INTERNATIONAL JOURNAL OF REFRIGERATION 32 (2009) 235–245

available at www.sciencedirect.com

journal homepage: www.elsevier.com/locate/ijrefrig

HFE-7100 pool boiling heat transfer and critical heat flux in inclined narrow spaces

*M. Misale**, *G. Guglielmini*, *A. Priarone*

DIPTEM, Sezione di Termoenergetica e Condizionamento Ambientale, Università degli Studi di Genova, Via all'Opera Pia 15a, 16145 Genova, Italy

ARTICLE INFO

Article history:
Received 5 September 2007
Received in revised form 9 May 2008
Accepted 11 June 2008
Published online 20 June 2008

Keywords:
HFE-7100
Secondary refrigerant
Experiment
Heat transfer
Critical heat flux
Pool boiling
Geometry
Channel

ABSTRACT

Experiments were performed to examine the pool boiling heat transfer and critical heat flux on a smooth copper circular surface, confined by a face-to-face parallel unheated surface, by changing both the orientation and the gap between the surfaces. Pool boiling data at atmospheric pressure were obtained for saturated HFE-7100. The gaps between the boiling surface and adiabatic one were 0.5, 1.0, 2.0, 3.5, 5.0, 10.0 and 20.0 mm. For each configuration, boiling curves were obtained up to the thermal crisis. The surface orientations investigated were 0° (horizontal upward surface), 45°, 90° and 135°. It was observed that the heat transfer coefficient improves at low wall superheat when the distance between heated and unheated surfaces decreases. However, at high wall superheat, a drastic reduction in heat transfer as well as CHF appears for confined boiling. For a fixed channel width, the CHF value strongly depends on the channel orientation, assuming a maximum value for near-vertical channels with up-facing heated surface. CHF data were compared with various literature correlations; a new empirical correlation that takes into account channel gap effects is proposed for horizontal confined surfaces.

HFE-7100 : transfert de chaleur lors de l'ébullition libre et flux critique dans les espaces inclinés

Mots clés : HFE-7100 ; Caloporteur ; Expérimentation ; Transfert de chaleur ; Flux critique ; Ébullition libre ; Géométrie ; Canal

1. Introduction

The effects of surface orientation and channel width on confined pool boiling heat transfer and critical heat flux have aroused increasing attention in recent years because of the potential benefits deriving from the use of pool boiling as a very efficient means of thermal control in several applications.

The nucleate pool boiling of dielectric fluids is often applied in thermal systems to remove heat, while keeping surface superheat relatively low. It offers several advantages: (a) low saturation temperatures; (b) good thermal contact with

* Corresponding author. Tel.: +39 010 3532576; fax +39 010 311870.
E-mail address: misale@diptem.unige.it (M. Misale).
0140-7007/$ – see front matter
doi:10.1016/j.ijrefrig.2008.06.003

Nomenclature

Bo	Bond number = s/L [–]
CHF	critical heat flux [$W\,cm^{-2}$]
d	boiling surface diameter [m]
D_h	equivalent heated surface diameter [m]
f	friction factor [–]
g	acceleration of gravity [$m\,s^{-2}$]
h	heat transfer coefficient [$W\,m^{-2}\,K^{-1}$]
h_{lv}	latent heat of vaporisation [$J\,kg^{-1}$]
l	characteristic length [m]
L	capillary length [m]
q''	heat flux [$W\,cm^{-2}$]
s	channel width [m]
T_{sat}	saturation temperature [K]
T_w	surface temperature [K]
ε	mean absolute error
λ	fraction of data predicted in the range ±30%
θ	orientation angle [°]
ρ_l	liquid density [$kg\,m^{-3}$]
ρ_v	vapour density [$kg\,m^{-3}$]
σ	surface tension [$N\,m^{-1}$]
ψ	Eq. (4)
ΔT_{sat}	wall superheat = $T_w - T_{sat}$ [K]

all components, even in narrow spaces; (c) excellent chemical compatibility with many materials; (d) low toxicity and good environmental characteristics.

Confined pool boiling has become a research subject of great importance as it is frequently encountered in many practical situations, such as high-performance compact heat exchangers and electronic component cooling. The effects of confinement on pool boiling depend on a complex interaction among geometry, channel width, heat flux and fluid properties. Channel orientation is also important when the main effect of the unheated surface of the channel is to cut off the trajectory of vapour bubbles after their departure from the boiling surface.

This paper reports an experimental study on the pool boiling of HFE-7100, a hydrofluoroether dielectric fluid ($C_4F_9OCH_3$) which has recently been proposed to replace FC-72 (C_6F_{14}), owing to its better environmental characteristics (lower global warming potential). The effects of heated surface orientation for a fixed value of channel width were systematically investigated: starting from the horizontal orientation (upward), the surface angle θ was fixed at 45°, 90° and 135°. Different channel widths s were analysed: 20, 10, 5, 3.5, 2, 1 and 0.5 mm.

2. Previous works

2.1. *Unconfined pool boiling: surface orientation effects*

The first studies on the effect of surface orientation on unconfined pool boiling date back to the 1960s and 1970s (Marcus and Dropkin, 1963; Githinji and Sabersky, 1963; Chen, 1978). Nishikawa et al. (1983) carried out a detailed study on the nucleate boiling of water at atmospheric pressure on a rectangular copper plate (175 × 42 mm) with different orientations ($\theta = 0° - 175°$). They tried to give a phenomenological interpretation of their experimental data. The fact that surface orientation seemed to affect only low heat fluxes was attributed to two different mechanisms associated with nucleate boiling on inclined surfaces: the sensible heat transport due to removal of the superheated thermal layer from the surface by the rising bubbles, and the latent heat transport due to the evaporation of the thin liquid film underneath the rising bubbles; the former is strongly influenced by orientation, while the latter is independent of orientation. At low heat fluxes, evaporation is weak and so the agitation mechanism is predominant, while at high heat fluxes evaporation becomes more important. Chang and You (1996, 1997) studied the effects of the inclination angle θ on the saturated nucleate boiling of FC-72 on two smooth (10 × 10 mm and 20 × 20 mm) copper surfaces. They reported an increase in nucleate boiling heat flux as θ increased from 0° to 45°, but a decrease for $\theta > 45°$. Recently El-Genk and Bostanci (2002) analysed the saturated boiling of HFE-7100 on a smooth, 10 × 10 mm copper surface; Priarone et al. (2004) and Priarone (2005) compared boiling heat transfer performances of FC-72 and HFE-7100 dielectric fluids on varying the orientation angle of a smooth copper surface (30 mm diameter). The results obtained confirmed some of the effects reported in the literature: in the low heat flux nucleate boiling region, the heat transfer coefficient increases markedly with the orientation angle; for higher heat flux values, the effect of orientation 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°.

2.2. *Confined pool boiling: surface orientation effects*

With regard to the confinement effects, the first studies date back to the end of the 1960s. Ishibashi and Nishikawa (1969) studied the nucleate boiling of water and ethyl alcohol in vertical annuli at pressures from 1 (channel width 1–20 mm) to 10 atm (channel width 0.6–2 mm). Later, Katto et al. (1977) studied the boiling of saturated water at atmospheric pressure on a horizontal upward-facing circular copper surface (11 mm diameter) confined by a parallel glass surface (channel width down to 0.1 mm). These experiments were performed from nucleate boiling region up to transition boiling in the relatively high heat flux region. They revealed significant effects of confinement both at low heat flux (increment of heat transfer performance on decreasing the channel width) and CHF (reduced CHF values decreasing the channel width). Yao and Chang (1983) analysed the boiling of R-113, acetone and water at 1 atm in vertical narrow annuli with closed bottoms (heights of 25.4 and 76.2 mm and channel widths of 0.32–2.58 mm). Bonjour and Lallemand (1997) studied the combined effect of confinement (0.3–2.5 mm) and pressure (1–3 bar) on the critical heat flux of R-113 in vertical channels: they noted a reduction in CHF on decreasing channel width at all pressures investigated. Subsequently, these Bonjour and Lallemand (1998) analysed flow patterns during the boiling of R-113 in narrow vertical spaces, and observed three different boiling regimes: nucleate boiling with isolated bubbles, nucleate boiling with coalesced bubbles and partial dryout; they also