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Effect of surface orientation on nucleate boiling and critical heat flux of dielectric fluids

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Abstract

Experiments were performed to analyse the effects of surface orientation on nucleate boiling of dielectric fluids from a smooth copper surface. Pool boiling data at atmospheric pressure were obtained with both saturated FC-72 and HFE-7100. For both fluids, the orientation angle of the copper surface from the horizontal plane was varied from 0°(upper surface) to 175°, with regular increments. For each orientation, the boiling curve was plotted up to thermal crisis conditions. The results obtained confirmed some of the effects of heater orientation on heat transfer coefficients reported in the literature: in the low-heat-flux nucleate boiling region, the heat transfer coefficient increases markedly with orientation angle; for higher heat flux values, the effect is evident only for angles greater than 90° and the heat transfer coefficient diminishes as the angle increases. The critical heat flux CHF decreases slightly as the orientation angle increases from 0° to 90°, while for downward-facing surfaces, the CHF decreases rapidly as the orientation angle increases towards 180°. CHF values obtained for both fluids and for different angles, normalized to the maximum value at 0°, showed good agreement with several literature correlations. The heat transfer coefficients and CHF values of HFE-7100 were found to be higher than those of FC-72. Finally, new correlations for heat transfer coefficients and CHF values as a function of inclination angle have been proposed.

Keywords: Dielectric fluids; Nucleate pool boiling; Orientation; Heat transfer coefficient; Critical heat flux

1. Introduction

The thermal control of electronic systems is a pressing problem, because of the need to dispose of ever-increasing thermal power densities. For very high heat fluxes, nucleate boiling is the most promising technique, as it enables large quantities of heat to be removed while keeping surface superheat relatively low.

The use of dielectric fluids offers several advantages:

(a) low saturation temperatures (40–85 °C), as required by most electronic junctions;
(b) good contact with all components, even in narrow spaces;
(c) excellent chemical compatibility with many materials;
(d) low toxicity and good environmental characteristics (see Table 1).

While several studies [1–3] have dealt with the boiling of the fluorinert FC-72 (C_6F_{14}), few have investigated HFE-7100 [4–6]. This new hydrofluoroether ($C_4F_9OCH_3$) dielectric fluid has recently been proposed to replace FC-72, as it has similar thermophysical properties and better environmental characteristics (lower GWP Global Warming Potential). Furthermore, as its latent heat of vaporisation is greater, it offers better nucleate boiling and critical heat flux (CHF).

Several parameters influence boiling, including surface configuration and orientation. The first studies on the effect of surface orientation date back to the 1960s and 1970s [7–9]. Nishikawa et al. [10] carried out a detailed study and tried to give a phenomenological interpretation of their experi-

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Nomenclature

$C_{f,w,\text{sat}}(\theta)$	coefficient, function of angle, in Eq. (7)	
$C_{\text{CHF,sat}}$	coefficient, function of angle, in Eq. (9)	
CHF	critical heat flux	$W\cdot cm^{-2}$
CHF_{max}	maximum critical heat flux ($\theta = 0$)	$W\cdot cm^{-2}$
CHF_{sat}	saturation critical heat flux	$W\cdot cm^{-2}$
c_{pl}	liquid specific heat	$J\cdot kg^{-1}\cdot K^{-1}$
C_{sf}	constant in Eq. (1)	
g	acceleration of gravity	$m\cdot s^{-2}$
h	heat transfer coefficient	$W\cdot m^{-2}\cdot K^{-1}$
h_{fg}	latent heat of vaporisation	$kJ\cdot kg^{-1}$
k	thermal conductivity	$W\cdot m^{-1}\cdot K^{-1}$
Pr	Prandtl number	
q''	heat flux	$W\cdot cm^{-2}$
$q''_{\max\theta=0}$	maximum heat flux (experimental detected before thermal crisis) for $\theta = 0°$	$W\cdot cm^{-2}$
r	exponent in Eq. (1)	
s	exponent in Eq. (1)	
T_p	surface temperature	K

Greek symbols

ΔT_{sat}	surface superheat ($T_w - T_{sat}$)	K
μ	viscosity	Pa·s
θ	orientation angle	°
ρ	density	$kg\cdot m^{-3}$
σ	surface tension	$N\cdot m^{-1}$

Subscripts

l	liquid
v	vapour

mental data. On analysing the nucleate boiling of distilled water at atmospheric pressure, for different orientations of a copper plate, they found that, at low heat fluxes and at the same surface superheat, heat flux increased as the angle θ increased from 0° (upward-facing surface) to 175°(downward-facing surface inclined 5°), while for greater heat fluxes, orientation had no significant effect. However, their experiments were limited to heat fluxes of up to about 70% of the CHF. Nishikawa et al. divided the nucleate boiling region into three zones: a low heat flux ($<7\ W\cdot cm^{-2}$, about 6% of maximum CHF) zone, in which orientation is significant; a medium heat flux (7–17 $W\cdot cm^{-2}$) zone, in which orientation effects tend to disappear; and a high heat flux ($>17\ W\cdot cm^{-2}$ about 15% of maximum CHF) zone, in which surface orientation has no influence.

Subsequently, Chang and You [11] studied the effects of the angle of inclination θ on the saturated nucleate boiling of FC-72 on a smooth, (10 × 10) mm copper surface. They noticed that, in the nucleate boiling regime, heat flux increased as θ increased from 0° (upward-facing surface) to 90°. This was attributed to an increase in the number of active nucleation sites. For $\theta > 90°$, however, the heat trans-

Table 1
Comparison of physical properties of the HFE-7100 and FC-72 dielectric liquids

	HFE-7100 ($C_4F_9OCH_3$)	FC-72 (C_6F_{14})
Saturation physical properties (0.1 MPa)		
Boiling point [°C]	61	56
Freeze point [°C]	−135	−90
Ave. Molecular weight [$g\cdot mol^{-1}$]	250	338
Liquid density [$kg\cdot m^{-3}$]	1370.2	1602.2
Vapour density [$kg\cdot m^{-3}$]	9.87	13.21
Liquid viscosity [$kg\cdot m^{-1}\cdot s^{-1}$]	3.70×10^{-4}	4.33×10^{-4}
Liquid specific heat [$J\cdot kg^{-1}\cdot K^{-1}$]	1255	1101
Latent heat of vaporisation [$kJ\cdot kg^{-1}$]	111.6	88.0
Liquid thermal conductivity [$W\cdot m^{-1}\cdot K^{-1}$]	0.062	0.054
Liquid surface tension [$N\cdot m^{-1}$]	1.019×10^{-2}	0.793×10^{-2}
Environmental properties		
Ozone depletion potential[a] ODP	0.00	0.00
Global warming potential[b] GWP	320	7400
Atmospheric lifetime ALT [yrs]	4.1	3200
Electrical properties 25 °C		
Dielectric strength [kV 0.1″ gap]	28	38
Dielectric constant	7.39 (100 Hz – 10 MHz)	1.75 (1 kHz)
Volume resistivity [Ωcm]	3.3×10^9	1.0×10^{15}

[a] CFC-11 = 1.0
[b] GWP-100 year integration time horizon (ITH)

fer coefficient decreased markedly, which is the opposite of what Nishikawa et al. reported. Chang and You ascribed this discrepancy to the fact that Nishikawa et al. had operated under decreasing heat flux conditions.

Later, Chang and You [12], again working with FC-72 and a (20×20) mm surface, reported an increase in nucleate boiling heat flux as θ increased from 0° to 45°, but a decrease for $\theta > 45°$.

Recently, some authors have compared the boiling behaviours of HFE-7100 and FC-72 in experiments that also involved varying heater surface orientation.

In experiments on saturated and subcooled pool boiling at atmospheric pressure, Liu et al. [13] noticed that FC-72 exhibited greater efficiency and a higher critical heat flux than HFE-7100 in the nucleate boiling mode. In the film boiling mode, however, this pattern was inverted.

On analysing the saturated boiling of HFE-7100 on a smooth, (10×10) mm copper surface, El-Genk and Bostanci [14] found that, for $\theta \leqslant 90°$, heat flux decreased as θ increased when surface superheat ΔT_{sat} was >20 K, but increased when ΔT_{sat} was <20 K; similarly, for orientation angles $>90°$ and $\Delta T_{sat} > 13$ K, heat flux decreased on increasing θ, while at low surface superheat, its behaviour seemed confused. El-Genk and Bostanci also studied critical heat flux and surface superheat at CHF on varying surface orientation. For horizontal upward facing surface, in accordance with the previous findings of Arik and Bar-Cohen [4], the CHF for HFE-7100 proved to be about 57% higher than that reported for FC-72.

However, when the CHF values were normalised to the value for $\theta = 0°$, both fluids showed similar patterns on varying the orientation angle θ.

El-Genk and Bostanci [15] went on to study the combined effects of surface orientation and subcooling.

The different results obtained by various authors on the effects of surface orientation, in particular in the low heat flux region, prompted us to develop a more detailed experimental study on nucleate saturated pool boiling and critical heat flux for both dielectric fluids FC-72 and HFE-7100.

2. Experiments

2.1. Experimental set-up

The experimental set-up (Fig. 1) was designed to study nucleate pool boiling heat transfer and critical heat flux and to analyse the effects of surface orientation.

The experimental apparatus is essentially made up of a pressure vessel, in which the instrumented test section is immersed in the fluid; a water-cooled coil condenser is located in the vapour zone inside the container.

The test vessel is cubic (side 230 mm) and made of stainless steel, with a wall thickness of about 10 mm. Five observation windows are located in the side walls.

The experimental apparatus is instrumented with pressure transducer, venting valve, safety valve, vacuum pump and five thermocouples: three measure the temperature of the fluid, one measures the vapour temperature and one is used by the regulator which modulates electrical power to the auxiliary heaters; located laterally on the external surface of the vessel, these heaters preheat the fluid and maintain it at the desired saturation temperature.

2.2. Test section

The test section, which is depicted in Fig. 2, consists of a cylindrical copper block heated at the bottom by an electric heater. The top, flat end of the copper block is the boiling surface, and has an area of 7.07 cm^2.

The copper test section is instrumented with nine armoured thermocouples (external diameter 0.5 mm), placed in holes of different depths at three different levels: 3, 21, 39 mm from the boiling surface. At each level, the holes are located at 120° to one another and, in order to avoid nonuniformity of temperature distribution in the copper block, the three levels are rotated so that only one thermocouple lies on each vertical line.

The copper block is housed in a bakelite support; the space between the copper and the bakelite is filled with insulating material and the upper seal is made of epoxy resin. The copper test surface has been sandblasted with particles of controlled dimension, and presents an average roughness of 0.6 µm.

The heat flux q'' is calculated through Fourier's law, assuming that heat conduction between the thermocouples and the surface is one-dimensional, and that both the positions of the thermocouples and the thermal conductivity of the copper are known: heat flux and surface temperature T_p are obtained from the average temperature value at each level.

Standard techniques were followed to obtain the uncertainty (Moffat [16]) in the experimental measurements. The measuring system used to read the signals from the thermocouples was accurate to ± 0.1 K on absolute temperature values and to ± 0.02 K on differential values. The overall uncertainty in the determination of heat flux proved to be dependent on operating conditions. In the single-phase natural convection zone and at the onset of nucleate boiling, the maximum error in the heat flux value was $\pm 15\%$. In the fully developed nucleate boiling region, the maximum error was less than 5%. Close to the thermal crisis, overall uncertainty increased to $\pm 8\%$. Finally, the error associated with surface temperature in the fully developed boiling region was less than ± 0.2 K.

2.3. Test procedure

Gases are known to dissolve easily in dielectric fluids. Dissolved gases can induce anomalous behaviour, especially at onset of boiling, with bubbles forming even at temperatures below the saturation temperature. Therefore, before

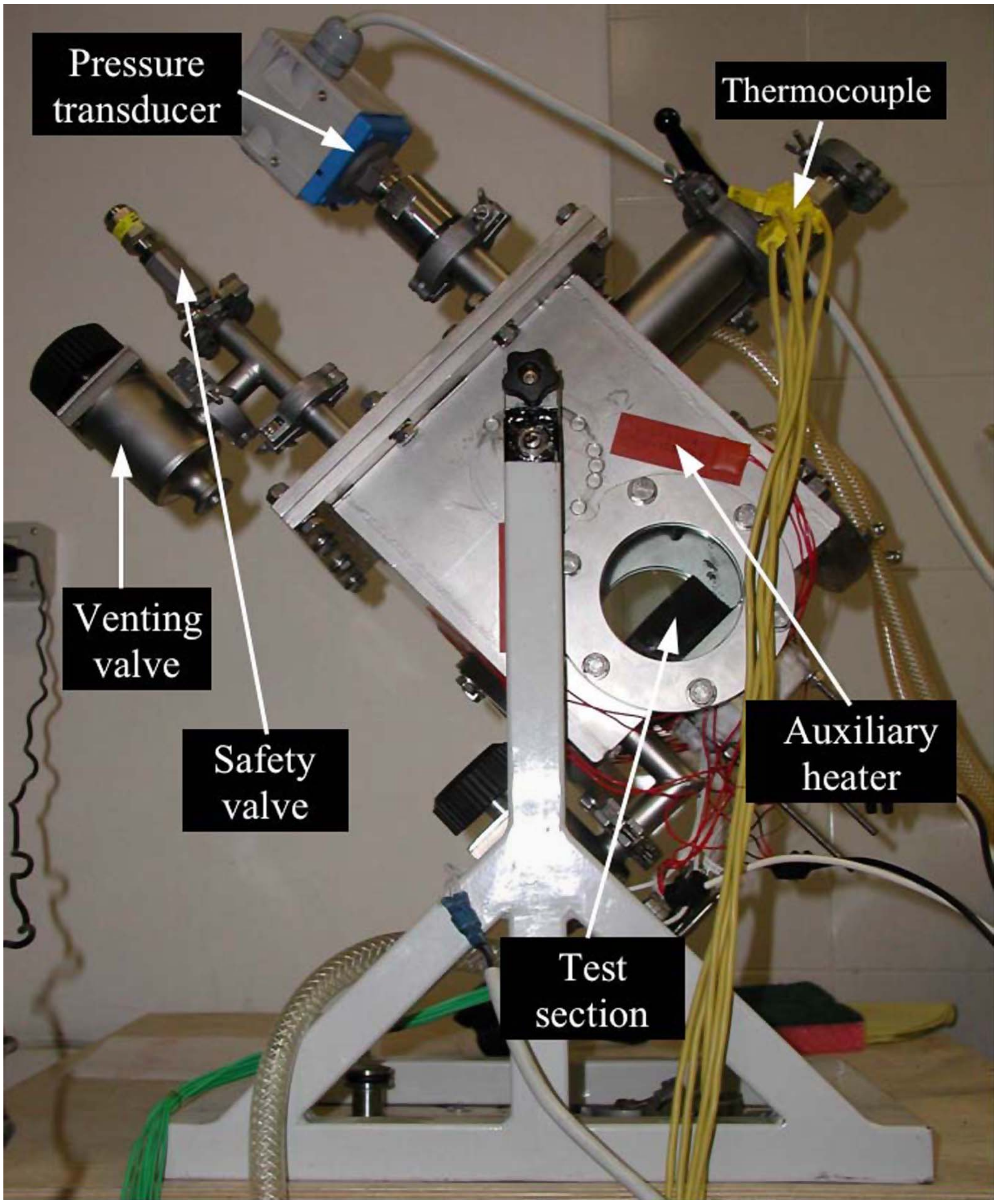


Fig. 1. Test vessel for pool boiling experiments.

each experimental run, a partial vacuum is created inside the vessel.

Once an adequate degree of vacuum has been achieved, the bulk liquid is introduced into the vessel. The auxiliary heaters are switched on in order to raise the internal pressure value above the external atmospheric pressure, thereby degassing the fluid. This operation is repeated until a satisfactory correspondence is achieved between the pressure inside the vessel and the liquid saturation temperature.

To obtain the boiling curves, the following procedure was followed: after half an hour of vigorous boiling at about 4 $W \cdot cm^{-2}$, experiments began at the lowest heat flux value (less than 1 $W \cdot cm^{-2}$) and all tests were then conducted under increasing heat flux conditions in order to avoid the delays in bubble cessation that are typical of downward-facing surfaces under decreasing heat flux conditions. This procedure enables all nucleation centres to be activated, thereby avoiding hysteresis phenomena and temperature overshoot at the onset of boiling.

For each heat flux value imposed, and once steady-state conditions had been reached after about 15–20′, all measurement parameters were acquired and recorded. There is good reproducibility for all pool boiling curves.

3. Results and discussion

During the experiments, the test section was immersed in FC-72 and HFE-7100 fluid pools at the pressure of 1 bar,

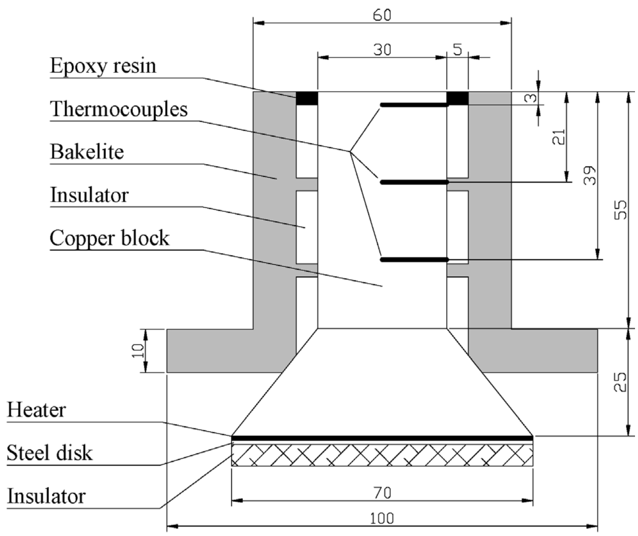


Fig. 2. Test section scheme.

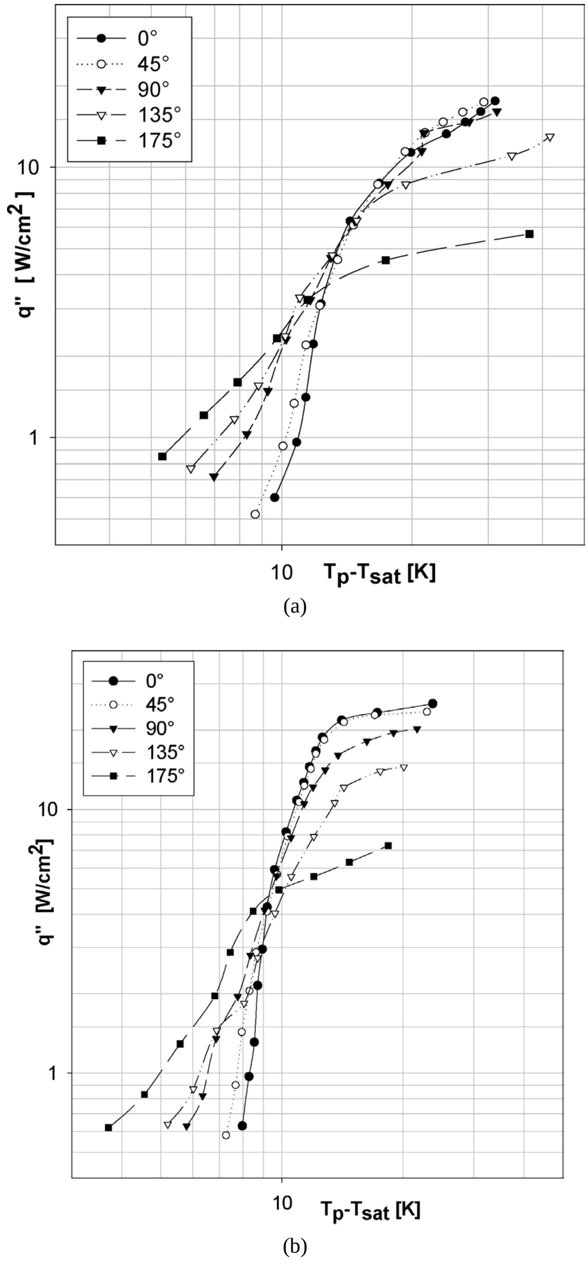


Fig. 3. Boiling curves for FC-72 (a) and HFE-7100 (b).

and the circular copper surface was successively placed at five different orientations: 0°, 45°, 90°, 135° and 175° from the horizontal.

3.1. Boiling curves

From the values of heat flux and surface temperature superheat, boiling curves were plotted for each orientation. Comparison of the different curves reveals the effect of orientation on heat transfer efficiency.

Examination of Fig. 3 shows that the boiling curves can be subdivided into the following different regions:

(1) low heat fluxes (for FC-72 up to 4 $W\cdot cm^{-2}$, about 23% of $q''_{\max\theta=0^\circ}$; for HFE-7100 up to 5 $W\cdot cm^{-2}$, about 20% of $q''_{\max\theta=0^\circ}$);
(2) high heat fluxes (for FC-72 greater than 6–7 $W\cdot cm^{-2}$, about 35–40% of $q''_{\max\theta=0^\circ}$; for HFE-7100 greater than 5–6 $W\cdot cm^{-2}$, about 20–25% of $q''_{\max\theta=0^\circ}$).

In the first zone, orientation exerts a marked influence: on increasing the orientation angle, a greater heat flux is transferred at the same surface superheat. This behaviour confirms the hypothesis put forward by Nishikawa et al. [10] and taken up by El-Genk and Bostanci [14], according to which, at low specific heat fluxes, where the sensible heat transport is the predominant mechanism, the movement of the bubbles along the plane surface shifts the superheated thermal layer and enhances heat transfer efficiency.

A recent study by Rini et al. [17] on FC-72 nucleate pool boiling has revealed that, at low heat flux level (about 1 $W\cdot cm^{-2}$), phase change accounts for only about 36% of the total heat flux. This contribution increases as the total heat flux increases: at 10 $W\cdot cm^{-2}$, the contribution made by phase change increases to 76% and is expected to be even higher near the CHF.

For high specific heat flux, on the other hand, two different trends are seen. For angles up to 90°, boiling curves match, while for angles greater than 90° the heat flux and the CHF decrease as the surface inclination increases. This can probably be attributed to a growing accumulation and coalescence of departing vapour bubbles near the boiling surface, which hinders the heat transfer rate. The size of the adiabatic annulus (external diameter 60 mm) surrounding the test surface may also influence the accumulation of vapour bubbles. Ishigai et al. [18] found that, when the ratio between the surface area of the heater and that of the surrounding adiabatic surface was held constant, the CHF decreased as the area of the heater increased.

The curves depicted in Fig. 3, especially referring to the FC-72 fluid, also show a zone of intermediate heat fluxes (from 4 to 7 $W \cdot cm^{-2}$), in which the curves for different orientations match, with the exception of the curve for the 175° orientation. In this zone, heat transfer is not appreciably affected by orientation.

In conclusion, our experimental results seem to confirm the behaviour observed by Nishikawa et al. [10] for water at low and intermediate specific heat fluxes and the effects at high specific heat fluxes reported by Chang and You [12] for FC-72 and by El-Genk and Bostanci [14] for HFE-7100.

The five windows in the test vessel enabled us to observe the phenomena occurring on the test surface and to identify various boiling regimes for each orientation.

A horizontal upward-facing surface ($\theta = 0°$) does not interact with the flow of bubbles, which can detach and rise vertically. At low heat fluxes, small rarefied bubbles form on the surface and are immediately detached by buoyancy forces; as heat flux increases, the bubbles become bigger and more densely clustered on the surface and their flow more tumultuous.

As the inclination angle increases, vertical bubble flow is no longer orthogonal to the surface. Consequently, the bubbles remain in the boundary layer for a longer time as θ increases, thereby increasing agitation in the thermal boundary layer and improving heat transfer efficiency owing to sensible heat transfer.

In the vertical orientation (90°), the bubbles drift along the surface, stirring the thermal layer and facilitating convective heat transfer.

At an angle of 135°, the surface becomes a real obstacle to upward motion and bubbles have to slide along the surface. At very low heat fluxes, there are only a few isolated bubbles. As heat flux increases, the bubbles coalescence, become elongated and rise more rapidly, giving the vapour the appearance of a wavy layer. For heat fluxes near to the CHF, this wavy layer becomes continuous and the liquid phase can reach the surface only at the inferior edge of the heater.

Some authors [10] claim that 175° is the last orientation at which there is still an improvement in heat transfer at low heat fluxes; indeed, a small angle of orientation from the downward-facing horizontal position still gives the bubbles a preferential direction in which to detach and rise.

On the basis of their observations of vapour behaviour just prior to the CHF, Howard and Mudawar [19] divided surface orientations into three different regions: upward-facing (0–60°), near-vertical (60–165°) and downward-facing (>165°). In the upward-facing region, buoyancy forces remove the vapour vertically from the heater surface. The near-vertical region, which covers almost 60% of all orientation angles, is characterised by a wavy liquid-vapour interface which sweeps along the heater surface. In the downward-facing region, the vapour repeatedly stratifies on the surface, greatly decreasing heat transfer at high heat fluxes.

In this regard, Yang et al. [20] observed a transition in boiling behaviour on shifting from near-vertical to downward-facing orientations between 150° and 174°.

3.2. Heat transfer coefficient

Fig. 4 shows heat transfer coefficients vs orientation angles for given heat flux values. At low heat fluxes q'', the heat transfer coefficient h increases as the orientation angle increases. On increasing the heat flux, this trend becomes progressively less marked and, at high heat fluxes, is actually reversed: i.e., the heat transfer coefficient decreases as the orientation angle increases.

As demonstrated in Fig. 4, the heat transfer coefficients for HFE-7100 are greater than those for FC-72, especially at high heat fluxes; this is in agreement with some literature reports [4,14,15], but contradicts [13].

In correlating the results obtained by varying the orientation angle, Rohsenow's [21] correlation seems to have the greatest flexibility, in that it accounts for the surface characteristics as well as orientation:

$$\frac{c_{\mathrm{pl}}\Delta T_{\mathrm{sat}}}{h_{\mathrm{fg}}} = C_{\mathrm{sf}}\left[\frac{q''}{\mu_{\mathrm{l}} h_{\mathrm{fg}}}\sqrt{\left(\frac{\sigma}{g(\rho_l-\rho_v)}\right)}\right]^r \left(\frac{c_{\mathrm{pl}}\mu_l}{k_l}\right)^s \tag{1}$$

In their study on the nucleate boiling of R-11 on plated metal surfaces and flat copper surfaces, Jung et al. [22] used correlation (1) to characterise boiling curves at different orientations, in the relatively low heat flux range, by taking C_{sf} and r as functions of the orientation angle θ and the fluid-surface combination. By setting the exponent s at 1.7, for the plane copper surface, they obtained:

$$C_{\mathrm{sf}} = 7.218 \times 10^{-3} - 1.74 \times 10^{-6}\theta \tag{2}$$

$$r = 0.256 - 1.514 \times 10^{-4}\theta + 1.778 \times 10^{-5}\theta^2 - 7.16 \times 10^{-8}\theta^3 \tag{3}$$

As the surface orientation angle increases from 0° to 165°, the exponent r increases by 40%, while the constant C_{sf} decreases slightly.

For enhanced surfaces, the values of C_{sf} and r remain constant, regardless of the surface orientation, except for a horizontal plate facing downward.

By rearranging correlation (1) in the form:

$$\log(Y) = -\frac{1}{r}\log(C_{\mathrm{sf}}) + \frac{1}{r}\log(X) \tag{4}$$

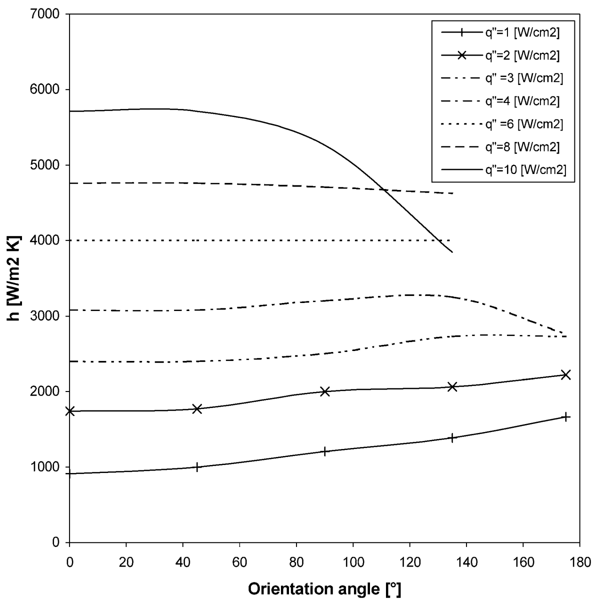
with

$$X = \frac{c_{\mathrm{pl}}\Delta T_{\mathrm{sat}}}{h_{\mathrm{fg}} Pr^{1.7}} \tag{5}$$

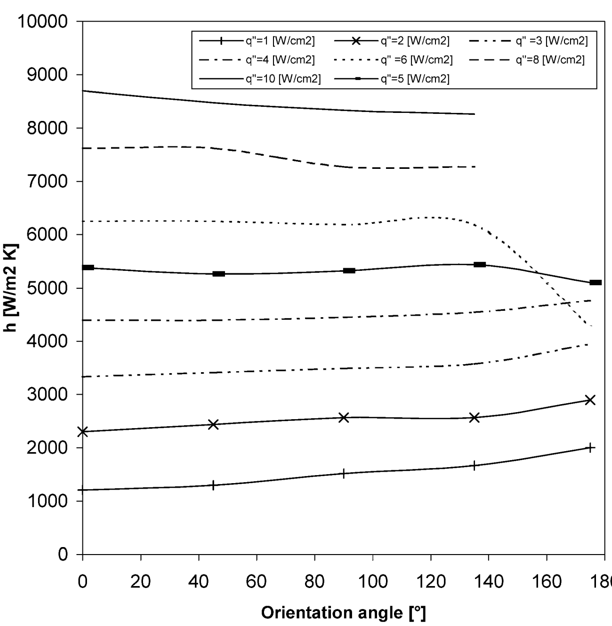
and

$$Y = \frac{q}{\mu_l h_{\mathrm{fg}}}\sqrt{\frac{\sigma}{g(\rho_l-\rho_v)}} \tag{6}$$

and maintaining the exponent s equal to 1.7, we calculated the C_{sf} coefficients and r exponents on the basis of the present experimental data.

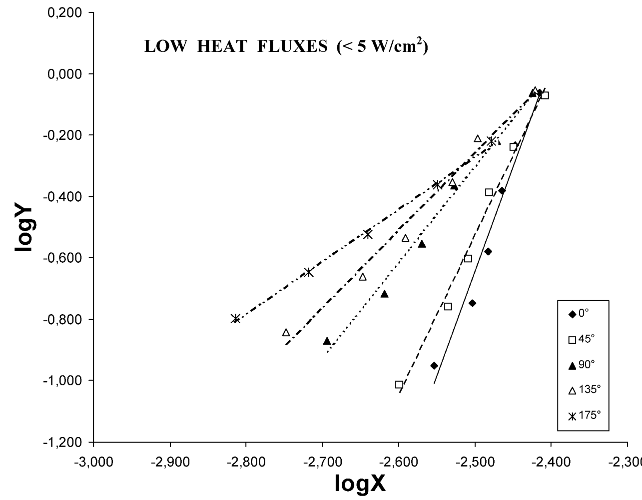


(a)

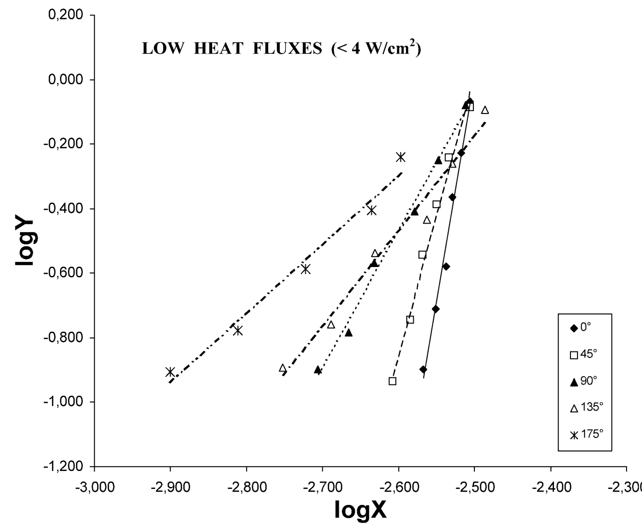


(b)

Fig. 4. Heat transfer coefficients vs orientation angles at different specific heat flux values, for FC-72 (a) and HFE-7100 (b).



(a)



(b)

Fig. 5. Comparison between experimental data and modified Rohsenow's correlation in the low heat flux zone for FC-72 (a) and HFE-7100 (b).

Table 2
C_{sf} coefficients and r exponents in Eq. (1)

Angle	FC-72		HFE-7100	
	r	C_{sf}	r	C_{sf}
0°	0.15	0.00393	0.07	0.00316
45°	0.19	0.00400	0.12	0.00315
90°	0.32	0.00397	0.24	0.00324
135°	0.40	0.00402	0.34	0.00363
175°	0.58	0.00454	0.47	0.00346

Log(Y) values as a function of log(X) are reported in Figs. 5(a) and (b), for FC-72 and HFE-7100, respectively, within the range of low heat fluxes defined above and for inclinations in the range $0° \leqslant \theta \leqslant 175°$.

Application of a least-squares regression and a linear approximation yielded the results showed in the following table (Table 2).

As will be seen, surface inclination has only a modest effect on C_{sf}, but a marked effect on exponent r (slope of the regression line in Fig. 5), which proves to be a growing quasi-linear function of θ. These conclusions confirm the results obtained by Naterer et al. [23] and Jung et al. [22].

On comparing the thermal performances of the fluids examined, it emerges that the C_{sf} values for HFE-7100 are about 25% lower than those for FC-72. This confirms the higher heat transfer coefficients of HFE-7100 in the nucleate boiling region examined.

Table 3
Effect of orientation on CHF

Angle	CHF [$W \cdot cm^{-2}$]	CHF/CHF_{max}
For FC-72		
0°	17.6	1
45°	17.4	0.99
90°	16.1	0.91
135°	13.0	0.73
175°	5.7	0.32
For HFE-7100		
0°	25.2	1
45°	23.47	0.93
90°	20.25	0.80
135°	14.51	0.57
175°	7.29	0.29

3.3. *Critical heat flux data and correlations*

We also analysed conditions close to the thermal crisis. To avoid compromising the integrity of the test section, heat flux was increased by regular steps until an anomalous rise in surface temperature was observed; this condition was identified as the thermal crisis and the corresponding heat flux was defined as the critical heat flux CHF.

Table 3 shows an indicative trend in maximum heat flux CHF versus the orientation angle θ of the surface for both fluids. In agreement with reports by other authors, CHF decreases as the orientation angle increases.

As in the experiments by Arik and Bar-Cohen [4], CHF values for HFE-7100 were more than 40% higher than those for FC-72. However, the normalized critical heat flux values (CHF/CHF_{max}), obtained by dividing by the CHF values obtained in the upward-facing position ($\theta = 0°$), show very similar trends for both fluids.

The experimental data obtained for both fluids can be correlated by using the following correlation, which is similar to that suggested by Kutateladze [24] and Zuber [25]:

$$CHF = C_{f,w,\mathrm{sat}} f(\theta)\left\{\rho_v^{1/2} h_{fg}\left[g\sigma(\rho_l - \rho_v)\right]^{1/4}\right\} \tag{7}$$

in which

$$f(\theta) = 1 - 0.0011117\theta + 7.79401 \times 10^{-6} \times \theta^2 - 1.37678 \times 10^{-7}\theta^3 \tag{8}$$

represents the influence of the orientation angle. Relation (7) refers to saturated pool boiling on very large heaters with negligible effects of heater thickness and thermal properties. In these conditions, the constant $C_{f,w,\mathrm{sat}}$ mainly depends on the fluid and in lesser extent on the surface preparation. The $C_{f,w,\mathrm{sat}}$ values obtained by experiments were 0.165 for FC-72 and 0.21 for HFE-7100. Chang and You [11] calculated $C_{f,w,\mathrm{sat}}$ as 0.15 for FC-72, while for HFE-7100, El-Genk and Bostanci [14] determined this constant as 0.229.

The term in curly brackets in (7):

$$\rho_v^{1/2} h_{fg}\left[g\sigma(\rho_l - \rho_v)\right]^{1/4}$$

is dimensionally a heat flux and contains only thermophysical properties of the fluid. It represents a "figure of merit" (FOM) of the fluid [26,27] with regard to critical heat flux. Its value, calculated for both fluids examined here, is 1066 $W \cdot m^{-2}$ for FC-72 and 1197 $W \cdot m^{-2}$ for HFE-7100, respectively. On the basis of fluid thermophysical properties, this difference would justify a critical heat flux for HFE-7100 about 12% higher than for FC-72. The experimental CHF data, which are confirmed by [11,14], show a difference of about 25% between the CHF of the two fluids for the same orientation angle during pool boiling at atmospheric pressure. In [4] CHF values 50–90% higher than FC-72 were obtained for HFE-7100 at various pressures and temperatures.

Correlation (7) is represented in Fig. 6(a) for FC-72 and in Fig. 6(b) for HFE-7100. In Fig. 6(b) the experimental data obtained here are compared with previous experimental data from El-Genk and Bostanci [14]. These authors proposed a correlation such as:

$$CHF_{\mathrm{sat}} = C_{CHF,\mathrm{sat}}(\theta)\rho_v^{1/2} h_{fg}\left[\sigma g(\rho_l - \rho_v)\right]^{1/4} \tag{9}$$

where $C_{CHF,\mathrm{sat}}(\theta)$ is a function of the fluid and the angle θ.

To highlight the effect of heater orientation on CHF, it is convenient to normalize the CHF values obtained for the different orientations by relating them to CHF_{max}, i.e. the maximum value of heat flux CHF, which is reached for the horizontal upward-facing surface ($\theta = 0°$).

Vishnev [28] was the first to correlate the effects of orientation on normalized CHF in pool boiling:

$$CHF/CHF_{max} = \frac{(190 - \theta)^{0.5}}{190^{0.5}} \tag{10}$$

Fig. 7 compares experimental data with those yielded by various correlations: the Vishnev correlation (10) and the Chang and You [11] correlation:

$$CHF/CHF_{max} = 1.0 - 0.00120\theta\tan(0.414\theta) - 0.122\sin(0.318\theta) \tag{11}$$

and the Brusstar and Merte [29] correlation, which takes into consideration the sliding effect of bubbles on inclined downward-facing surfaces and is valid only for angles from 90° to 180°:

$$CHF = CHF_{max}\left|\sin(180° - \theta)\right|^{1/2} \tag{12}$$

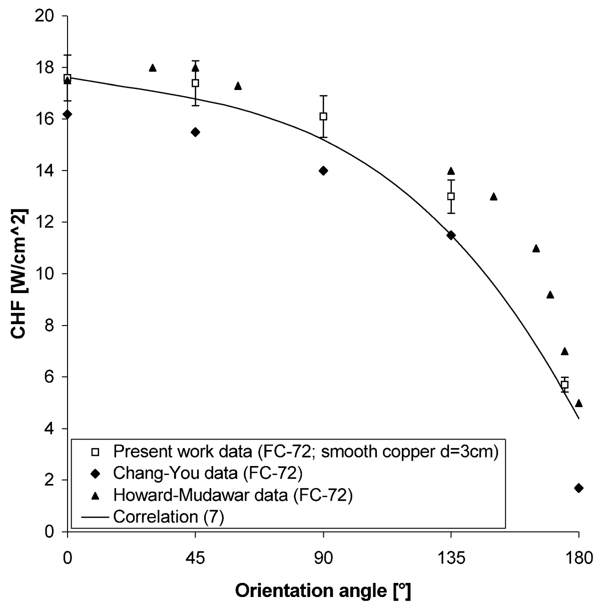
The figure also shows El-Genk and Bostanci's [14] data and correlation:

$$CHF/CHF_{max} = \left[(1 - 0.00127\theta)^{-4} + (3.03 - 0.016\theta)^{-4}\right]^{-0.25} \tag{13}$$

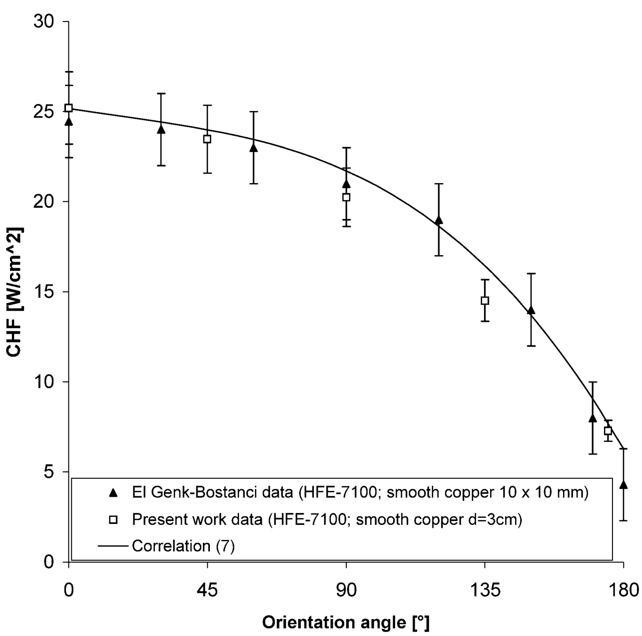
together with some data obtained for fluorinert FC-72 (You [30]).

4. Conclusions

An experimental study on nucleate boiling and critical heat flux of the dielectric fluids FC-72 and HFE-7100 has



(a)



(b)

Fig. 6. Critical heat flux CHF vs orientation angle for FC-72 (a) and HFE-7100 (b).

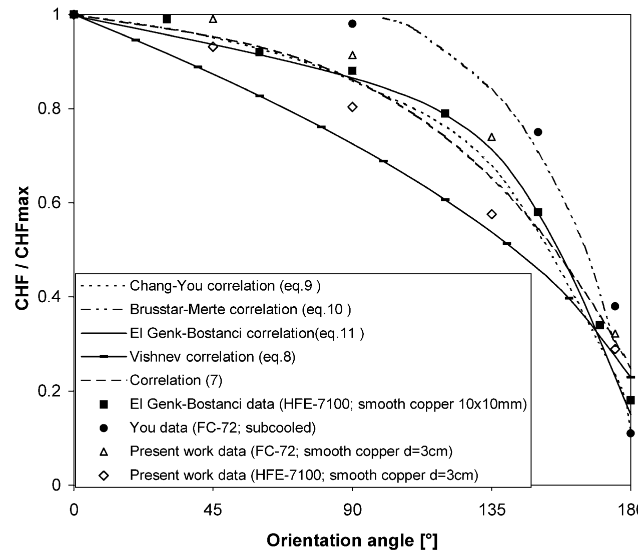


Fig. 7. CHF/CHF_{max} vs orientation angle: correlations and experimental data for FC-72 and HFE-7100 from literature.

been conducted to analyse the effects of surface orientation during saturated boiling at atmospheric pressure from a smooth copper surface. The orientation of the boiling surface strongly influences both the nucleate pool boiling heat transfer coefficient and the critical heat flux. This behaviour is relevant for cooling applications. A comparison has been made between the thermal performances of the two fluids considered.

(1) The influence of the orientation angle on boiling curves substantially varies for different values of heat flux. In the low-heat-flux nucleate boiling region, increasing the surface orientation angle from 0° (upward-facing surface) to 175°, markedly increases the heat transfer coefficient. This behaviour confirms the hypothesis that sensible heat transfer is considerably enhanced by the compulsory removal of the thermal layer as a result of the movement of the rising bubbles across the inclined surface.
For higher heat flux values, the boiling curves almost coincide for angles up to 90°, while for orientation angles greater than 90° (downward-facing surface), the nucleate boiling heat transfer coefficient diminishes markedly as the angle increases. Indeed, in such conditions, the accumulation of vapour bubbles near the surface substantially reduces the heat transfer coefficient.
(2) The experimentally recorded trend in normalized critical heat flux confirms previous findings by other authors. CHF is maximal for horizontal upward-facing surfaces and decreases slowly as the orientation angle increases from 0° to 90°. For downward-facing surfaces, the CHF decreases rapidly as the orientation angle increases towards 180°.
(3) Heat transfer coefficients in the nucleate boiling region and critical heat flux values, respectively, prove to be 25% and 40% higher for HFE-7100 than for FC-72 in the same operating conditions.

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