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Experimental investigations and a simplified model for pool boiling on micro-fins with sintered perforated foil

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ABSTRACT

The paper presents experimental data for two kinds of copper enhanced surfaces: micro-fins with sintered perforated foil (MFP, hole diameter 0.05–0.3 mm) and a micro-fin structure without a covering (MF). The experiments were carried out for water and FC-72 at atmospheric pressure. Micro-fins of 0.5 and 1 mm in height were uniformly spaced on the base surface. At all heat fluxes for water and low heat fluxes (below 25 kW/m^2) for FC-72, surfaces with micro-fins covered with perforated foil produced the highest heat transfer coefficient. Maximum heat flux from the MFP surface increased 130% for water and 75% for FC-72 in relation to the smooth surface.

The results for both working fluids were compared in terms of the dimensionless Bond number.

The simplified model was proposed for determining total heat flux for the studied surfaces. It was assumed that the structure formed a system of connected perpendicular horizontal tunnels between the micro-fins confined by a top porous covering. The heat fluxes were determined for evaporation in the tunnels and for convection on the perforated foil based on the calculated departure bubble parameters (diameter, nucleation sites density, frequency). The predicted heat fluxes, when compared with the experimental results, showed satisfactory agreement for boiling water at medium and high superheats.

1. Introduction

A growing demand for miniaturization of mechanical and electronic components has prompted the search for more efficient cooling technologies able to prevent temperature overshoot. The phase change accompanying boiling and condensation processes can be used to obtain the highest heat flux at a small temperature difference between the heating surface and the working fluid on a small heat removal surface.

The proposed surfaces with perforated foil-covered micro-fins combine advantages of both classical tunnel-pore structures and enhanced surfaces, and can be considered a cheaper alternative to pricier surfaces with nanostructures that have recently been studied extensively. Tunnels coated with a perforated foil or a mesh produce high heat transfer coefficients. The technology involves joining (typically by soldering) the base surface to the upper perforated or porous structure. Owing to relatively high manufacturing precision and the repeatability of measurements, a large number of boiling models have been developed for these surfaces, particularly with regard to the *suction–evaporation* mode of boiling.

Forerunners of research on tunnel-pore structures, Nakayama et al. [1], used tunnels of rectangular cross-sections with triangular pores. They found that the surface pores of about 0.1 mm in size (equivalent to the inscribed circle diameter) ensured the best heat transfer enhancement for the boiling of water, R-11 and liquid nitrogen. They did not report the effect of pore pitch, tunnel size or shape on heat transfer coefficient values. Arshad and Thome [2] studied flat surfaces similar to those used by Nakayama et al. [1], but the structures had rectangular, triangular and circular cross-sections. The range of pore diameters was 0.15–0.25 mm and the working fluid was water. The structure with pores of 0.25 mm diameter provided the optimum heat transfer enhancement. Ma et al. [3] analyzed boiling heat transfer for water and methanol on surfaces with parallel grooves with rectangular, triangular or rectangular/triangular cross sections, covered with a wire mesh or, additionally, a plate with pores 220, 160 and 80 mm in diameter. The optimum diameter for boiling water was 160 μm. The experiments described by Chien and Webb [4,5] were carried out for R-11 and R-123 on surfaces with tunnels 0.5–1.5 mm in height, 0.25–0.4 mm in width and fin tips wrapped in foil with 0.12–0.28 mm diameter pores. The pores 0.23 mm in diameter

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Nomenclature

Bo	Bond number
CHF	critical heat flux
C_{1-2}	growth period constant
c	specific heat at constant pressure, J/kg K
DHF	dry-out heat flux
d	diameter, mm
f	frequency, Hz
h	micro-fin height, mm
i_{lv}	latent heat of vaporization, J/kg
L	capillary length, mm
l	distance, mm
MF	surface code (micro-fin)
MFP	surface code (micro-fin with perforated foil)
m	fin parameter, m^{-1}
n	nucleation site density, m^{-2}
p	pitch, mm
q	heat flux, kW/m^2
$q+$	increasing heat flux
r	radius of the meniscus, mm
s	distance between micro-fins, mm
T	temperature, K
t	time, s
W	working fluid code (water)
FC	working fluid code (Fluorinert FC-72)
w	width, mm

Greek symbols

α	heat transfer coefficient, kW/m^2 K
δ	thickness, mm
Δt	period, s
ΔT	superheat referred to the micro-fin base, K
λ	thermal conductivity, W/m K
ρ	density, kg/m^3
σ	surface tension, N/m

Subscripts

0–1	waiting
1–2	growth
1,2, ..., 8	thermocouple number
b	departing bubble
bs	base
Cu	structure material (copper)
d	connected with pore diameter
ex	external
exp	experimental
l	liquid
m	mean
p	pore
p1	pore pitch direction
p2	pore pitch direction
s	smooth
th	thermocouple
theor	theoretical
tip	micro-fin tip
tun	tunnel
v	vapor

provided highest values of the heat flux. Pastuszko [6] presented comprehensive experimental investigations of boiling heat transfer from a tunnel-pore structure formed with 5 mm high fins. For water and ethanol, the smallest of the pores investigated, i.e., 0.3 mm gave the highest heat transfer coefficient.

Developed in the 60s of the 20th century, research devoted to finned surfaces in terms of their boiling heat transfer application potential has found that mini- and micro-fin arrays increase the heat transfer area and the density of nucleation sites, expand the range of heat fluxes removed and shift the nucleate boiling crisis toward higher heat flux values. Several experimental studies have been proposed involving pool boiling on micro-fins arrays. Rainey and You [7] analyzed pool boiling from plain and microporous pin fins in saturated FC-72. Pool boiling of FC-72 on square pin fin arrays was experimentally studied by Gugliemini et al. [8]. Their surfaces had 3 or 6 mm long fins, uniformly or non-uniformly spaced on the base surface. Yu and Lu [9] focused on FC-72 boiling heat transfer from a system of 1 mm thick mini-fins, at variable interfin space widths (0.5–2 mm) and heights (0.5–4 mm). The heat transfer coefficient decreased with decreasing gaps between the fins and with the increase in their height. Chan et al. [10] reported the results from their studies of finned surfaces for boiling at low pressures (2 and 9 kPa) and fins 0.75–15 mm high and 0.5–2 mm wide. Honda et al. [11], Wei and Honda [12] and Wei et al. [13] studied boiling heat transfer for FC-72 on micro-fins manufactured by dry etching directly on silicon semiconductor wafers with dimensions $10 \times 10 \times 0.5$ mm^3. The cross-sections did not exceed 50×50 μm^2 and the heights were up to 270 μm, which provided a fourfold increase in the maximum heat flux value. In their review of microstructures (micro-fins, micro-recesses, tunnel-pore structures, porous and rough structures, etc.), Honda and Wei [14] noticed that compared with a smooth surface, microstructures contribute to the extension of the vapor bubble residence time, which is one of the factors that determine boiling heat transfer intensification. Pastuszko [15] conducted experimental investigations of pool boiling heat transfer on micro-fin arrays covered with a copper wire mesh. The wire mesh with aperture of 0.32, 0.4 and 0.5 mm sintered with the fin tips formed a system of connected perpendicular horizontal tunnels. Structures with micro-fins 1 mm high presented the best boiling heat transfer performance for water at all the heat fluxes used and at the medium and highest heat fluxes for FC-72.

Microchannels, in addition to narrow channels, have been widely used for the enhancement of flow boiling heat transfer. Over the last several years, many research studies analyzing pool boiling on such surfaces have been published [16–18]. Applying narrow channels is a relatively simple enhancement method, in which the width of the space (channel) relative to the configuration and size of the surface, the type of the boiling liquid, and the range of the applied heat fluxes have to be selected experimentally. These types of surface arrangement can be used for cooling electronic subassemblies or in micro-heat exchangers [19,20].

Enhanced surfaces are now being studied in terms of their potential for use in pool and flow boiling. The most often used are microstructures or micro-recesses formed on the walls of narrow channels [21,22].

The article focuses on the comparison of boiling efficiency of enhanced structures in the form of micro-fins (0.5/1.0 mm in height) with and without a perforated covering. The purpose of the study was to find the optimal diameter of pores in the foil sintered to the micro-fin tips for the highest heat transfer coefficient. The authors also proposed the simplified model for heat flux deter-