heat transfer coefficient should be function of Reynolds and Prandtl numbers, and others geometries parameters.

3.4 Temperature superheating

Temperature superheating is referred to the temperature of the surface above of saturation temperature of liquid. In convective heat transfer, Chyu and Bergles (1987) found that nonboiling heat transfer coefficient is not affected by the increasing of the wall superheating because there is not a change at the film thickness (no thinning). However, Awad and Negeed (2008) found that the increasing of the temperature difference between the film and the tube wall yields to the increasing of the evaporation rate due to the decreasing of the thickness film. Moreover, the thermal resistance decreases and the heat transfer coefficient increases.

Under nucleate boiling conditions: a small amount of bubbles could appear on the tube wall. However, the bubbles grew up at the bottom of the tube and then broke, but this had almost no effect on the fluctuation of the wall. Hence, the heat transfer coefficient is not affected (Xu *et al,* 2004). But, if the temperature superheating is achieved by increasing the heat flux, it may affect the falling film evaporation (Li *et al,* 2011). If dry patches began to appear on the tube, larger temperature difference will make the dry areas stay on the tube surfaces and become larger, because higher heat flux makes more liquid to evaporate. But, if the temperature difference is not high enough, the dry patches may be rewetted, and good heat transfer capacity will return (Fujita and Tsutsui, 1998).

3.5 Saturation temperature

Operation on falling film evaporation system with high temperature may be a disadvantage. It might increase the fouling in the evaporator tube, then decrease in the heat transfer coefficients. However, the heat transfer coefficient increases with the rise of the saturation temperature (Saravacos *et al,* 1970). In a system dominated by convection, which increasing the saturation temperature makes the average thickness of the liquid film decrease. Meanwhile the increment of heat transfer coefficient yields a decrease of the surface tension of the liquid. Thus, the fluctuation swing increases and waving intensity is aggravated (Xu *et al,* 2004; Li *et al,* 2011). Shahzad *et al* (2012) showed a linear increase in the overall heat transfer coefficient with an increasing saturation temperature due to the drop in the specific volume of vapor.

Nucleate boiling falling film evaporation has a similar trend than the convective case. The heat transfer coefficient increases with the increase of the saturation temperature. Chen and Jebson (1997) found that the heat transfer coefficient increased as the evaporating temperature increased. It was more evident to sugar solution than to water due to the viscosity. The decreasing of the viscosity was a little more for sugar solution than for water. Fletcher (1975) observed the same results for sea water films on horizontal tubes.

3.6 Heat flux

In process dominated by convection, the heat transfer coefficient should not be a direct function of heat flux (Fletcher *et al,* 1975; Hu and Jacobi, 1996; Sarma and Saibabu, 1992). Chien and Tsai (2011) concluded that at low heat flux the heat transfer coefficient of falling film evaporation is greater than that of pool boiling, however when the heat flux is medium and high, the heat transfer coefficient in pool boiling is similar to the one to falling film evaporation. Moreover, an increasing of the heat flux could be impair the heat transfer coefficient due to increasing of the number of bubbles on the surface tube, therefore, the conditions of the impingement changes.

Sarma and Saibabu (1992) presented the Eq. (5) to limit at the wall temperature, for a given system or the admissible value for heat flux. It represents the value of the potential temperature necessary to begin the nucleation. From that point, the bubble nucleation density increases as the heat flux increases.

$$\frac{T_{\mathrm{w}} - T_{\mathrm{s}}}{T_{\mathrm{s}}} = \frac{0.017\sigma}{h_{\mathrm{lv}}\rho_{\mathrm{v}}\delta} \tag{5}$$

The heat transfer coefficient should increase with the heat flux because of contributions to heat transfer coefficient due to both convection and nucleate boiling, however when there are small immersed bubbles inner the falling film thickness will increase the heat transfer resistance due to the lower heat conductivity of water vapor. An another part, the wave-breaking and bubbles formation will increase heat transfer by the turbulence generation, and therefore the evaporation rate (Johansson *et al,* 2009). Yang and Shen (2008) observed that these increasing of the heat transfer coefficient are due to falling film turbulence flow enhanced. Fletcher *et al* (1975) found an increasing of overall heat transfer with the increasing the heat flux due to increasing of the nucleation.

Li *et al* (2011) believed that the heat flux contributes to increase heat transfer coefficient because more liquid will evaporate, so the film becomes thinner and the film evaporation performance better. However, it possible that a premature local dryout occurs due to increasing the heat flux (Habert, 2009).

3.7 Surface and perimeter of tube

At the top part of tube, the local heat transfer coefficient is the highest due to impingement region (order of magnitude $10^5 W/m^2K$), but jet impingement is effective in a small region. Thus, the contribution over the average heat transfer is only a small portion (Chyu and Bergles, 1987). Hu and Jacobi (1996) found changes significant of the local heat transfer coefficient over the tube perimeter. They concluded the local heat transfer coefficient is higher in the impingement region than the bottom of the tube, and this top part is most sensible to changes of Reynolds number. They explained this behavior due to the fluid is decelerated in the surface normal and accelerated in the circumferential direction. Thus when the thermal boundary layer grows through of perimeter, the Nusselt number decreases until reaches a constant number when the thermal boundary layer is fully developed. It applies to sheet pattern. However, in droplet and jets patterns they found that there is a significant change in the local heat transfer coefficient around the circumferential and axial directions. The local heat transfer coefficient in the axial position improve when there are interactions between neighboring jets that cause the formation of an interaction ring.

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Gambaryan-Roisman and Stephan (2003) studied of falling R-11 film evaporation on vertical copper (plate) grooved surfaces. They worked for laminar region, hydrodynamic and thermally boundary layer developed, heat flux constant and surface without nucleation. They found that there is an increment of the heat transfer coefficient for the grooved surface in comparison with smooth tube. However, the heat transfer coefficient has a complicated dependency between groove sizes and mass flow. It is meaning that exist an optimal design of those parameters to improve the heat transfer. Salvagnini and Taqueda (2004) studied the falling film evaporation process with internal promoters. They concluded that the heat transfer with promoter increased to three times the evaporation in comparison with heat transfer without promoter.

In convective heat transfer, there are several surfaces enhanced used in the falling film evaporation system. But the profiles could be used to breakdown the boundary layer. Hence, the partial destruction of the laminar boundary layer by grooves increases the heat transfer coefficient. Putilin *et al* (1996) studied various profiles on the surface, and they concluded that the triangular profile is the best arrangement to improve the heat transfer. Finally, they concluded that the profiles can be increases up 1.7 times the heat transfer coefficient for smooth tube. Wang *et al* (2010) studied the heat transfer on hydrophobic material surface. They found highest heat transfer coefficient at the coated division tubes due to the increase in the effective contact angle of the surface.

On the other hand, new metal treatments and new shapes of the evaporating surface are used with the objective to promote nucleate boiling, resulting in substantial increases of the heat transfer coefficients (Saravacos *et al,* 1970). Fletcher *et al* (1975) studied a newly manufactured (knurled) tube. They concluded the enhancement could help to create many active nucleating sites but with the time the tube became less active due to aged tube. Chien and Tsai (2011) investigated the heat transfer performance on horizontal copper tubes using refrigerant R-245fa. They used a plain tube, a boiling enhanced (mesh) tube, and a finned tube to improve the heat transfer coefficient. They showed the behavior the coefficient on different surfaces. They concluded that the mesh tube supplied higher heat transfer coefficient (5-7 times) than smooth and fin tube.

3.8 Feeding

Yang and Shen (2008) observed that the liquid feeder height can affect the heat transfer coefficient because the fluid will gain slightly more velocity, this increase in velocity over the heating tubes helps to enhance the heat transfer. When the fluid reaches higher velocity, the convective heat transfer increases and this allows the heat exchanger to run to efficiently. However, raising the distance too high can result in an ineffective fluid covering of the heating tubes (dryout), yielding a low heat transfer coefficient. They concluded that there is a maximum height above which there are many dry spots on the tube.

Nonboiling heat transfer coefficient is slightly affected by the feeder height in a turbulent region. However, the heat transfer coefficient is less sensitive to the change in liquid feed height for low Reynolds number. (Chyu and Bergles, 1987).

Parken *et al* (1990) found higher heat transfer coefficient for similar conditions using a distribution system with a perforated plated distribution (used by Fletcher *et al,* 1974) in comparison with a system with a thin-slot distribution system. Therefore, the perforated plated can offer a thinner boundary layer than the thin slot distribution.

4. CONCLUSIONS

In this work an overview of falling film evaporation focused in one component has been presented. We have analyzed the main parameters influencing the heat transfer occurring in convective and nucleate boiling falling film process. Those parameters are numerous and everyone requires a separate study. We concluded that the hydrodynamic and thermal studies should be revised due to the fact that both of them affect the heat transfer coefficient. Regarding to the parameters that have been studied it is concluded that,

(1) The mass flow rate affects the heat transfer coefficient. In convective heat transfer, an increasing of the Reynolds number can lead to two behaviors: if the flow is laminar, an increasing of the Reynolds number implies a thickening of the film or an increasing of the thermal resistance, and therefore the heat transfer coefficient decreases. On the other hand, if the flow is turbulent, an increasing of the Reynolds number involves changes of the fluctuations. Thus, the heat transfer increases.

(2) In falling film evaporation, the intertube spacing and flow pattern parameters should be analyzed to guarantee the best performance of the devices. The most important parameters are breakdown of the film, fully wetting of the tube, departure site spacing and flow contraction. For the thermophysical and hydraulically characterization of the flow pattern two nondimensional numbers are used, Galileo and Reynolds numbers, respectively.

(3) The temperature superheating and the heat flux influence the falling film evaporation with nucleate boiling, because a higher heat flux increases the evaporation rate and the bubble generation intensifies the turbulence of the film. However, for a higher heat flux is also likely that premature local dryout occurs. In falling film evaporation without nucleation, neither the temperature superheating nor heat flux affects significantly the heat transfer coefficient.
(4) The tube surface and the feeding are important parameter in falling film evaporation surveys. When the process is dominated by the nucleate boiling, the tube surface performance is improved by creating more sites of activation. However, in falling film evaporation with convective heat transfer, the surface performance is improved by generating fluctuations, which leads to the partial destruction of the laminar boundary layer.

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