介電流體 FC-72 在熱傳增強表面之池沸騰特性研究

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摘要

本論文係以實驗方式研究介電流體 FC-72 於熱傳增強表面之飽和沸騰特性，在水平與垂直的加熱面指向性下，探討熱傳增強表面之鰭片陣列的高度、間距及孔穴陣列的密度、直徑與深度對於沸騰起始過熱度、臨界熱通量及熱傳係數的影響，並透過觀測氣泡的生成與脫離，進一步了解熱傳增強結構的沸騰模式。

實驗中所使用的熱傳增強表面分別為小型及微型矩形鰭片陣列（材質為無氧銅）與人工微孔穴陣列（材質為單晶矽），小型與微型矩形鰭片陣列係利用放電加工法製作而成，小型矩形鰭片陣列是在基底面積為 10mm×10mm 的無氧銅上製作出三種鰭片間距（0.5mm、1.0mm 及 2.0mm）與四種鰭片高度（0.5mm、1.0mm、2.0mm 及 4.0mm）的鰭片陣列（鰭片寬度均為 1.0mm）；而微型矩形鰭片陣列係在相同基底面積的銅塊上製作出三種鰭片高度（0.5mm、1.0mm 及 2.0mm）的鰭片陣列（鰭片間距與寬度均為 0.5mm）；最後，人工微成核孔穴表面則以乾蝕刻方式在單晶矽表面蝕刻出三種孔穴直徑（200、100 及 50μm）與兩種孔穴直徑深度（200 及 110μm）的微孔穴，而微孔穴密度分別為 33x33、25x25 及 16x16。所有的實驗工作條件均設定在介電液 FC-72 於一大氣壓下，飽和溫度 56.6℃。

實驗的第一部份探討平滑加熱面於飽和FC-72 的沸騰實驗，其目的是作為增強表面沸騰特性比較時的基準，並與參考文獻中平滑表面沸騰關係式作比較，以驗證本實驗的準確性。結果顯示平滑加熱面有極高的沸騰起始過熱度及明顯的沸騰遲滯現象，而比較沸騰次數的實驗發現，由於表面成核孔穴被活化的結果，後續實驗的起始過熱度明顯降低許多，沸騰曲線亦向左偏移，且臨界熱通量也有些微增加。垂直平滑表面的沸騰起始過熱度較低，這是由於流體受熱後沿加熱面向上流動並持續受到加熱面加熱，因此在加熱面熱邊界層最厚，溫度也較高，因此能較水平面提前沸騰。加熱面指向性對沸騰性能的影響在低熱通量（熱通量低於 9.7 Wcm^{-2}）時最為明顯，垂直平滑表面的熱傳會較水平面好，而在中高熱通量時（熱通量高於 9.7 Wcm^{-2}），其熱傳表現則呈現相反的趨勢，且垂直平滑表面的臨界熱通量亦較水平平滑表面小。

實驗的第二部份探討水平鰭片陣列於飽和FC-72 之飽和沸騰熱傳，其結果顯示鰭片愈高或間距愈小的鰭片陣列，其沸騰起始過熱度愈低，且由流譜的觀察發現，發生沸騰起始的區域多為鰭片的頂端，隨著加熱量的增加，沸騰區域會逐漸擴大，通常都是由鰭片頂端向下擴展。鰭片高度較低的鰭片陣列在中高熱通量區具有較佳的熱傳係數，同時

鰭片間距愈大，趨勢愈明顯。此外，間距0.5mm且高度4mm的鰭片陣列，其熱傳係數並不隨熱通量的升高而增加，在中高熱通量區，其熱傳係數保持在一固定值，而其它低深寬比的鰭片陣列，熱傳係數則是隨著熱通量升高而增加，到了高熱通量區，熱傳係數會有一最大值，之後會隨熱通量增加而遞減。間距0.5mm且高度4mm的鰭片陣列其基底面積臨界熱通量（$9.8\times10^{5}\ \mathrm{Wm}^{-2}$）為平滑加熱面的5倍。

第三部份主要探討垂直鰭片陣列於飽和FC-72的沸騰實驗，由飽和沸騰曲線中發現垂直鰭片陣列的起始過熱度均較水平陣列表面低，當沸騰起始時，鰭片陣列上僅有部分表面有汽泡產生，大部分的表面仍處於自然對流狀態，且汽泡的生成大部分皆位於鰭片朝下的底面。經由流譜的觀察發現，垂直增強面上水平延伸出去的鰭片陣列，會對沿加熱壁面向上流動的脫離汽泡造成流動的阻抗，造成在高熱通量狀態下，其熱傳性能的降低，此現象在較密或較高的鰭片陣列最為顯著。間距0.5mm且高度4mm的鰭片陣列其基底面積臨界熱通量（$89.6\mathrm{Wcm}^{-2}$）為平滑加熱面的4倍。

實驗的第四部份探究微型鰭片陣列於飽和FC-72之飽和沸騰熱傳特性，由飽和沸騰曲線中發現，微型鰭片陣列的起始過熱度與溫度偏移均較小型鰭片陣列小且較不明顯，而沸騰熱傳衰減的現象則提前發生在中低熱通量區，此外，實驗結果顯示鰭片微形化與緊密的鰭片陣列並未造成其熱傳量的衰減。

最後部份則以實驗探討FC-72在人工微孔穴陣列的飽和沸騰熱傳特性與汽泡的生成、成長與脫離過程，結果顯示矽基加熱面的沸騰起始過熱度與溫度偏移均較金屬基材的加熱面高且明顯，而孔穴密度對沸騰熱傳性能的影響在高熱通量區最為顯著，臨界熱通量會隨著孔穴密度的增加而提昇，而提昇的幅度會隨孔穴密度的增加而降低。在中低熱通量區，孔穴直徑的影響可以忽略，而在高熱通量區，孔穴直徑的增加會造成熱傳係數的提前衰減。

關鍵字：飽和池沸騰、流譜、鰭片表面、微孔穴表面、沸騰起始過熱度、沸騰遲滯、臨界熱通量

Experimental Study of Pool Boiling Heat Transfer of Dielectric Fluid FC-72 on Enhanced Surfaces

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ABSTRACT

Measurements have been conducted to investigate the saturated pool boiling heat transfer of dielectric fluid FC-72 on thermal enhanced surfaces. Besides, the geometric parameters (including fin spacing, fin length, cavity density, cavity diameter, and cavity depth), orientations, and associated flow pattern observation of bubbles on tested surfaces are also examined in present study.

There are three kinds of thermal enhanced surfaces studied in present study including mini finned surfaces, micro finned surfaces, and artificial micro-cavity surfaces. The mini finned surfaces are manufactured on a 10mm×10mm base area copper block with three fin spacing (0.5mm, 1.0mm and 2.0mm) and four fin lengths (0.5mm, 1.0mm, 2.0mm and 4.0mm). The micro finned surfaces are designed that 10×10 micro fins with one fin spacing (0.5mm) and three fin lengths (0.5mm, 1.0mm and 2.0mm) on a 10mm×10mm base area. Finally, the artificial micro-cavity surfaces are respectively manufactured on a 625μm thick and 10mm×10mm square silicon plate. The treated cavities are all cylinders with three diameters 200, 100 and 50μm and two depth 200 and 110μm. All experiments are performed test surfaces immersing in FC-72 with saturated state and 1 atmospheric condition.

In the first part of present study, the characteristics of saturated pool boiling heat transfer for dielectric fluid FC-72 on a plain surface are investigated experimentally. Specially, the data for the boiling incipience temperature, CHF value, saturated boiling heat transfer coefficient affected by the numbers of the test run and orientation are to be examined in detail. Moreover, the test results are compared with the empirical correlations of reference literatures to verify the accuracy of present pool boiling experiment. The test results indicate the higher boiling incipience and lower CHF value for a new plain surface at first test run and slightly improvement at last two test runs. The nucleate boiling curves base on horizontal and vertical orientation can be subdivided into the different regions: low heat flux (up to 9.7 Wcm^{-2}) and high heat flux (greater than 9.7 Wcm^{-2}) regions which are consistent with the results of literature. In low heat flux region, the nucleate boiling heat transfer performance of plain surface on vertical orientation is found better than horizontal orientation due to the facilitating convective heat transfer by the movement of bubbles drift along the vertical surface. However, in low heat flux region, vapor bubble departure behaviors obstruct the heat transfer and result worse boiling and CHF performance.

In second part of this study, the flow patterns and pool boiling heat transfer performance of copper rectangular finned surfaces that immersed in saturated FC-72 are experimental investigated. The effects of geometric parameters (fin spacing and fin length) are also examined. The photographic images show that different boiling flow patterns among the test surfaces with varied heat flux. The photographic images also indicate that closer fin spacing or longer fin length yield a greater flow resistance to obstruct the bubble/vapor lift off in adjacent fins. Moreover, as the heat flux approach to CHF, numerous vapor mushrooms periodically extruded from the perimeter of fin array are observed. This mechanism will cause the dry-out situation in the central part of fin array. The closer fin spacing and longer fin length can provide larger heat transfer. However, the results also demonstrate that early decay on overall heat transfer coefficient as the fin spacing is closer or fin length is longer. The maximum value of CHF on base area is 9.8×10^{5} Wm^{-2} for the test surface with 0.5mm fin spacing and 4.0mm fin length which is 5 times that of the plain surface.

In third part of this study, the experimental study are conducted to investigate the flow patterns and pool boiling phenomena of copper rectangular finned surfaces in vertical orientation, which is simulate the heat sink immersed in saturated dielectric fluid FC-72. The effects of fin length and fin spacing are also examined. The photography observations show that initial boiling generally occurred at the downward-facing surfaces of fins and fin spacing will induce the flow resistance to vapor in lift-off process. The results also indicate that, decreasing the fin spacing or increasing the fin length substantially raise the critical heat flux. Moreover, the closer fin spacing and longer fin length also show that the significant decay on overall heat transfer coefficient in nucleate boiling region. The maximum value of CHF on base area is 89.6Wcm^{-2} for the test surface with fin spacing 0.5mm and fin length 4.0mm, which was 4 times greater than that of plain surface.

In fourth part of this study, the flow pattern and pool boiling heat transfer performance for rectangular micro-fin array heat sinks are investigated. The effects of the variables such as fin length, orientation are also examined. The measurement data show that the boiling incipience superheat of micro-finned surfaces is relatively low for both orientations and the temperature excursions of boiling curves are quite unclear. Moreover, the incipience superheat and temperature excursion of micro-finned surfaces are significantly lower than those of mini-finned arrangements. The heat transfer rate of micro-finned surfaces is similar to that of mini-surfaces which having the same overall heat transfer area. Furthermore, the boiling curves are affected by the orientation arrangements. For low profile finned surfaces, there is a negligible difference of nucleate boiling at high heat flux region. However, for high profile finned surfaces at low heat flux region, the boiling heat transfer performance is comparable. The decline behavior in heat transfer coefficients for present test surfaces are shift to lower heat flux region than that of mini finned surfaces due to the larger flow resistance to the re-wetting liquid and departure bubbles.

In fifth part of this study, the artificial micro-cavity surfaces with different geometric

parameters and orientations are tested for investigating the boiling characteristics. The results indicate that boiling incipience superheat and temperature excursions of silicon based surfaces are more significant and higher than those of metal based surfaces. The effects of cavity density are stronger at high heat flux region than that in low heat flux region because of the bubble/vapor coalescence in adjacent cavities. The critical heat flux is dependence on the cavities density and the CHF enhancement is almost proportional to the area enhancement of the cavity surfaces. The influence of the cavity diameter in heat transfer coefficients during low heat flux region that below 8×10^{4} Wm^{-2} can be ignored. In moderate and high heat flux region, larger cavity diameter surface show that earlier decay and lower peak value in boiling heat transfer coefficients. Increasing the depth of cavities will result premature rapid decline of overall heat transfer coefficients due to the larger flow resistance of deeper cavities obstruct the re-wetting liquid entering the these cavities. Comparison between boiling characteristics on two orientations shows significant decrease in CHF with the vertical orientation due to the vapor coalescence along the heating surface, vapor trapped inside the cavities and dry-out situation inside the cavity on vertical heating surface.

Keywords: Saturated pooling boiling, Flow pattern observation, Mini-finned surface, Micro-finned surface, Micro-cavity surface, Boiling hysteresis, Boiling incipience superheat, Temperature excursion, Critical heat flux.

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NOMENCLATURE

A - area (m^{2})
Bo - Bond number
CHF - critical heat flux (W m^{-2})
C_P - specific heat (W kg^{-1} K^{-1})
C_{sf} - constant of the modified Rohsenow’s correlation
D_d - bubble departure diameter (mm)
d_c - diameter of the artificial cavity (µm)
f - bubble departure frequency (s^{-1})
g - gravitational acceleration (m s^{-2})
H_c - depth of the artificial cavity (µm)
I - current (A)
i_{lv} - latent heat of vaporization (J kg^{-1})
Ja - Jacob number
k - thermal conductivity (W m^{-1} K^{-1})
L - fin length (mm)
h - heat transfer coefficient (W m^{-2} K^{-1})
M - molecular weight of liuid
m - exponent of the cooper’s correlation
n - numbers of fins
Pr - Prandtl number
P - pressure (Pa)
$\dot{Q}$ - heat transfer rate (W)
q'' - heat flux (W m^{-2})

R_a - surface roughness (μm)

r - exponent of the modified Rohesnow's correlation

S - fin spacing (mm)

s - exponent of the modified Rohesnow's correlation

T - temperature (K)

T_m - temperature (K)

ΔT - wall superheat (K)

V - voltage (V)

W - fin width (mm)

Greek Symbols

α - aspect ratio of the fin (L/S)

β - coefficient of thermal expansion (K^{-1})

ϑ - dimensionless surface roughness parameter

θ - surface inclination angle from horizontal upward position (^{o})

ρ - density (kg m^{-3})

σ - surface tension (N m^{-1})

Subscripts

b - base surface area

c - cavity surface

CHF - critical heat flux

crit - critical condition

ext - base on extended surface

f - finned surface

l - saturated liquid

mc - micro convection

nc - natural convection

p - plane surface

sat - base on saturation condition

sub - subcooled condition

sys - system or total

t - overall finned surface area

v - saturated vapor

w - wall

Z - Zuber’s critical heat flux correlation