

EXPERIMENTAL RESEARCH OF THE EFFECT OF SURFACE ORIENTATION ON THE SUBCOOLED FLOW NUCLEATE BOILING OF WATER AT LOW PRESSURE

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ABSTRACT

The toughening emission standards and the costs saving requirements are pushing to the limits the design of compact heat exchangers in the automotive industry, meaning that today's heat exchangers need to operate with a controlled level of boiling in their coolant side. Most of the experimental literature available tackle boiling in horizontal flat plates or vertical tubes, while the information regarding other orientations is much scarcer. However, in a compact heat exchanger all orientations are present therefore orientation parametrizations in boiling models are particularly important since upper-heating orientations have a strong influence on heat transfer mechanism and the critical heat flux due to the cancelation of the bubbles floatability forces that help their departure. Therefore the limiting heat flux in those parts is generally governed at boiling orientations not determined with precision. The experimental work presented in this paper analyses the dependence of the heat transfer coefficient with the inclination of the heated surface under subcooled boiling regime. Due to the heating method selected, the test part consists in an AISI 316 thin strip with a thickness of 0.5 mm brazed to a copper base, to ensure an industry-like heat exchange material as primary surface but avoiding unmanaged temperatures and heating powers. Experimental tests have been carried out on a single face heated rectangular channel under several operating conditions of bulk velocity, temperature, pressure and flow orientation: 0.1-0.9 (m/s) – 76.5-93.5 (°C) – 110-190 (kPa) – 0-180 (°), to cover some of the most common conditions found in the automotive compact heat exchanger industry. The heat flux employed in each test ranged from 0.1 to more than 1 MW/m². After the data analysis some main dependences were identified and suggested that a global boiling model should include some parameters accounting for the relative orientation of the heated part and the coolant flow. This could be a valuable tool during the development of an automotive heat exchanger in which nucleate boiling is present.

INTRODUCTION

The new requirements in terms of incipient boiling demanded to current compact heat exchangers claim not only a better knowledge of the still partially unresolved boiling mechanism [1], but also in the characterisation of the process according to the relative position between the flow and the heated surface. The rising compactness of thermal automotive motors and the daily operational circumstances cannot ensure the optimal working conditions of these devices all the time, so it is

necessary to control and maintain the working point below certain limits to avoid the thermal burnout.

The influence of the orientation in the flow boiling curve has been previously studied by several authors. Brusstar and Merte [2] analysed the critical heat flux (CHF) point regarding the importance of floatability as the key aspect at low velocities. Steiner et al. [3] studied the influence of orientation in the film boiling transition point, Bower and Klausner [4] dealt with the dependence of the gravity in the subcooled regime and Gersey and Mudawar [5] and Konishi et al. [6] studied the orientation effects in the CHF point under several conditions.

It is generally accepted [3][5][6] that flow velocity has a strong influence in the CHF point at low velocities, whereas this effect becomes irrelevant at higher velocities where the drag and shear forces clearly dominate over floatability.

In this work, a set of experiments of subcooled boiling of water analysis is performed under different flow and thermodynamic conditions varying the orientation of the heating surface with respect to the gravity. These experimental tests have permitted to determine some influences in the boiling curves characterized by the differences observed in the heat transfer coefficient values before the CHF has been reached.

NOMENCLATURE

HTC	[W·m ⁻² ·K ⁻¹]	Heat transfer coefficient
G	[kg·s ⁻¹ ·m ⁻²]	Mass flux
p	[Pa]	Pressure
q	[W·m ⁻²]	Heat flux
T	[K]	Temperature
v	[m·s ⁻¹]	Velocity
Subscripts		
b		Bulk conditions
w		Wall conditions
Abbreviation		
CHF		Critical heat flux
HTC		Heat transfer coefficient

EXPERIMENTAL SETUP

Experimental Bench

The test bench (Figure 1) designed to carry out the experimental work is comprised of the test area and the secondary devices to achieve the flow control in terms of bulk temperature, pressure and flow rate. As a common facility of

previous works, further details can be found in [7]. In Figure 2 a cutting plane section for the test area is shown. It consists of a rectangular channel (5) of 25×20 mm with a total length of 1200 mm.

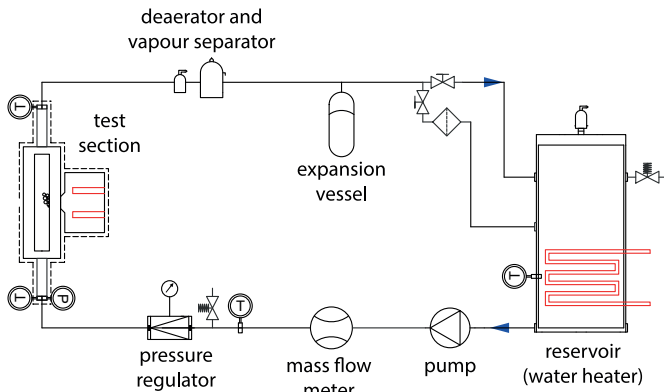


Figure 1 Experimental bench

The heating surface is performed by four heating cartridges (1) embedded in a copper heating block (2) with a total power of 2,000 W. This block transfers the heat by conduction to the test part. The test part (3), with an upper surface of 50×10 mm in touch with the water, is insulated from the rest of the system by a PTFE skin (4).

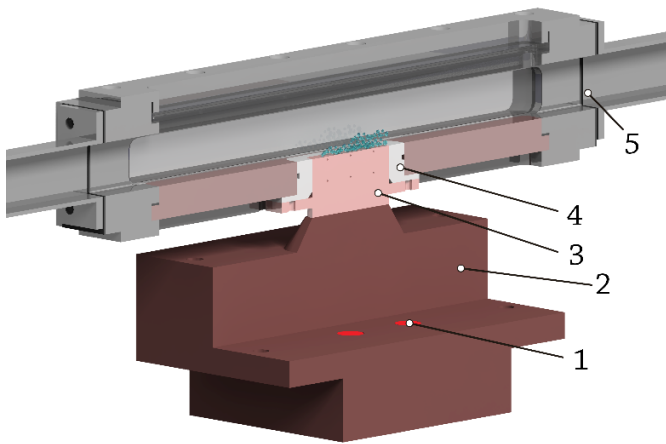


Figure 2 Test section

The measurement of the temperature is performed using 6 K-type thermocouples –class-2 tolerance, 0.5 mm diameter and 0.03 s response time– which are located on the test part as shown in Figure 3. Data acquisition comprises of a data acquisition card acquiring values at 1 kHz for the temperatures (bulk and hot part), volumetric flow and pressure. Applying Fourier's law the wall heat flux was calculated with the thermal gradient given by the values of the embedded thermocouples. The wall temperature is calculated assuming a linear profile for the temperature distribution inside the solid.

The heated surface consists of a copper base part with an AISI 316 thin strip of 0.5 mm thickness attached to its upper surface by brazing. This manufacturing method was selected to avoid the big amount of installed power needed to heat a hypothetical solid part made entirely from steel and the unmanageable expected temperatures.

Design of experiments

The selected independent variables to perform the experimental points have been the bulk temperature, pressure

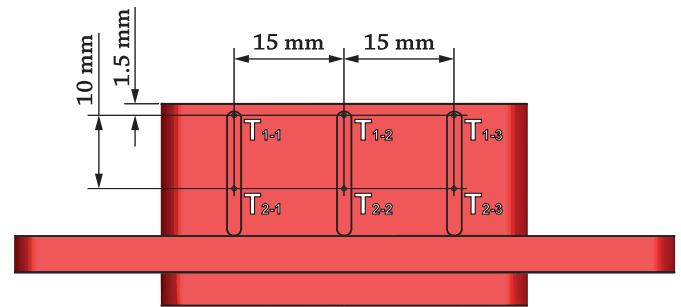


Figure 3 Thermocouples arrangement

and flow velocity. Assuming three different values –low, medium and high– for each of the properties, results in seven experimental points. The assumed tolerances and uncertainties are shown in Figure 4 next to the test points.

Point	T_b [°C]	p [kPa]	v [m·s ⁻¹]	ΔT_{sub} [°C]	G [kg·s ⁻¹ ·m ⁻²]	Variable	Uncertainty
1	76.5	150	0.5	34.8	487.0		
2	85.0	150	0.1	26.3	96.9	T_b	± 0.35 K
3	85.0	110	0.5	17.3	484.3	p	± 3000 Pa
4	85.0	150	0.5	26.3	484.3	v	± 4.6 mm·s ⁻¹
5	85.0	190	0.5	33.6	484.3	T_w	± 0.82 K
6	85.0	150	0.9	26.3	871.8	q_w	± 66 kW·m ⁻²
7	93.5	150	0.5	17.8	481.5		

Figure 4 Test points (left) and uncertainties (right)

The experimental array have been tested under different heated surface and flow orientation –whose designation is shown in Figure 5– measuring the values for the different thermocouples.

In order to avoid differences when comparing the boiling curves between experimental rounds due to the well-known effect of ageing [8], a reference test based on a reference point – assumed to be the centred test point (number 4) at 0°-upward flow– has been repeated and checked to be the same before and after each round of tests to ensure the independence of the curves for the different orientations with the current ageing state of the surface

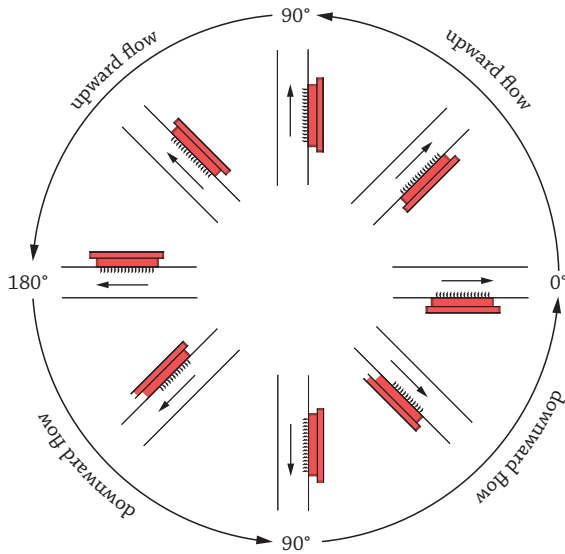


Figure 5 Orientation designation

RESULTS AND DISCUSSION

Once the values for the q_w and T_w have been calculated, the heat transfer coefficient value (HTC) could be estimated assuming Newton's cooling law for the surface:

$$HTC = \frac{q_w}{T_w - T_b} \quad (1)$$

Although the variation in T_b between inlet and outlet was negligible in most of the cases, an averaging value has been used here for better performance.

For analysing the results, two zones for the HTC-orientation dependence have been considered: the partial boiling zone and the fully developed boiling zone. Also, some of the herein presented curves are normalized by a HTC reference value consisting of the aforementioned reference point value, just for comparing purposes inside the same family of curves.

First quadrant –0° to 90°, upward flow–

As shown in Figure 6, the HTC strongly depends on the subcooling caused by either changes in the bulk temperature (Figure 6a) or system pressure variations (Figure 6b) while the velocity of the flow (Figure 6c) has little effect on the fully developed boiling region. Together with the subcooling effect, the system pressure also controls the boiling process since it has great influence on the size of the cavities that can become active [9] and hence in the nucleation sites density for a given surface. The observed effect of subcooling is in agreement with the general accepted behaviour when employing wall heat flux partitioning models which generally assume that once nucleate boiling appears, the flow of cold liquid injected towards the surface in order to replace the volume abandoned by the bubble quenches the hot surface. In contrast, the enhanced effect of flow velocity in the single-phase region begin to vanish once the first bubbles appear, converging all the boiling curves with the pool

boiling case at high heat flux. Again this fact agrees with the commonly appealed suppression factor as a function of mass flux, firstly introduced by Chen [10] and still widely used in boiling models.

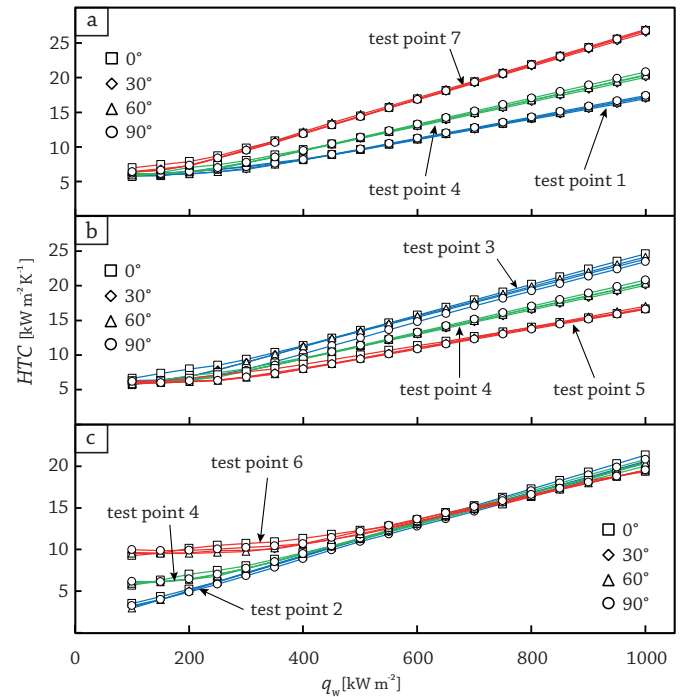


Figure 6 HTC for 0°-90° upward flow. (a) Varying bulk temperature; (b) varying pressure; (c) varying mass flux

In the first quadrant and for the tested conditions, the HTC has been found to be practically independent of the relative orientation. To illustrate this lack of dependence, the HTC- q_w curves are shown in the Figure 6a, b and c, where the points for the selected orientations are practically overlapping.

Second quadrant –90° to 180°, upward flow–

When the heated element is tilted and positioned between 90° and 180° upward flow, inclination starts to manifest some influence on the boiling behaviour of the surface. It has been demonstrated in Figure 6 that at 90° the effect of inclination is negligible. The results of the tests performed at 90°, 150° and 180° are shown in Figure 7 as these angles summarize the effects found in this quadrant. In this case to permit a better assessment of the behaviours at different orientations the curves are represented using the HTC rated by the corresponding value for the reference curve instead using of the absolute value.

For the three bulk temperatures tested the highest HTC is achieved with the 180° orientation. This fact could be explained due to the higher number of bubbles forced to slide along, merge and reside in contact with the heated surface, yielding to a rise in the boiling activity as more nucleation areas are present. Moreover, the lower the quenching effect the higher the difference in HTC of the different orientations, due to the magnification of the effect because of the rise in the boiling intensity. Despite this, when the bulk temperature is low

(76.5°C), subcooling effects are dominant and orientation seems to be negligible in this range which therefore means that it is comparable with the first quadrant.

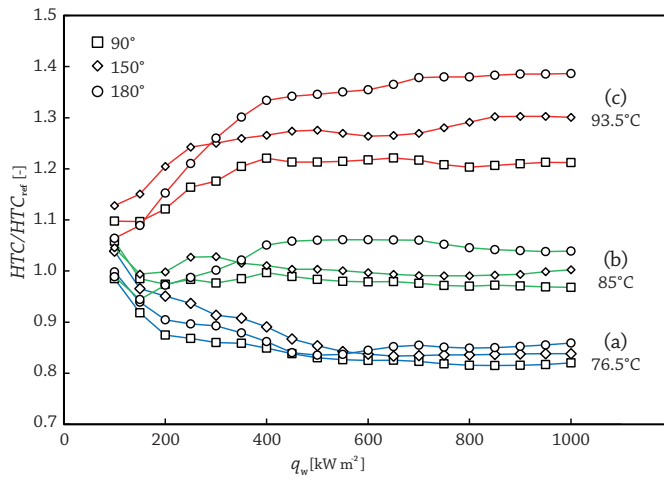


Figure 7 HTC for 90°-180° upward flow varying bulk temperature. (a) Low temperature; (b) medium temperature; (c) high temperature

Analysing the variation of the pressure together with the orientation angle (Figure 8), the results follow the aforementioned trend due to the effect of the pressure on the subcooling. However the magnification has not been stated for the lowest value of the pressure indicating that the pressure effects in the bubble force balance –and hence in its movement– and in the activation of the nucleation sites dominates over the sliding effect since all the orientations seem to activate a number of cavities enough to release all the heat.

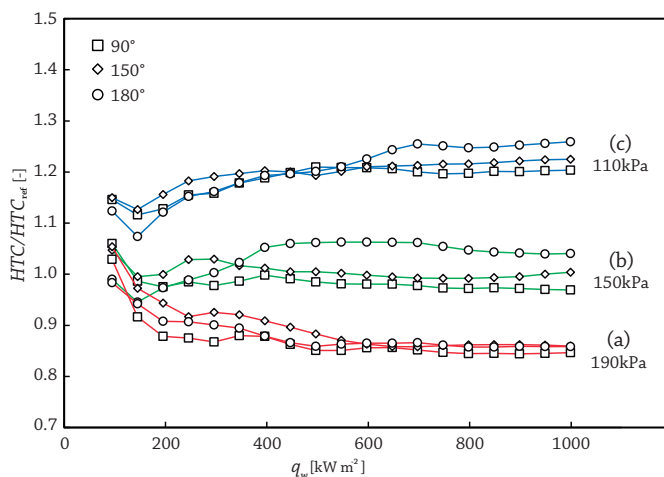


Figure 8 HTC for 90°-180° upward flow varying pressure. (a) Low pressure; (b) medium pressure; (c) high pressure

The effect of velocity is shown in Figure 9. As has been seen for the first quadrant, orientation has little or no influence when the set variable is the velocity. When the bulk velocity is low (0.1

m/s) (Figure 9a) above 600 kW/m² the 180° plate exceeds its CHF and the boiling is suddenly disturbed generating an abrupt reduction in the HTC motivated by the creation of big vapour regions attached to the surface. Generally CHF starts as a local process and only when the heat flux is increased, can become a global process on the whole plate. As its experimental observation will require to capture the heat flux at several locations of the heated plate to determine if it has been reached somewhere, no generalization of its value should be based on the information given in this work. Furthermore, the details of the boiling process above this point are beyond the scope of the present study and will not be analysed here. However, it can be observed that at the same flow rate, if the heating element is tilted (blue line corresponding to 150°), though some disturbance of the HTC is apparent beyond 600 kW/m² no boiling crisis was found, at least up to 1000kW/m². This is probably due to the buoyancy force that helps to evacuate the bubbles from their nucleation point avoiding the stratification. These forces are helped by drag at higher bulk velocities and therefore CHF has not been found with 0.5 m/s (Figure 9b) and 0.9 m/s (Figure 9c) even at 180°. This extremely low value for CHF found for the horizontal orientation with downward heating, has already been studied in the past [3][5] as well as the gravity dependence found in the low velocity region encountered along the transition between pool and flow boiling at relatively high velocities [2] [4].

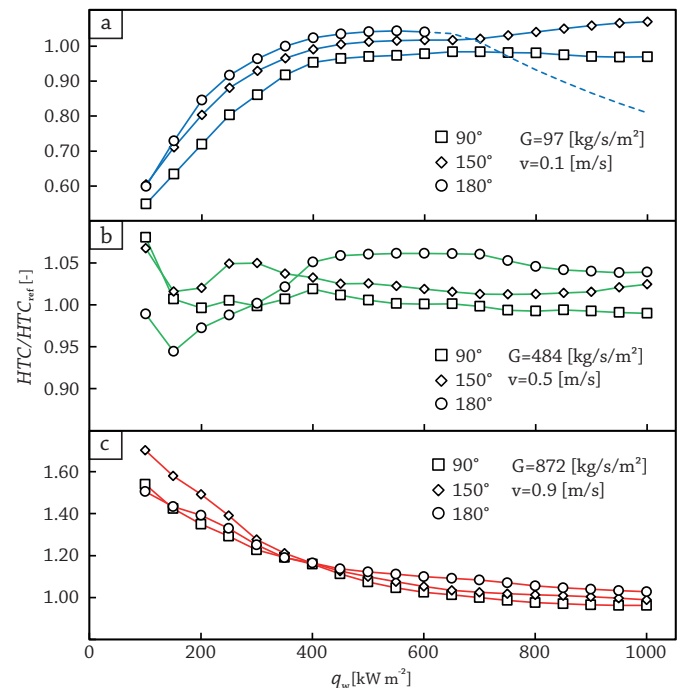


Figure 9 HTC for 90°-180° upward flow varying mass flux. (a) Low velocity; (b) medium velocity (c) high velocity

Third quadrant –180° to 90°, downward flow–

In this case the nomenclature of the inclination of the surface can be misleading. If the rotation of the plate is increased further, the angle with respect to the reference case will vary from 180° to 270°, however in the literature, if no reference is made, the same

configuration can be defined as a surface with an inclination between 180° to 90° with a downward flow.

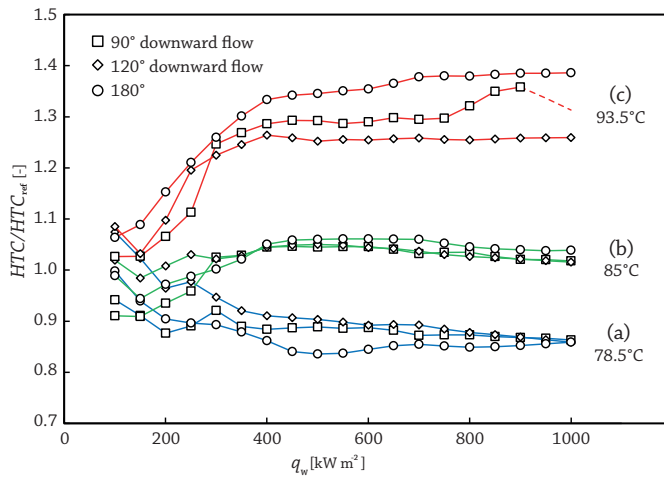


Figure 10 HTC for 90° - 180° downward flow varying bulk temperature. (a) Low temperature; (b) medium temperature; (c) high temperature

Figure 10 shows the effect of bulk temperature on the third quadrant. As seen in Figure 10a and Figure 10b, while the level of subcooling is high (lower bulk temperatures), the effect of inclination in this quadrant is almost insignificant, especially at higher heat flux. However, at 93.5°C , with a lower level of subcooling, the difference between 180° and 270° becomes apparent. The HTC at 180° is the highest in this quadrant and HTC is reduced as the angle is increased up to 270° probably due to the fact that the buoyancy forces, that may help in the removal

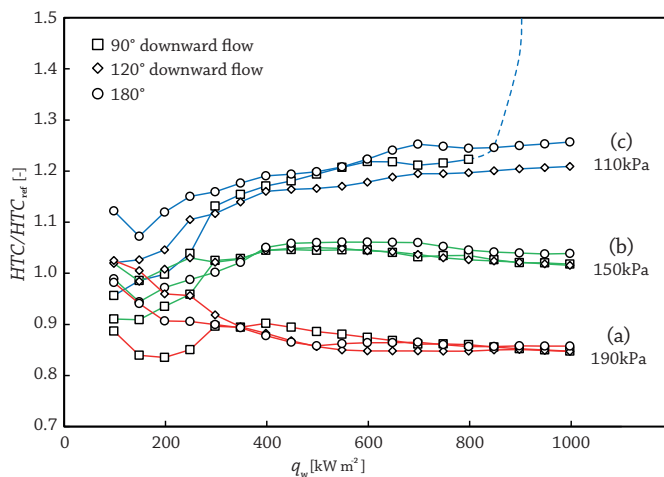


Figure 11 HTC for 90° - 180° downward flow varying pressure. (a) Low pressure; (b) medium pressure; (c) high pressure

of the bubbles and that are expected to be highest at 270° , are counteracted in this situation by the drag forces generated by the flow of liquid. In fact despite being out of the scope of this work, the CHF point for the lowest subcooling values, is achieved for

the downward flow configuration at a slightly lower value (800 - 900 kW/m^2) than for the horizontal one (incipient CHF at 1000 kW/m^2), indicating that bubble acting forces play a key role when the fresh liquid pumping mechanism becomes weak. Previous researchers have found this behaviour due to the fact that bubble stagnation overcomes the vapour stratification [5].

In relation to the system pressure variations (Figure 11) very little differences have been observed between the three orientations in this quadrant so no effects due to the orientation could be clearly stated.

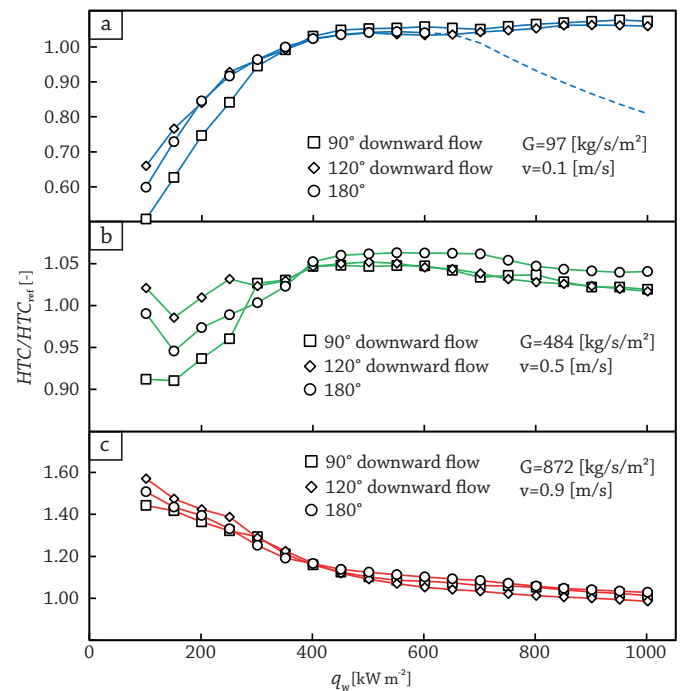


Figure 12 HTC for 90° - 180° upward flow varying mass flux. (a) Low velocity; (b) medium velocity (c) high velocity

When varying the flow velocity for the three orientations selected for the third quadrant (Figure 12), they show basically the same behaviour, apart from the aforementioned CHF achievement in the horizontal configuration.

Fourth quadrant -90° to 0° , downward flow–

In the fourth quadrant, the HTC of the vertical configuration is relatively higher than for the other orientations where the variations in the bulk temperature were selected (Figure 13). A possibility is that, in contrast to the other crosswise and horizontal configurations, the 90° downward one does not permit the floatability to help the surface in transversally getting rid of vapour, so bubbles can manage to enhance, by sliding, the activation of more sites and in consequence, improve the transfer coefficient.

For the variations in velocity and pressure no enhanced orientations have been observed for the tested range of operational conditions.

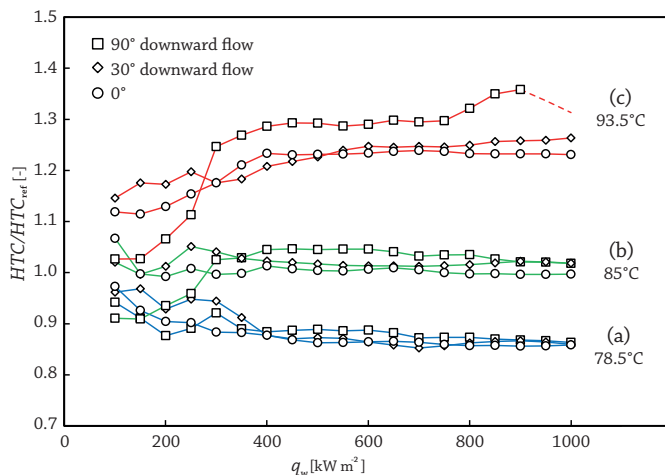


Figure 13 HTC for 0°-90° downward flow varying bulk temperature. (a) Low temperature; (b) medium temperature; (c) high temperature

CONCLUSION

In the boiling incipient range where the first bubbles appear, the curves generally show a scatter behaviour independent of the orientation, subcooling and saturation temperature (i.e. system pressure). Due to the deep effect of mass flux in the forced convection HTC, differences between different velocities are observed but in the end, no homogeneous effect due to orientation has been noticed. This clearly indicates the erratic behaviour typical of transition zones and commonly solved in modelling by a linking curve between the two zones. While boiling mechanisms commence to dominate over the single-phase transfer, data is becoming steady and some trends can be observed:

- Relative orientation of the heated surface with the gravity direction has insignificant effects on the HTC when mass flux is varied for all the performed orientations. Concerning the CHF and based on the literature survey –consistent with the here in exposed results–, this is also true above a critical value for the velocity.
- When the system pressure and the bulk temperature are the chosen parameters to vary, the tests for the second quadrant –90° to 180° upward flow– and the symmetrical –180° to 90° downward flow– in the third quadrant show significant differences depending on the orientations of the heated surface. At high bulk temperatures, differences in the HTC up to 15% higher than for the 90° upward flow configuration and 6.5% higher with respect to the 90° downward case have been encountered. For the different tested pressures results show fewer values, reaching almost 8% between 180° and 90° upward flow with no significant differences for the third quadrant. The horizontal upward heating surface configuration has resulted in having the higher value for the HTC possibly induced by the higher number and time of residence of sliding and merging bubbles which permits the

activation of a greater number of nucleation sites by vapour entrapment mechanisms.

- In the case of rising the bulk temperature, yielding to lower subcooling values but keeping constant the system pressure, the number of sites activated by vapour entrapment at the cavities dominate the process.
- For the evaluated conditions at the lowest pressure value, the system pressure has found to be determinant as it expands the morphological range in which the existence of a nucleation site is possible. This effect caused the heating surface for all the orientations, to have the capacity of promoting enough nucleation sites, restricting, to some extent, the sliding bubble effect. Anyway, further work is required to analyse and quantify the latter statement if possible.

REFERENCES

- [1] H. Steiner, G. Brenn, F. Ramstorfer, and B. Breitschadel, "Increased cooling power with nucleate boiling flow in automotive engine applications," in *New Trends and Developments in Automotive System Engineering*, M. Chiaberge, Ed. InTech, 2011, pp. 249–272.
- [2] M. J. Brusstar and H. Merte, "The Effects of buoyancy on the critical heat flux in forced convection," in *31st AIAA Aerospace Sciences Meeting and Exhibit*, 1993.
- [3] H. Steiner, G. Brenn, and B. Breitschadel, "Onset of partial film boiling on a downward facing heated surface," in *Proc. 6th International Conference on Multiphase Flow*, 2007.
- [4] J. S. Bower and J. F. Klausner, "Gravity independent subcooled flow boiling heat transfer regime," *Experimental Thermal and Fluid Science*, vol. 31, pp. 141–149, 2006.
- [5] C. O. Gersey and I. Mudawar, "Orientation effects on critical heat flux from discrete, In-line heat source in flow channel," *ASME Journal of Heat Transfer*, vol. 115, pp. 973–985, 1993.
- [6] C. Konishi, I. Mudawar, and M. M. Hasan, "Investigation of the influence of orientation on critical heat flux for flow boiling with two-phase inlet," *International Journal of Heat and Mass Transfer*, vol. 61, pp. 176–190, 2013.
- [7] M. C. Paz, M. Conde, E. Suárez, and M. Concheiro, "On the effect of surface roughness and material on the subcooled flow boiling of water: Experimental study and global correlation," *Experimental Thermal and Fluid Science*, vol. 64, pp. 114–124, 2015.
- [8] C. Paz, M. Conde, J. Porteiro, and M. Concheiro, "Effect of heating surface morphology on the size of bubbles during the subcooled flow boiling of water at low pressure," *International Journal of Heat and Mass Transfer*, vol. 89, pp. 770–782, 2015.
- [9] Y. Y. Hsu, "On the size range of active nucleation cavities on a heating surface," *ASME Journal of Heat Transfer*, vol. 84, pp. 207–216, 1962.
- [10] J. C. Chen, "Correlation for boiling heat transfer to saturated fluids in convective Flow," *Industrial Engineering Chemistry Process Design and Development*, vol. 5, no. 3, pp. 322–329, 1966.