AN OVERVIEW OF STUDIES CONCERNING CONDENSATION, POOL AND FLOW BOILING PERFORMED AT THE DEPARTMENT OF MECHANICAL ENGINEERING OF ESCOLA DE ENGENHARIA DE SÃO CARLOS OF UNIVERSITY OF SÃO PAULO

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Abstract. *This paper presents an overview of studies concerning heat transfer with phase change performed since 1994 in the Department of Mechanical Engineering at the Escola de Engenharia de São Carlos of University of São Paulo. The review covers technical reports, book chapters, and journal and conference papers published by members of the research group located at EESC-USP. This group performed several studies on pool boiling heat transfer on a single tube and on an array of horizontal tubes. The effects on the pool boiling heat transfer coefficient of fluid type, reduced pressure, surface material and roughness and the number of tubes in an array have been investigated. Flow boiling heat transfer and pressure drop of nanofluids and halocarbon refrigerants inside micro- and macro-scale channels and structured tubes were also investigated. Studies addressing condensation of halocarbon refrigerants inside micro-scale tubes were also performed. New correlations and mechanistic models were proposed. Here, all these studies are summarized and critically described. The main conclusions from state-of-the-art reviews published by the group are also pointed out.*

Keywords*: flow boiling, pool boiling, convective boiling, microchannels, heat transfer.*

1. INTRODUCTION

Studies on heat transfer with phase change and two-phase flow of halocarbon refrigerants are being performed at the Department of Mechanical Engineering at the Escola de Engenharia de São Carlos of the University of São Paulo since 1994. From the results of these studies, several papers were published and a large number of Ph.D. and M.Sc. students were graduated. From 1994 to 2005, the group working in this area was headed by Prof. Saíz-Jabardo. After his retirement from the University of São Paulo in 2005 and from 2006 until now, the studies were headed by Prof. Ribatski, a former M.Sc. and Ph.D. student of Prof. Saíz-Jabardo. Most of the researches were experimental investigations and covered a broad range of related topics in the two-phase flow field as pool boiling on single tubes and on tube bundles, flow boiling heat transfer, two-phase pressure drop, $\Delta p_{2\phi}$, and flow pattern in horizontal micro- and macro-tubes, heat transfer enhancement techniques, in-tube condensation, nanofluids flow boiling and two-phase flow instrumentation. New correlations and mechanistic models were proposed. Several literature reviews were also published. So, the present paper was written in order to summarize and present to the heat transfer and two-phase flow community a resume of the contributions made by the researchers that have worked on these studies.

2. POOL BOILING

2.1. Pool boiling on single-tubes

Ribatski and Saiz-Jabardo (2003) reported the results of an experimental investigation on saturated pool boiling of halocarbon refrigerants. Their experiments covered a wide range of reduced pressures, p_r, and heat fluxes, being carried out on copper, brass and stainless steel horizontal cylindrical surfaces with different finishing conditions. From their study the following conclusions were drawn: i) as a general rule, the nucleate boiling heat transfer coefficient of higher pressure refrigerants (R12, R22 and R134a) is higher than that of lower pressure refrigerants (R11 and R123); ii) p_r and surface material and roughness affect the boiling curve in a degree that strongly depends on the particular refrigerant; iii) nucleate boiling heat transfer is more intensely affected by the surface roughness at low p_r; iv) the material of the heating surface affects the boiling curves in a combined fashion with the particular refrigerant. Transient conduction effects in the material seem to affect marginally the boiling curve. Additionally, based on Ribatski and Saiz-Jabardo (2000) and Cooper´s (1984) correlation, Ribatski and Saiz-Jabardo (2003), using their own database, have proposed the following correlation for pool boiling of halocarbon refrigerants:

$$h \Big/ \left(\phi^{0.9-0.3p_r^{0.2}}\right) = f_w p_r^{0.45}\left[-\log(p_r)\right]^{-0.8} Ra^{0.2} M^{-0.5} \qquad (1)$$

where h is the heat transfer coefficient (W/m^{2}K), ϕ is the heat flux (W/m^2), M is the molecular mass (kg/kmol) and Ra is the arithmetical mean deviation of the profile (μm) defined according to ISO 4287/1:1984. The heat surface material parameter, f_w, assumes the following values for copper, brass and stainless steel, respectively: 100, 110 and 85. This correlation presented an overall average deviation with respect to the experimental data equal to 9.6%. The proposed correlation has been also compared to independent results from literature with resulting deviations in the ±20% range.

Ribatski and Saíz-Jabardo (2003) have also pointed out the intermittence of the boiling pattern within the heat flux range between 10 and 20kW/m^2. This behavior was characterized by alternate appearance and disappearance of bubble clusters in several regions of the boiling surface, and is particularly intensified in stainless steel surfaces. Later on, in order to investigate such a phenomenon, Ribatski *et al.* (2004) performed an experimental analysis of the temperature distribution along the external perimeter of a horizontal cylindrical surface submitted to nucleate boiling. They found that under nucleate boiling conditions and lower ϕ, the surface temperature profile presents a maximum at the surface top, diminishing down to a minimum value at the bottom. An opposite trend has been found at high ϕ. The shifting ϕ has been found to be higher on a stainless steel surface. It has also been noted that its value increases with p_r. According to the authors, these trends seem to be closely related to the thermal conductivity of the heating wall and the influence of natural convection effects, both aspects being related to the active site density and bubble frequency.

Saiz-Jabardo *et al*. (2004) performed an investigation on the performance of the Rohsenow's (1952) type of correlation when applied to the nucleate boiling of halocarbon refrigerants over horizontal cylinders of different material. They found that the exponents *m* and *n* in the Rohsenow correlation, given by the equation below, are weakly affected by the refrigerant, and surface material and finishing.

$$\left(c_{p,l}\Delta T\right)/h_{lv} = C_{sf}\left\{\left[\phi/\left(h_{lv}\mu_l\right)\right]\left[\sigma/\left(g\left(\rho_l-\rho_v\right)\right)\right]^{1/2}\right\}^m \mathrm{Pr}_l^n \qquad (2)$$

where, $c_{p,l}$ is the liquid specific heat (J/KgK), ΔT is the surface superheat (K), h_{lv} is the latent heat of evaporation (J/kg), μ_l is the liquid dynamic viscosity (Pa.s), σ is the surface tension (N/m), g is the gravitational acceleration (m/s^2), Pr_l is the liquid Prandtl number, and ρ_l and ρ_v are the liquid and vapor densities (kg/m^3), respectively. Based on their database, Saiz-Jabardo *et al*. (2004) have found m=0.21 and n=1.03, and then, they have proposed for $\phi \geq 5$kW/m^2 a equation to predict C_{sf} as a function of p_r, Ra and the liquid-surface material combination given as follow:

$$C_{sf} = c\left\{\left[0.0077\ln(Ra) - 0.0258\right]p_r - 0.0036\ln(Ra) + 0.0138\right\} \qquad (3)$$

Table 1 presents the values of the liquid-surface material coefficients in Eq. (3). Values of C_{sf} in Eq. (2) for specifics surface roughness and liquid/surface material were also proposed by the authors keeping the values of *m* and *n* equal to 0.33 and 1.7 , respectively, as proposed by Rohnenow (1952) for fluids different than water.

Table 1. Coefficient for the C_{sf} correlation, Eq. (3).

fluid/surface-material	**c**	**fluid/surface-material**	**c**	**fluid/surface-material**	**c**
R11/copper	1.00	R123/SS	1.30	R134a/brass	0.90
R11/SS	1.30	R123/brass	0.95	R12/copper	1.00
R11/brass	0.90	R134a/copper	1.00	R12/brass	1.00
R123/copper	1.00	R134a/SS	1.15		

Stelute *et al*. (2006) and Saiz-Jabardo *et al*. (2009) presented results of an experimental investigation carried out to determine the effects of *Ra* of different materials on nucleate boiling of refrigerants R134a and R123. Experiments have been performed on cylindrical surfaces of copper, brass and stainless steel. Sand paper and shot pinned roughened surfaces and polished surfaces were used in order to obtain an average roughness varying from 0.03μm to 10.5μm. Boiling curves at different p_r have been raised as part of the investigation. The results have shown that brass performs the best and stainless steel the worst. Polished surfaces seem to present slightly better performance than the sand paper roughened. Boiling on very rough surfaces presents a peculiar behavior characterized by good thermal performance at low ϕ, the performance deteriorating at high ϕ with respect to smoother surfaces. The slope of the heat flux is within the typical range for the low range of average roughness. However, for larger roughness values, the slope diminishes attaining values of the order of 0.3 for *Ra*=10.5μm, a level way out of the typical range. Saiz-Jabardo *et al*. (2009) finished their work highlighting that care must be exercised in using nucleate boiling correlations for rough surfaces due to their inadequate prediction of the roughness effect.

2.2. Pool boiling on an array of horizontal tubes

Da Silva (2005) and Ribatski *et al*. (2008) have presented an investigation of nucleate boiling on a flooded vertical array of horizontal plain tubes. Experiments were performed with refrigerant R123 at p_r varying from 0.022 to 0.64, tube pitch to diameter ratios of 1.32, 1.53 and 2.00, and ϕ from 0.5 to 40 kW/m^2. Brass tubes with external diameters, D_e , of 19.05 mm and Ra of 0.12 μm were used in the experiments. They found that in the ϕ range corresponding to the partial nucleate boiling regime, h increases in the upward direction up to a maximum, beyond which it remains essentially constant. On the other hand, in the fully developed nucleate boiling ϕ range, effects of tube positioning on h are negligibly small. It has been determined that inter-tube spacing effects on the local h are not significant.

Based on the heat transfer behaviors displayed by their experimental results and on a previous correlation proposed by Danilova and coworkers (1992), a new correlation for the prediction of local heat transfer coefficients under nucleate boiling conditions on a vertical array of horizontal tubes was proposed, given as follow:

$$\frac{h_N}{h_1} = 1 + 0.345\left[160 - 85.2\exp(-0.3N)\right]p_r^{-1.4}\phi^{-1}\exp\left\{-0.37\,p_r^{-0.4}\left[\ln\left(\phi/\left(\left(65+1200\exp(-0.3N)\right)p_r^{-0.7}\right)\right)\right]^2\right\} \tag{4}$$

where N is the tube row number and h_1 is the heat transfer coefficient for a single tube.

Ribatski *et al*. (2008) have shown that most of h obtained in their study was predicted within ±15% by Eq. (4). Their correlation compared reasonably well also with independent data from the literature as shown in Fig. 1 where the results given by Eq. (4) were compared against the data of Hsieh *et al*. (2003).

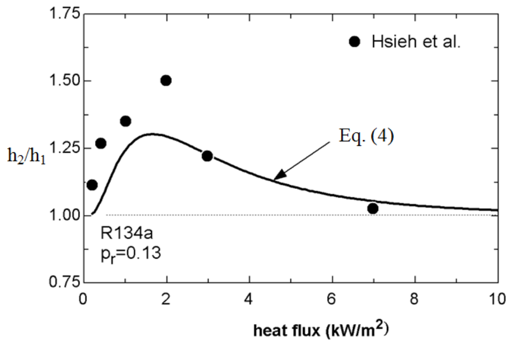

Figure 1. Comparison by Ribatski *et al.* (2008) of Eq. (4) and the experimental results of Hsieh *et al.* (2003).

3. FLOW BOILING

The studies on flow boiling performed by the group are described in the paper with the topics segregated as follow: i) *macro-scale* studies for smooth tubes having hydraulic diameters larger than 3 mm; ii) *micro-scale* studies for smooth tubes having hydraulic diameters smaller than 3mm; iii) *enhanced tubes*, flow boiling studies in internally structured tubes in order of improving heat transfer performance.

2.1. Macro-scale plain tubes

Saíz-Jabardo and Bandarra Filho (2000) performed an experimental study on convective boiling of R22, R134a and R404A in a 12.7 mm internal diameter horizontal copper tube for saturation temperatures, T_{sat}, of 8°C and 15°C, vapor quality, x, of 5% to saturated vapor, mass velocity, G, from 50 to 500 kg/m^{2}s and ϕ between 5 and 20 kW/m^2. Based on their data, the authors suggested that nucleate boiling effects may persist even at high x based on the fact that h keeps increasing with augmenting ϕ. The heat transfer coefficient associated to refrigerant R404A attains the highest values whereas the lowest correspond to refrigerant R22 in the low quality region. In the high x region this trends are inverted, with the highest h corresponding to refrigerant R-134a, and the lowest to R404A. A mass velocity of the order of 200 kg/sm^2 was indicated as a threshold between annular and stratified-wavy flows. The correlations by Kandlikar (1990) and Jung and Radermacher (1991) over predicted their experimental data. Saíz-Jabardo *et al*. (2000) have also compared flow boiling results of R404A and R407C in a horizontal copper tube of 12.7 mm I.D. and T_{sat} of 8^{o}C. According to their results, h tends to remain constant for the lower G (100 kg/m^{2}s) while it presents a clear rising trend for the higher values (200 and 300 kg/ m^{2}s), specially for x larger than 30%. New values of 1.55 for R404A and 1.50 for R407C were obtained by Saíz-Jabardo *et al*. (2000) for the fluid type parameter in Kandlikar´s (1990) correlation.

An extensive investigation on the effect of internal tube diameter, D_i, on the flow patterns during flow boiling of R134a was performed by Barbieri and Saíz-Jabardo (2006). Their experiments were performed in horizontal smooth tubes of D_i varying from 6.2 to 17.4 mm. Tests have been carried out for T_{sat}= 5°C, G from 25 kg/m²s to 500 kg/m²s. and x up to 90%. Flow patterns were identified from photographs taken through a sight class at the test section exit.

Three flow patterns were found dominant: intermittent, stratified and annular. Misty Flow was observed only for reduced D_i and high x. They also found that x for the transition between intermittent and annular flow increases with increasing D_i. For the experimental conditions covered in their study, stratified flows were observed at G lower than 150kg/m^{2}s and D_i equal or larger than 12.6mm. It should be mentioned here that due to the pump flow rate limitations different G ranges were run according to D_i. Later on, Barbieri *et al*. (2008), based on this database and in order to update the Kattan *et al*. (1998), have proposed a new criterion for the intermittent-annular transitions in terms of the Martinelli parameter and the only liquid Froude number.

Barbieri *et al*. (2004) have proposed a semi-empirical correlation for the interfacial friction factor under convective boiling annular flow pattern conditions. The correlation is based on their $\Delta p_{2\phi}$ results for refrigerants R134a and R22 inside tubes with D_i varying from 6.4 to 17.4 mm, at T_{sat}= 5^{o}C and G between 200 kg/m^{2}s and 1100 kg/m^{2}s. The correlation is give as follows:

$$fi/fv = 1.65 + 31.42\left[-\left(2.98(\delta/D_i)^{-0.15}\right)/2.045\right] \tag{5}$$

where f_i and f_v are the interfacial and the vapor-tube friction factors for the vapor flowing alone in the tube, respectively, and δ is the liquid film thickness.

2.2. Micro-scale channels

Extensive literature reviews on flow boiling in micro-scale channels were performed by Ribatski and co-workers. Most of these studies were developed in order to evaluate the predictive methods by comparing them against experimental data from literature. Tibiriçá *et al*. (2008) have gathered an extensive database from literature that comprises both subcooled and saturated CHF results covering 7 fluids, G up to 134,000 kg/m^{2}s and experimental critical heat fluxes, CHF, up to 276 MW/m^2. Based on this database, nine macro- and micro-scale CHF prediction methods for saturated and subcooled conditions were evaluated. The method proposed by Shah (1987) for macro- and micro-scale channels gave the best fit of the complete CHF database. In particular, the correlations proposed by Zhang *et al*. (2006) and Hall and Mudawar (2000) provided the most accurate predictions of saturated and subcooled CHFs, respectively. Felcar and Ribatski (2008) have performed a similar study concerning $\Delta p_{2\phi}$ in micro-scale channels. They gathered an extensive experimental database from the literature covering the following experimental conditions: water, ammonia, air+water, N_2+water, propene, R113, R12, R134a, R22, R236ea, R245fa, R404A and R410A as working fluids; circular, rectangular and semi-triangular cross sections; D_h from 0.1 to 6.25 mm; horizontal and vertical flows; G from 21 to 6000 kg/m^{2}s. The obtained results were compared against 17 frictional pressure drop, $\Delta p_{2\phi,fric}$, predictive methods from literature. The best predictions were obtained through the homogeneous model with the two-phase viscosity given by Cicchitti *et al*. (1960). Felcar and Ribatski (2008) also evaluated the methods by segregating the experimental data according to flow patterns using the predictive method by Felcar *et al*. (2007) and they suggested that the macro-scale predictive method by Friedel (1979) provided good predictions during elongated bubble flows. Tibiriçá and Ribatski (2008) have obtained 2500 flow boiling heat transfer data points from the literature covering 15 fluids, D_h from 0.4 to 2.9 mm, G from 50 to 1600 kg/m^{2}s and h up to 40 kW/m^{2}K. The overall database and data segregated according to flow patterns by using the method proposed by Revellin and Thome (2007) were compared against 7 flow boiling predictive methods. As previously concluded by Ribatski *et al*. (2006), although some heat transfer trends were captured by the methods, in general they poorly predicted the database. This is not surprising since an analysis of the trends of the experimental results revealed large discrepancies between different data sets, even at similar conditions.

Based on Taitel and Dukler (1976), Felcar *et al*. (2007) proposed a new flow pattern method valid for macro- and micro-scale channels. They altered the transition from stratified to annular flow by adding a new parameter to the criterion proposed by Taitel and Dukler (1976). This parameter becomes negligible for large D_i and is a function of the modified Eötvos number, relating capillary and gravitational effects, and the Weber number, relating inertial and surface tension effects. The transition from intermittent to annular flow is determined according to a superficial void fraction threshold given as a function of the Weber and Eötvos numbers, the latter being defined in terms of only the surface tension instead of the capillarity effects. A new definition of the Eötvos number neglecting wettability effects was reasonable since under intermittent and annular flow patterns the internal surface of the tube is wet with no meniscus present. Felcar *et al*. (2007) method was adjusted based on air–water data from literature and worked reasonably well in predicting its own database.

Arcanjo *et al*. (2010) have performed quasi-diabatic two-flow pattern visualizations and measurements of elongated bubble velocity, frequency and length. The tests were run for R134a and R245fa evaporating in a tube with D_i=2.32 mm, G ranging from 50 to 600kg/m²s and T_{sat} of 22, 31 and 41°C. The visualized flow patterns were compared against predictions by methods from literature. It was found that the methods proposed by Felcar *et al*. (2007) and Ong and Thome (2009) predicted relatively well the database. The authors found that the bubble velocity increases with increasing G and x and decreases with increasing T_{sat}. In their study, the bubble velocity was correlated as linear functions of the two-phase superficial velocity. Sempértegui and Ribatski (2010) have developed and implemented an objective method to characterize two-phase flow patterns. The method is based on the characteristics of the signals provided by transducers measuring local temperature and pressure plus the intensity of a laser beam crossing the two-phase flow. The statistical characteristics of these signals were used as input features for the k-means clustering method. In order to implement the method, experimental flow patterns were obtained during flow boiling of R245fa in a 2.32 mm ID tube. The cluster classification was compared against flow patterns segregated based on high speed camera images (8000 frames/s) and a reasonable agreement was obtained. Araújo *et al.* (2010) have designed a three-layer, feedforward neural network in order to identify flow patterns in micro-scale tubes. Mass velocity, x and T_{sat} were adopted as input data. The artificial neural network (ANN) was developed based on two-phase flow data for refrigerant R134a in a micro-scale channel. The validity of the adopted neural network was evaluated by cross validation. The results showed that the neural network can provide good flow pattern predictions.

Tibiriçá and Ribatski (2011) have obtained $\Delta p_{2\phi}$ results for R245fa in a 2.32mm tube. The data were parametrically analyzed, compared against predictive methods and the following conclusions were summarized: (i) $\Delta p_{2\phi}$ increases with increasing G and x and decreasing T_{sat}. Heat flux has a negligible effect on $\Delta p_{2\phi,fric}$; (ii) the predictive methods of Cioncolini *et al.* (2009) worked the best for adiabatic and diabatic data. New $\Delta p_{2\phi}$ results in a microscale tube for R134a were presented by Tibiriçá *et al.* (2011). The experiments were performed under diabatic conditions in a horizontal tube of D_i=2.3 mm. Pressure drop gradients up to 48 kPa/m were measured. These data were analyzed and compared against thirteen Δp_{fric} prediction methods. Comparisons based on the data segregated according to flow patterns were also performed. Overall, the method by Cioncolini *et al.* (2009) provided accurate predictions. Most recently, Da Silva *et al.* (2011) have obtained $\Delta p_{2\phi,fric}$ in a horizontal 1.1 mm I.D tube for R245fa. The frictional pressure drop data was obtained under adiabatic conditions. Pressures drop gradients ranging from 30 to 170 kPa/m were measured. Four $\Delta p_{2\phi,fric}$ predictive methods were compared against the database. Cioncolini *et al.* (2009) method was found to work the best.

Tibiriçá and Ribatski (2010) have obtained flow boiling heat transfer results in a horizontal 2.3 mm I.D. tube with heating length of 464 mm, R134a and R245fa as working fluids, G ranging from 50 to 700 kg/m^{2}s, ϕ from 5 to 55 kW/m^2, exit T_{sat} of 22, 31 and 41^{o}C, and x ranging from 0.05 to 0.99. They observed that h increases with increasing ϕ, G and T_{sat}. Distinct heat transfer behaviors with increasing x were observed according to a threshold G of 200 kg/m^{2}s. Stratified flows were not observed; however, flow stratifications were visualized and according to them, based on local wall temperature measurements, causes higher h along the top region of the tube perimeter. Tibiriçá and Ribatski (2010) have also detected two-phase flow temperature and pressure amplitude oscillations during churn, annular and dryout flow patterns. They observed from high-speed visualizations that liquid front waves occur in phase with temperature and pressure maximums. The authors suggested that these liquid front waves seem to explain the fact, as shown in Fig. 2 from their study, that h keeps increasing at x of almost one due to the internal surface rewetting. The correlation by Saitoh *et al.* (2007) provided the best predictions of their database and captured the fact that, under certain ϕ and G conditions, h increases with increasing x until high vapor qualities. Tibiriçá *et al.* (2011) have presented new experimental flow boiling heat transfer results obtained in horizontal 1.0 and 2.2 mm I.D. stainless steel tubes for R1234ze, a new refrigerant fluid developed as substitute of the R134a. They summarized the following conclusions:, Katto and Ohno (1984) provided the best prediction of their data with mean absolute errors of 6.3%. The heat transfer coefficient results were best predicted by Saitoh *et al.* (2007) with mean absolute error of 19.4%. R1234ze demonstrated similar performance to R134a when running at similar conditions.

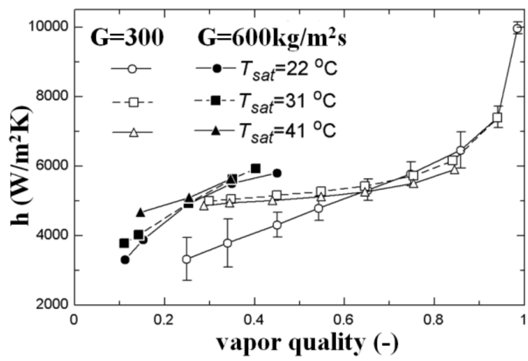

Figure 2. Illustration of the effect of T_{sat} on h for R134a; ϕ=15 kW/m^2 (Tibiriçá and Ribatski (2010).

Tibiriçá *et al.* (2010) have measured saturated CHF in a horizontal 2.20 mm ID stainless steel tube with heating lengths of 361 and 154 mm for R134a and R245fa. They found that the CHF increases with increasing G and inlet subcooling and decreases with increasing T_{sat} and heated length. The data also indicated for similar experimental conditions that the refrigerant R245fa provided a higher CHF than R134a. The experimental data were compared against four CHF predictive methods. Katto and Ohno (1984) and Ong and Thome (2011) provided the best predictions.

Cabral and Ribatski (2010) developed a theoretical model to predict *h* of nanofluids under flow boiling conditions inside horizontal micro-scale channels. The model was developed based on Liu and Winterton (1991) method with the nucleate boiling parcel given by Stephan and Abdelsalam (1978) and the convective parcel modeled as conduction and evaporation through a liquid film during annular flow. In the new method, transport properties of nanofluids were evaluated according to methods from literature. The constant and exponents of the Stephan and Abdelsalam (1978) correlation were modified in order to fit nanofluid pool boiling data. The nucleate boiling suppression factor and the forced convective heat transfer enhancement factor were also modified. According to the proposed model, the heat transfer coefficient increases with increasing nanoparticle concentration and *x*. The model seems to predict accurately well independent pure water data by Cioncolini *et al*. (2007) and nanofluid data by Peng *et al*. (2009).

Tibiriçá *et al*. (2010a) performed a comprehensive review on the literature concerning the methods used to measure two-phase liquid film thicknesses in macro- and micro-scale systems. The methods were described and the main difficulties related to their use in microscale systems were pointed out. They suggested that methods based on the total internal reflection of light are appropriate solutions for measuring time average film thicknesses under annular flow conditions since this technique is simple to implement, non-intrusive, non-expensive, self-calibrated, and presents a reasonable accuracy. According to Tibiriçá *et al*. (2010), laser focus displacement is also a non-intrusive method that allows dynamic measurements of extremely thin films, therefore its use should be considered for future studies. They also indicated that florescence intensity based methods seem a promising approach despite of the facts that addition of dye particles may affect the fluid properties and intrinsic difficulties of its use are present under evaporating conditions. Finally, they concluded that further engineering efforts are still necessary to adapt the current methods capable of measuring thin films for performing measurements under micro-scale conditions. Do Nascimento *et al*. (2008) have developed a measurement device based on the total internal reflection of light somewhat similar to the one by Shedd and Newell (1998). They were able to measure film thicknesses down to 0.2 mm with an error inferior to 10%.

Gonzales-Mamani (2001) has investigated the heat transfer and $\Delta p_{2\phi}$ during condensation in micro-scale channels of pure R134a and R410A and their mixtures with the oil lubricant polyol-ester ISO VG-22 for oil mass concentrations, ω, of 0.25 and 0.45%. Experiments were performed for square and round channels with D_h of 1.214 and 1.494mm, respectively. Their experiments covered *G* from 410 to 1135kg/m^{2}s, *x* from 0.15 to 0.9, T_{sat} of 40 and 50^{o}C and ϕ=5kW/m^2. Based on this database, the following correlations were proposed for $\Delta p_{2\phi,fric}$ and *h*, respectively:

$$\Delta p_{2\phi,fric}/\Delta p_L = 1+6.92\left\{1\Big/\left\{\left[(1-x)/x\right]^{0.9}(\rho_v/\rho_l)^{0.5}(\mu_l/\mu_v)^{0.1}\right\}\right\}^{1.55} \quad (6)$$

$$\Delta p_{oil+refrigerant} = \Delta p_{2\phi}(1+2.869\omega) \quad (7)$$

$$h_{2\phi} = h_l\left\{1+0.9281\left\{1\Big/\left\{\left[(1-x)/x\right]^{0.9}(\rho_v/\rho_l)^{0.5}(\mu_l/\mu_v)^{0.1}\right\}\right\}^{0.9726}\right\} \quad (8)$$

$$h_{oil+refrigerant} = h_{2\phi}e^{-2.8\omega} \quad (9)$$

where μ_v is the vapor dynamic viscosity, $h_{2\phi}$ is the two-phase *h*, Δp_L is the pressure drop for the liquid phase flowing alone in the tube and h_L is the single-phase heat transfer coefficient.

2.3. Heat transfer using enhanced surfaces

Bandarra Filho *et al*. (2004) have experimentally investigated $\Delta p_{2\phi}$ of R134a under convective boiling conditions in horizontal smooth and microfinned copper tubes. Experiments have been performed for tube with D_e of 7.0, 7.93, and 9.52 mm with wall thicknesses of 0.38 (smooth) and 0.30 mm (microfinned). Mass velocities and *x* varied in the following ranges: 70–1100 kg/m^{2}s and 5–95%. The annular flow pattern has been observed to occur over most of the operational conditions. Frictional pressure drop enhancements up to 83% were observed. A correlation of the two phase flow multiplier in terms of the Martinelli's parameter has been developed which fits the data considered on its development with an average absolute deviation of the order of 6.3%. The correlation fitted also reasonably well the data obtained by Kattan (1996) and Choi *et al*. (1999) for microfinned tubes of different diameter and microfin geometry. The correlation is given as follow:

$$\Delta p_{2\phi,fric}/\Delta p_L = 1+3.0\left\{\left[(1-x)/x\right]^{0.9}(\rho_v/\rho_l)^{0.5}(\mu_l/\mu_v)^{0.1}\right\}^{-0.83} \quad (10)$$

Bandarra Filho *et al.* (2006) have reported an experimental study on convective boiling heat transfer and $\Delta p_{2\phi}$ of refrigerant R134a in smooth, microfin and herringbone copper tubes of 9.52 mm external diameter. Tests have been conducted under T_{sat} of 5 °C, x from 5 to 90%, G from 100 to 500 kg/sm^2, and ϕ=5 kW/m^{2}K. Figures 2 and Table 2 illustrate the tube internal characteristics of the tested tubes.

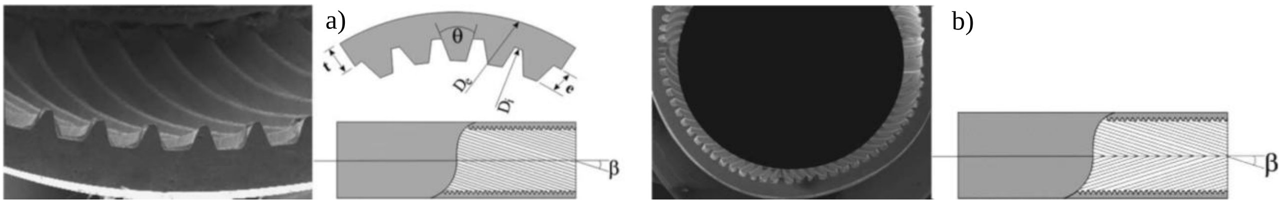

Figure 2. Microphotography and a cut-way view of (a) microfinned and (b) herringbone tubes, Bandarra Filho *et al.* (2006).

Table 2. Geometric characteristics of tubes used by Bandarra Filho *et al.* (2006)

Tube	D_e (mm)	D_i (mm)	t (mm)	e (mm)	fin density (fin/m)	β (°)	θ (°)	AR*
Smooth	9.52	8.76	0.38					1.00
Microfin	9.52	8.92	0.30	0.2	52	18	33	1.91
herringbone	9.52	8.92	0.30	0.2	70	18	33	1.78

* *total finned area over root smooth area.*

According to their results, thermal performance of the herringbone tube has been found better than that of the standard microfin in the high range of G, and worst for the smallest G (100 kg/m^{2}s) at x higher than 50%. The herringbone tube pressure drop is higher than that of the standard microfin tube over the whole range of G and x. The enhancement parameter, given by the ratio of heat transfer and $\Delta p_{2\phi}$ augmentations, was higher than one for both structured tubes for G lower than 200 kg/m^{2}s. Values lower than one have been obtained for both structured tubes in the G upper range as a result of a significant $\Delta p_{2\phi,fric}$ increment not followed by a correspondent increment in the h.

Recently, Kanizawa *et al.* (2011) presented a broad literature review on single and $\Delta p_{2\phi,fric}$ inside tubes with twisted-tape inserts focusing on the physical mechanism and the effects of the use of twisted-tape. A new correlation to estimate the friction factor for two-phase and single flows inside tubes with twisted-tape was also proposed by them, based on data available in the literature. Contrarily to previous studies, the proposed correlation presents reasonable predictions under single and two-phase flow conditions and obeys the trends when the twisted-tape ratio tends to zero and infinite. In their method, the frictional pressure drop factor for tubes containing twisted-tape inserts, f_s, given as:

$$f_s / f_p = \left\{1 + 2y^{-0.4}\left[G^2 / \left(gD_h\rho_H^2\right)\right]^{-0.1}\right\}^{1.5} \tag{11}$$

where y is the twist ratio given by the ratio between the tape turn length of 180° along its axis and the tube diameter, G is the mass velocity based on the internal diameter, ρ_H is the homogeneous density and D_h are given, respectively, by the following equations:

$$\rho_H = \left[(1-x)/\rho_l + x/\rho_v\right]^{-1} \tag{12}$$

$$D_h = D_i\left[\pi/(\pi+2)\right] \tag{13}$$

The frictional pressure drop is given as follow:

$$\Delta p_{2\phi,fric} = f_s\left[\left(2G^2L\right)/\left(\rho_H D_h\right)\right] \tag{14}$$

The plain tube friction factor is calculated from the Müller-Steinhagen and Heck (1986) correlation keeping in Eq. (14) ρ_H, D_h and G based on D_i. It is important to highlight that in Müller-Steinhagen and Heck (1986) method, $\Delta p_{2\phi}$ is basically given as an empirical interpolation between liquid and vapor frictional pressure drop given by Blasius method. Therefore the correlation can also be used under single-phase flow conditions. Most recently, Kanizawa and Ribatski

(2011) performed experiments for R134a, T_{sat} of 5 and 15 °C, G from 75 to 150 kg/m²-s, x ranging from 0.05 to 0.95, D_i of 15.9 mm and y of 3, 4, 9, 14 and ∞, corresponding to a plain tube without inserts. Flow pattern visualizations using a high speed camera (2000 frames/s) were also performed. Their experimental data were compared against the predictive methods of Müller-Steinhagen and Heck (1986) for plain tubes and Kanizawa *et al*. (2011) abovementioned. They found that Müller-Steinhagen and Heck (1986) predicts reasonably well the plain tube data while Kanizawa *et al*. (2011) failed to predict the independent experimental data at the lowest G. They also found that using twisted-tape insert causes a drastic increase in $\Delta p_{2\phi,fric}$. Moreover, the pressure drop peak occurs at lower x for the tube containing twisted-tape inserts than for the tube without tape. A pressure drop inflection point at x about 0.2 was also observed for the lowest G. By comparing the flow images and the respective $\Delta p_{2\phi}$ results, they found that this behavior is occurring at the transition from slug to annular flow.

5. CONCLUSIONS

A review on the studies on heat transfer with phase change and two-phase flow of halocarbon refrigerants performed in the Department of Mechanical Engineering at EESC-USP were described and their main results presented in an organized manner.

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