In this work, experimental data obtained in the boiling flow of refrigerants R-134a and R-600a in a 2.6 mm ID tube were used as a database to study the heat transfer phenomena. An analysis of heat transfer coefficient behavior as a function of heat flux, mass velocity and vapor quality is presented, considering heat fluxes between 10 and 160 kW/m², mass velocities between 188 and 930 kg/m²·s and vapor qualities from 0 to 0.9, for the saturation temperature of 22 °C. Images of flow patterns are also presented and compared results predicted by a flow pattern map from the literature for small channels. The main differences among the refrigerants are exploited and discussed. Experimental results for the boiling heat transfer coefficient are compared to predictions from different correlations – namely the ones by Kandlikar and Balasubramanian; Bertsch et al.; Saitoh et al. and Kim and Mudawar. The correlation by Kim and Mudawar was the one that best fitted experimental results, giving a mean square error (RMSE) of about 24% for both refrigerants. The effects of nucleate boiling (NB) and convective boiling (CB) are quantified using these correlations, providing basis to the adjustment of existing models and possibly the introduction of specific models for each refrigerant, in view of more reliable correlations.

**Keywords:** boiling in mini tube, heat transfer behavior, correlations, R-134a and R-600a

**1. INTRODUCTION**

In the last few years, compact refrigeration equipment consisting of mini/micro channels with boiling flows have been developed and applied for thermal dissipation in various applications, such as automotive air conditioning and microchip cooling. The reduced size of these devices allows high heat dissipation per unit volume, with low refrigerant charge.

The improvement of heat transfer coefficient with a reduction of channel size has been reported in literature. Researches regarding flow boiling in tube diameters less than 3 mm and different refrigerants were presented by Lazarek and Black (1982), Tran *et al.* (1996), Yan and Lin (1998), Saitoh *et al.* (2005), Choi *et al.* (2007), Ong and Thome (2009), Tibiriçá and Ribatski (2010), Oh *et al.* (2011) and Charmay *et al.* (2012). However the results show discrepancies regarding the effects of vapor quality, mass velocity, saturation pressure and heat flux on the heat transfer coefficient, as analyzed by Ribatski (2012) and Tibiriçá and Ribatski (2013).

With decreasing channel size, the heat transfer dominant mechanism, nucleation or advection, differ much from the macroscale. In the transition from macro to micro behaviors, bubble confinement within the channel and the importance of different forces - gravitational, inertial and surface tension - must be considered (Kandlikar, 2010). For example, while gravity plays an important role in macroscale, it has less effect in microscale due to the contrasting effect of surface tension, consequently modifying the flow patterns. Studies about flow patterns in microscale have indicated the suppression of the stratified and stratified-wavy flow regimes, the convergence of slug and plug flows into the elongated bubble flow regime, and early transition of elongated bubble flow to churn-annular or annular flow regime with respect to vapor quality (Revellin and Thome, 2007; Arcanjo *et al.*, 2010, Ong and Thome, 2011).

The lack of knowledge concerning two-phase transport phenomena limits the ability to predict heat transfer performance in small channels. Correlations for the heat transfer coefficient in general are based on the combined effects of nucleate boiling (NB) and convective boiling (CB). However, these correlations are seldom generally applicable. Kim and Mudawar (2013), for example, introduced a correlation based on a database of 10,805 experimental points from 31 authors, from experiments using different tube diameters, fluids and operating conditions. Nevertheless, this correlation resulted in errors of the order of 30%.
In this work, experimental data obtained in the boiling flow of refrigerants R-134a and R-600a in a 2.6 mm ID tube are used as a database to study the heat transfer and flow phenomena, and also to investigate the flow patterns and the fitting to existing correlations.

An analysis of local heat transfer coefficient behavior as a function of vapor quality, $X$, mass velocity, $G$ and heat flux, $q''$, is presented. Flow patterns for both refrigerants were investigated using images and a map proposed by Ong and Thome (2011). Experimental data are compared to results predicted by heat transfer coefficient correlations of Kandlikar and Balasubramanian (2004), Bertsch et al. (2009), Saitoh et al. (2007) and Kim and Mudawar (2013). The effects of nucleate boiling (NB) and convective boiling (CB) were quantified using these correlations. The flow pattern maps were used to investigate the role of each mechanism of heat transfer in the heat transfer coefficient.

2. EXPERIMENTAL DATABASE AND ANALYSIS

A database comprising 646 datapoints for R-134a and 226 for R-600a was obtained in an experimental bench for boiling studies, in which the test section is a single circular horizontal channel of stainless steel with 2.6 mm ID, 185 mm length and absolute internal roughness of 2.05 µm. This tube is directly heated by Joule effect. The experimental bench consists of a closed flow circuit, where the refrigerant is pre-heated in a separated section to establish the initial saturation condition, and after the test section the fluid undergoes a transparent tube of the same diameter, where the flow patterns are shoot by a high speed camera. To close the cycle, the refrigerant is condensed and subcooled. A frequency inverter is used to control the pump flow rate and a needle-valve, upstream the entrance of main circuit is employed to reduce pressure instabilities.

A detailed description of test rig and the experimental work carried out with both refrigerants are found in Copetti et al. (2011) and (2013), respectively for R-134a and R-600a. The test conditions employed with each of the refrigerants are shown in Table 1.

During the tests, refrigerant temperatures, absolute and differential pressures were registered in the pre-heater and test section for different flow rates and heat fluxes. Moreover tube wall temperatures were measured in 5 positions along the tube, by four thermocouples per position along the tube perimeter. Then, local values for vapor quality and heat transfer coefficient were calculated.

The local saturation temperature was assumed by considering the local pressure a linear function and the measures of pressure drop from inlet to outlet of the test section tube. The internal wall temperature for each position was calculated assuming radial conduction through the wall, subjected to internal heat generation (Copetti et al., 2011).

<table>
<thead>
<tr>
<th>Refrigerants</th>
<th>R-600a</th>
<th>R-134a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test section heat flux, $q''$ (kW/m²)</td>
<td>33, 47, 67, 100 and 160</td>
<td>10, 20, 33, 47, 67, 87 and 100</td>
</tr>
<tr>
<td>Mass velocity, $G$ (kg/m²s)</td>
<td>188, 240, 280, 370 and 440</td>
<td>240, 440, 556, 740, 932</td>
</tr>
<tr>
<td>Saturation temperature, $T_{sat}$ (°C)</td>
<td>22</td>
<td>22 and 12</td>
</tr>
</tbody>
</table>

2.1 Local heat transfer behavior

2.1.1 Local heat transfer coefficient behavior with different parameters

The influence of heat flux, $q''$, on local heat transfer coefficient, $h_i$, is shown in Figs. 2 and 3, for refrigerants R-134a and R-600a and two different mass velocities, $G$, respectively.

In Fig.2 is possible to see this influence in the low quality region ($X < 0.4$), independent of $G$. But as $X$ increases this effect tend to disappear and $h_i$ decreased, in agreement with Choi et al. (2007). For higher $G$ (Fig. 2b) $h_i$ increases with increasing in $q''$ and $X$, until an inflexion point. Different behavior was observed for low $G$, when $h_i$ decreases with $X$. In this condition, for low $q''$, $h_i$ is almost constant.

For R-600a, Fig. 3 depicts the importance of $q''$ in the $h_i$ dependence on $X$, especially for higher heat fluxes. Heat transfer coefficients of R-600a are higher than those of R-134a. The trend of these experimental results is similar to those shown by Shin et al. (1997) and Lee et al. (2006), for the same refrigerants, but boiling in macro tubes. As heat transfer coefficients are so much influenced by the fluid properties, Table 2 summarizes some of the thermodynamic and thermophysical properties that most affect thermal and flow behavior, for both refrigerants investigated.
The lower viscosity (\( \mu \)) and higher thermal conductivity (\( k \)) of R-600a contributed positively to the heat transfer coefficients higher than those of R-134a. The latent heat (\( i_{fg} \)) of hydrocarbon R-600a is almost twice that of the R-134a, and this makes possible the use of more compact heat exchangers and, together with the greater specific volume of the hydrocarbon, it results in a reduction of the refrigerant charge in the system.

The effect of mass velocity, \( G \), on the heat transfer coefficient, \( h_z \), is shown in Fig. 4, for both refrigerants. For low heat flux, \( q'' \), as \( G \) increases, \( h_z \) also increases, but for the highest \( q'' \), \( h_z \) is higher and almost independent of \( G \) (Fig. 3). The same trends happen for R-600a, but for a lower \( G \) than R-134a. It was also observed that the \( h_z \) experiments an increase and a sudden decrease, that occurs at a lower \( X \) for higher \( G \)'s. These results agree with those of Shin et al. (1997) for R-600a in a conventional tube and Tibiriçá (2010) for R-134a in small tubes.
2.1.2 Average heat transfer coefficient behavior with different parameters

Complementing the local analysis, Figs. 5 and 6 show the behavior of the average heat transfer coefficient, $h$, and the influence of the heat flux, $q''$, and mass velocity, $G$, for refrigerants R-134a and R-600a. These results were taken for a fixed inlet vapor quality, $X_i$, for each refrigerant.

It is evident that, for both R-134a and R-600a, $h$ is most affected by $q''$ than by $G$. The influence of increasing $G$ on $h$ is greater at low heat fluxes. For high heat fluxes $h$ remains practically constant (Figs. 5a and 6a). Still for a fixed $G$, $h$ may increase up to 3 times (Figs. 5b and 6b) if $q''$ is increased. This result can be attributed to the dominance of nucleate boiling in relation to the convective mechanism.
2.2 Flow pattern analysis

In convective boiling, it is assumed that the flow pattern is a crucial characteristic to the phenomenon of heat transfer and so is directly related to the coefficient of heat transfer.

According to several authors, the flow patterns observed in small diameter tubes are (i) dispersed flow, which includes bubbling flow, where gas bubbles with smaller diameter than the tube are dispersed in the continuous liquid phase; (ii) intermittent flow, when the flow shows periodic characteristics, and includes the elongated bubble, plug/slug and churn flow; (iii) annular flow, characterized by a core of continuous gas, which can contain droplets and is surrounded by a liquid film along the tube surface. In the macro scale, flow patterns suffer significant influence of gravity forces and inertial forces; nevertheless in small channels surface tension forces surpasses gravity. This results in the absence of stratified flows, promoting the appearance of elongated bubbles (EB) and the uniformity of the film thickness along the tube perimeter.

Another effect observed when the channel diameter is reduced is that the bubbles get confined and then elongated. Kew and Cornwell (2001) introduced the Confinement number, \( Co \), which represents the ratio of capillary length to the channel diameter and may be used to delineate the transition from macrochannel to microchannel flows. The authors suggested the threshold of \( Co = 0.5 \) for the minimum \( Co \) of macrochannels. For the refrigerants and conditions of the present database and the same tube diameter, i.e., 2.62 mm, the values of the confinement number are \( Co = 0.325 \) for R-134a and \( Co = 0.5333 \) for R600a. So according to Kew and Cornwell (2001), this tube would be a microchannel for R-134a and a mini channel for R-600a. The difference is due to the higher surface tension of R-600a, as verified in Tab. 2.

Ong and Thome (2011) published a study that focuses on investigating the transition from macro to microscale during flow boiling in small scale channels of different sizes (1.03, 2.20 and 3.04 mm diameter) with different refrigerants (R134a, R236fa and R245fa) over a range of saturation conditions to investigate the effects of channel confinement on two-phase flow patterns and liquid film stratification in a single circular horizontal channel. Based in this study the authors proposed a flow pattern map that includes the effects of gravity, inertia and surface tension and the determination of the flow patterns transitions. The model considers the transition to macroscale slug/plug flow at a confinement number of \( Co = 0.3-0.4 \) and, from the top/bottom liquid film thickness comparison results, the authors concluded that the gravity forces are suppressed and overcome by the surface tension and shear forces when \( Co \to 1.0 \) (microscale). The map considers transitions from Isolated Bubble (IB) to Coalescent Bubble (CB) to Annular (A) (smooth and wavy) flow for microchannels. For channels classified as mini, the IB flow pattern is replaced by Plug/Slug (PS) pattern that constitutes a long vapor bubble separated by liquid plugs that exhibits strong buoyancy effects and a thick stratified layer of liquid at the bottom of the elongated bubbles.

In Fig. 7 some images recorded during the tests, for different conditions, are shown, with the identification of flow pattern observed. Then, considering the data base of this work the maps were built and the results are shown in Fig. 8.

![Figure 7. Flow patterns images for (a) R-134a and (b) R-600a.](image)

The Plug/Slug (PS) was observed both for R-134a (\( Co = 0.325 \)) and for R-600a (\( Co = 0.5333 \)). This pattern, according to the map by Ong and Thome (2011), would not exist (Figs. 8a and 8b, respectively). The annular (A) flow regime gradually expands and spans over a wider range of vapor qualities with increasing mass velocity. The CB/A transition is reached when the inertia force dominates over the surface tension force, promoting coalescence to form a continuous vapor core. The earlier CB/A transition trend is associated to the less dominant surface tension forces (IB
and PS) compared to inertia, reducing the ability of the flow to keep the liquid slug hold up between the vapor bubbles. Then in annular regimes the shear forces dominate.

The results in Figs. 8a and 8b are in accordance with previous Fig. 4: for higher mass velocity the vapor quality for transition CB/A occurs at lower values of vapor quality. However, for both refrigerants the plug and slug flow patterns identified fall in the coalescing bubble (CB) region of the map, independent of mass velocity. The analysis of the maps in Figs. 8a and 8b indicate that the curves transition could be displaced to the right, towards higher vapor quality.

![Figure 8](image_url)

**Figure 8.** Two-phase flow pattern and transition lines by Ong and Thome (2011) for (a) R-134a and (b) R-600a at saturation temperature of 22 °C and for 2.62 mm channel.

### 3. CORRELATIONS FOR SMALL TUBES AND COMPARISON

In this section, the experimental results of this work are compared to results predicted by existing boiling flow heat transfer correlations. The selected correlations are the ones of Kandlikar and Balasubramanian (2004), Saitoh *et al.* (2007), Bertsch *et al.* (2009) and Kim and Mudawar (2013). These correlations were developed for small channels and their main characteristics are summarized below.

A correlation to predict the heat transfer coefficient in flow boiling in tubes with internal diameter ranging between 0.19 and 2.59 mm was proposed by Kandlikar and Balasubramanian (2004). These authors used experimental data of the refrigerants R-113, R-134a, R-123, R-141b and water, mass velocities from 50 to 570 kg/(m²s), heat fluxes varying between 10 and 40 kW/m², and also considered the fluid and tube materials to adjust their correlation. The heat transfer coefficient in flow boiling takes into account both domain of nucleate boiling (NB), as domain of convective boiling (CB). Moreover the correlation considers flow boiling in mini and micro channels and it extends the prediction to transition and laminar flow. The heat transfer coefficient for flow boiling corresponds to the dominant process, NB or CB.convective boiling.

The Saitoh *et al.* (2007) correlation for R-134a separates the process in pre and post-dryout. For pre-dryout the authors proposed modifications in the Chen correlation to consider the influence of tube diameter by using Weber number. They used Stephan and Adselsalam model for heat transfer coefficient in NB. For post-dryout data, the authors developed a correlation based on annular flow model considering the thickness of uniform liquid film to predict both heat transfer coefficient as dryout quality. According to the authors, such correlation is applied to tubes with internal diameters between 0.5 and 11 mm.

Bertsch, Groll and Garimella (2009) proposed a correlation for flow boiling in mini and micro channels also based on Chen correlation and on experimental data with hydraulic diameter ranging from 0.16 to 2.92 mm, mass velocities from 20 to 3000 kg/(m²s) and heat flux from 4 to 1150 kW/m². Such correlation was fitted for 12 different refrigerants and saturation temperatures ranging from -194 to 97 °C. Its main characteristic is related to NB component and the relation between the suppression factor, S, and vapor quality as a linear function. Because as vapor quality increases, it inhibits the growth of bubbles and this leads to drying. About CB, and the intensification factor, F, this one is influenced by confinement of bubbles in channels with reduced diameters, which is the main reason for observed differences in heat transfer in conventional tubes, mini and micro channels. Therefore, the authors proposed an equation for F as a function of confinement number, Co. They took into account the effect of roughness on surface and the heat transfer coefficient for two-phase flow is calculated as the average of the heat transfer coefficients from liquid and vapor phase.

Recently, Kim and Mudawar (2013) suggested a correlation to predict the heat transfer coefficient for flow boiling in mini and micro-channels, and a vapor quality to define the transition to dryout. The authors developed a correlation based on a set of 12,974 data points from 31 sources containing 18 refrigerants, including R-134a. The mass velocities ranging between 19.4 and 1,608 kg/(m²s), hydraulic diameters from 0.19 to 6.5 mm and reduced pressures in
range of 0.005 to 0.69. This correlation is based on superposition of the NB and CB contributions. And according to the authors, the correlation predicts with good accuracy the heat transfer coefficient for all working fluids based on all parameters both of single and for multi-channels and for pre-dryout conditions.

Figures 9 and 10 presents the evolution of the heat transfer coefficient with vapor quality, comparing the measured data and those given by the different correlations.

Figure 9. Heat transfer coefficient evolution with vapor quality according to the experimental data and predictive methods for R134a. (a) $G = 440$ kg/m²s; (b) $G = 556$ kg/m²s, and $q'' = 10$ and 87 kW/m².

Figure 10. Heat transfer coefficient evolution with vapor quality according to the experimental data and predictive methods for R134a. (a) $G = 188$ kg/m²s; (b) $G = 280$ kg/m²s, and $q'' = 33$ and 123 kW/m².

The performance of the models was evaluated based on two statistical criteria: root mean square error (RMSE), which indicates the dispersion of the regression; and mean bias error (MBE), which indicates the variation of the predicted values with respect to the ones calculated from experimental measures.

As shown in Fig. 9, for R-134a, it may be observed that for lower $q''$ the models underestimate the experimental values, but a significant difference between the models cannot be observed. Nevertheless for the higher $q''$ the model that best fits the behavior of $h_s$ in the pre-dryout zone is the one by Kim and Mudawar (2013): for $G = 440$ kg/m²s and $q'' = 67$ kW/m², a value of RMSE of 19% was obtained and for $G = 556$ kg/m²s and $q'' = 87$ kW/m², a value of RMSE of 4.2% was obtained, while for the other correlations the errors were usually higher than 20%.

For the R-600a, Fig. 10, the least data dispersions were found for $q'' = 33$ kW/m², regardless the mass velocity, $G$. For the highest $q''$, the values of RMSE are higher, for example for $G = 190$ kg/m²s the model of Kandlikar and Balasubramanian (2004) results in 56% of RMSE.

Kim and Mudawar (2013) correlation is for the pre-dryout zone only. They provide a correlation to calculate the quality of incipience of dryout. The tendency of the model agrees well with the experimental results. The quality of incipience of dryout decreases when $G$ increases, as observed in Fig. 4. However, the values of quality of incipience of dryout from the model are higher than those observed experimentally.

Table 3 depicts the average results for the complete data base. It is possible to observe that the dispersion of the experimental results to predicted ones is around 30%, with slightly higher values for R-600a. It is important to consider that none of these models take into account the kind of refrigerant in the model coefficients, they are all made general over dimensionless parameters.
It is also observed from Figs. 9 and 10 and the MBE data of Tab. 3 that the correlations always underestimate the calculated values from the experiments.

Table 3. Deviations of correlations for flow boiling heat transfer coefficient.

<table>
<thead>
<tr>
<th>Correlation</th>
<th>R-134a</th>
<th>R-600a</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MBE (%)</td>
<td>RMSE (%)</td>
</tr>
<tr>
<td>Kandlikar &amp; Balasubramanian (2004)</td>
<td>-17</td>
<td>29</td>
</tr>
<tr>
<td>Saitoh et al. (2007)</td>
<td>-19</td>
<td>30</td>
</tr>
<tr>
<td>Bertsch et al. (2009)</td>
<td>-15</td>
<td>30</td>
</tr>
<tr>
<td>Kim &amp; Mudawar (2013)</td>
<td>-8</td>
<td>24</td>
</tr>
</tbody>
</table>

In general, the tested models are based on superposition of the effects of convection and nucleate boiling. When considering these effects separately using the measured data, the models indicate that nucleate boiling is the prevailing effect.

4. CONCLUSIONS

Experimental results for the flow boiling of R-134a and R-600a in a horizontal small tube under the variation of mass velocity, heat flux and vapor quality were presented. The behavior of the local heat transfer coefficient was investigated and the following conclusions could be drawn from this study:

- In the low quality region, the influence of heat flux on the heat transfer coefficient was observed. In the high vapor quality region, for high mass velocities, this influence tended to vanish, and the coefficient decreased.
- The influence of mass velocity on the heat transfer coefficient was detected in most tests for a threshold value of vapor quality, which was higher as the heat flux increased. For higher heat flux the heat transfer coefficient was nearly independent of mass velocity.

The flow patterns visualization during the tests showed the patterns slug, churn and annular. Elongated bubbles flow was verified only for high mass velocity and low heat flux and vapor quality.

A flow pattern map for mini and microchannels (Ong and Thome, 2011) was analyzed with these data base of heat transfer coefficient behavior at various vapor qualities and images of flow patterns. The trends of transition curves match, but they should be corrected, displacing them to higher vapor qualities. Isolated bubble regime (IB) was not observed. For higher mass velocity and heat flux the vapor quality for transition CB/A occurs at lower values of vapor quality. The R-600a yields the lowest IB/CB and CB/A vapor quality transition when compare with R-134a behavior.

Among the correlations used to predict the heat transfer coefficient for the test conditions, the one by Kim and Mudawar (2013) was the one that best fitted the experimental results, giving a RMSE of about 24% for both refrigerants. The effects of nucleate boiling (NB) were found to be dominant in the present range of operating conditions. These results provide basis to the adjustment of existing models and possibly the introduction of specific models for each refrigerant, in view of more reliable correlations.

5. ACKNOWLEDGEMENTS

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6. REFERENCES


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