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Effect of space distance for boiling heat transfer on micro porous coated surface in confined space

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ABSTRACT

This work provides an experimental analysis of the boiling heat transfer of methanol on plain and micro porous coated surfaces inside confined space. Three space confinements with distance of 1.0, 2.0, 3.0 mm and an unconfined space were tested on plain and micro porous coating surfaces. Effects of space confinement, surface treatment and heat flux on the heat transfer coefficient and critical heat flux were discussed. From the test results, we may deduct that the boiling heat transfer performance in confined spaces was affected by four major effects, i.e. (a) vapor blowing and liquid suction effect, (b) thin film evaporation, (c) vapor leaving resistance and (d) partial dryout effect on plain surface. But only (a) and (c) are important on micro porous coating surface. The combination of these effects resulted in the micro porous to plain surfaces heat transfer enhancement ratio to have different characteristics at low, moderate and high heat flux conditions. Micro porous coating is a very effective boiling heat transfer enhancement treatment at low and moderate heat fluxes conditions. The enhancement ratio reduced in very narrow space confinement or at very high heat flux condition.

1. Introduction

Owing to the rapid development of semiconductor industry, the heat dissipated from electronic devices increases drastically with increasing device logic gate number and operation speed. The maximum power dissipation is expected to reach 150 W in the near future. Most of the heat is generated from a small area of the so-called hot spot where the heat flux can be as high as 500 W/cm^2. Traditional direct air cooling methods would not be able to accommodate this high heat flux owing to their space limitation [1]. The cooling technologies have undergone evolutionary changes from air-cooled fin geometry to copper base and vapor chamber heat spreader. More thorough methods such as forced convective liquid cooling and two-phase evaporating cooling have been explored in recent years. Attributed to its high heat transfer coefficient, evaporating cooling involving the use of micro heat exchangers is considered a possible thermal management solution for cooling of high heat flux electronic devices. The desire to develop high-performance micro heat exchangers operating in the evaporation regime provides a major motivation for the present work.

The boiling heat transfer in micro heat exchangers is generally confined in a very narrow space. The heat transfer characteristics are indeed different from those of conventional unconfined boiling. Several studies have been conducted for boiling heat transfer in confined space with various space heights and heat fluxes [2–10]. Three boiling regimes were observed by Yao and Chang [2] and Bonjour and Lallemand [3], i.e., isolated deformed bubbles, coalesced bubbles and partial dryout at low, moderate and high heat flux respectively. At low and moderate heat flux, the heat transfer was enhanced by an expanded area liquid layer under the bubbles and the forced removal of the superheated liquid due to the bubble departure. However, the heat transfer degraded by the delay of bubble departure and the early dryout of the heater wall at high flux condition [4].

Yao and Chang [2] observed flow regimes for confined boiling of water, acetone and R-113 in annular space with distances 0.32, 0.80 and 2.58 mm. Isolated deformed bubbles and coalesced deformed bubbles occur for small gaps at low heat fluxes and moderate heat fluxes respectively. Those two regimes resulted in a heat transfer enhancement. Dryout regime was observed while the heat flux closed to the CHF. Nucleate boiling with slightly deformed bubbles took place in the large gap size annulus at high heat fluxes.

Bonjour and Lallemand [3] used hot-wire anemometry to detected the flow regime of R-113 at atmospheric pressure in confined spaces with gap size 0.5, 1.0, and 2.0 mm. Three boiling regimes were observed, i.e., isolated deformed bubbles, coalesced bubbles and partial dryout at low, moderate and high heat fluxes respectively. Both first regimes resulted in a heat transfer enhancement whereas the latter implied a heat transfer deterioration. At low heat flux conditions, bubbles were squeezed in the narrow channel and the thin layer of liquid between the wall and the base

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Nomenclature

A	heat transfer area (m^2)
A_b	cross section area of heating block (m^2)
Bo	Bond number, $Bo = s/[\sigma/g(\rho_l - \rho_v)]^{1/2}$ (dimensionless)
g	gravity (m/s^2)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
L_i	distance from thermocouple to the heating block (m)
q	heat transfer rate (W)
q''	heat flux (W/m^2)
s	confined space distance (m)
t	plate thickness (m)
T_c	bottom heating wall center temperature (°C)
T_i	local wall temperature (°C)
T_s	saturation temperature (°C)
T_w	top wall center temperature (°C)
ΔT_{sat}	superheat temperature (°C)

Greek symbols

ρ_v	density of vapor (kg/m^3)
ρ_l	density of liquid (kg/m^3)
σ	surface tension (N/m)

of the bubble was enlarged which resulted in the heat transfer enhanced with decreasing the confined space. However, at high heat flux conditions, heat transfer deterred and CHF occurred while the confined space decreased. A new flow pattern map for confined boiling, based on the Bond number and a reduced heat flux (ratio of the heat flux to the critical heat flux), has been developed in order to determine the regimes.

Ishibashi and Nishikawa [5] conducted a series of experiments on the boiling heat transfer in confined spaces with gap sizes from 0.97 to 20.0 mm and an unconfined space with equivalent size of 82.5 mm. The tested heat flux varied from 0.82 to 67.3 kW/m^2. Their test results showed that the boiling regime in narrow spaces can be classified as isolated bubble and coalesced bubble depending on the space dimension and boiling pressure. By following the reducing of the space distance, the boiling regime changed from isolated bubble to coalesced bubble and then to liquid deficient regime. A thin liquid film on the heating surface was found in the coalesced bubbles regime. It significantly enhanced the heat transfer performance in comparing to that in the isolated bubble regime. The heat transfer coefficient increased with decreasing space distance.

Katto et al. [6] observed the boiling phenomenon of water in confined spaces with range from 0.1 to 2.0 mm and heat flux from 116 to 1510 kW/m^2. They found that the boiling heat transfer performance in 2.0 mm is almost identical to that in unconfined space beside the early appearance of critical heat flux. The heat transfer coefficient increased with decreasing space distance at low heat flux attributed to the rapid evaporation of a thin liquid formed on the heated surface at the bubble bottom. However, the heat transfer coefficient decreased with decreasing the distance at high wall heat flux due to the partial dryout on the heating surface.

Fujita et al. [7] tested water at atmospheric pressure in confined spaces with gap sizes of 0.15, 0.6, 2.0 and 5.0 mm. They found that the heat transfer coefficient increased up to a certain maximum value with decrease of the gap size at moderate heat flux, while degradation occurred for a further decrease of the gap size over the entire heat flux range. The high heat transfer rate was achieved in large gaps due to the two-phase mixture agitation in a narrow space. In the moderate gaps, highly enhanced heat transfer was attributed to the liquid film evaporation. Most of the heating surface was steadily covered with vapor in small gap sizes, and retarded its heat transfer. Lee et al. [8] measured water and dilute aqueous sodium lauryl sulfate (SLS) solutions within a confined space with gap size from 0.1 to 10 mm. Their experimental results showed that the heat transfer coefficient increased up to a certain maximum value with decreasing gap size. It agreed well with the result by Fujita et al. [7]. The heat transfer coefficients in the gap of sizes between 0.3 and 3 mm increased to as much as 200% of those measured for conventional pool boiling. Based on the experimental results, the micro-layer evaporation with fluid flow driven by the gradient of disjoining pressure was discussed and considered as an important heal transfer mechanism for nucleate pool boiling in confined spaces.

Misale et al. [9,10] used the Bond number as the criterion for analyzing the confinement gap effect. At low heat flux, the effect of confinement was not significant if $Bo > 1$, but for $Bo \leqslant 1$ the heat transfer coefficient increased as the channel width decreased. They attributed the heat transfer enhancement to the liquid film evaporation which the same as that described by Katto et al. [6]. At high heat flux, vapor trapped between the heating surface and the confined surface, a drastic reduction in both heat transfer and CHF was seen when the channel width decreased.

Numerous enhancement techniques for improving the boiling heat transfer performance involving tube surface treatment have been developed in the past decades [11]. Porous coating surface was proved as one of the surfaces that obtained the most heat transfer enhancement performance. Yang and Fan [12] and Fan and Yang [13] found that the heat transfer mechanism for porous tubes is majorly due to increasing bubble density and frequency. It is perhaps an appropriate method for boiling heat transfer enhancement in micro heat exchangers.

Micro-porous coatings are extra-thin porous coatings having layer thicknesses that are less than the superheated liquid layer thickness for activation of the cavities during nucleation [14]. O'Connor and You [15] applied silver flakes consisting of particles of diameters varying from 3 to 10 μm on heating surface. The coating was found to enhance pool boiling in saturated FC-72 with almost 80% reduction in nucleate boiling superheat and a 109% increase in the CHF limit over the non-painted surface. O'Connor et al. [16] used fine diamond particles of diameters varying from 8 to 12 μm to develop a dielectric paint. When applied on a silicon chip, they obtained an enhancement of nearly 24% in the CHF limit. Chang and You [17] studied the nucleate boiling heat transfer and CHF for uncoated and coated surfaces using micro-porous coatings made of copper particles (1–50 μm) and aluminum particles (1–20 μm). For both aluminum and copper micro-porous coatings, approximately 80% reduction in incipient superheat, 330% enhancement in nucleate boiling heat transfer, and 100% enhancement in CHF were found relative to an uncoated surface. Chang and You [14] also investigated the effects of particle size on the boiling performances of micro-porous coatings using different sizes of diamond particles. They observed an increase in both the nucleate boiling heat transfer and the CHF with decreasing particle size due to increased number of nucleation sites.

Dizon et al. [18] performed an experimental study involving the use of metallic micro-porous coatings for enhancing boiling heat transfer on the outer surface of a hemispherical vessel. They found that the use of an aluminum micro-porous coating could result in local CHF enhancement of 42–112% for different angular locations along the vessel wall. A subsequent study by Yang and Cheung [19]