International Journal of Thermal Sciences 125 (2018) 197–209

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Pool boiling heat transfer on micro-fins with wire mesh – Experiments and heat flux prediction

Robert Pastuszko

Faculty of Mechatronics and Mechanical Engineering, Kielce University of Technology, Al. Tysiąclecia P.P.7, 25-314 Kielce, Poland

ARTICLE INFO

Keywords:
Pool boiling
Enhanced structure
Micro-fins
Wire mesh

ABSTRACT

The article presents experimental data for two kinds of enhanced surfaces: a micro-finned structure without a covering (MF) and micro-fins covered with a copper wire mesh (MFM). The experiments were carried out for water, ethanol and FC-72 at atmospheric pressure. Micro-fins of 0.5/1 mm in height were uniformly spaced on the base surface. The wire mesh with apertures of 0.32, 0.4 and 0.5 mm was sintered with the micro-fin tips. The widths of spaces between the micro-fins (tunnel widths) were 0.6, 1.0 and 1.5 mm. The highest heat transfer coefficients for ethanol used as the working fluid and 1 mm high micro-fins were obtained at the largest mesh aperture size and tunnel widths of 1 mm and plain micro-fins with 0.6 mm wide tunnel. For 0.5 high micro-fins, the highest heat transfer coefficient was obtained for the structure with the widest, 1.5 mm tunnels.

The measurement data collected for the three working fluids helped generalize the results in the form of a graph of the increase in heat transfer coefficient as a function of the dimensionless numbers.

Visualization studies aimed at identifying nucleation sites and determining the diameter and frequency of departing bubbles for boiling water. A different mechanism of pool boiling was observed for plain micro-fins and micro-fins covered with wire mesh.

A simplified model was proposed for determining the total heat flux for micro-fins with the wire mesh. It was assumed that the structure formed a system of connected perpendicular horizontal tunnels limited with a porous top covering. Regarding the calculated bubble parameters (diameter, nucleation sites density, frequency), the heat fluxes were determined for the evaporation in the tunnels between the micro-fins and for the convection on the wire mesh surface. The predicted heat fluxes, when compared to the experimental results, showed satisfactory agreement for boiling water at medium and high heat fluxes (range from 70 to 355 kW/m^2). Less accurate results were obtained for ethanol and FC-72.

1. Introduction

Heat transfer to liquids boiling on specially prepared structural surfaces is drawing wide attention across industries for its application to heat removal in devices generating high heat fluxes. Despite commercial use of copper mesh surfaces in heat pipes, few publications have addressed the issue of nucleate pool boiling from such surfaces.

There are numerous passive and active methods for boiling heat transfer enhancement. Surfaces with a wire mesh and/or micro-fins fall into seven categories (Table 1).

To describe theoretically a boiling process on structural surfaces, it is necessary to know the mechanism of vapor bubble nucleation, growth and departure. State-of-the-art digital technology of recording and processing images (a high speed digital camera) as well as appropriate modification of the main test module to allow obtaining images of vapor bubble generation, makes it possible to acquire the necessary knowledge. The results of visualization become the basis for building a semi-analytical calculation model to determine heat fluxes for different working fluids.

Wei et al. [7] presented visualization of boiling FC-72 on 0.06–0.2 mm high micro-fins and described bubble growth in the inter-fin gaps. Yu and Lu [3] took photographs of boiling structures for the array of copper micro-fins (height: 0.5–4.0 mm, inter-fin space width: 0.5–2.0 mm). The diameters of the departing bubbles were estimated to be 0.2–0.3 mm. Tsay et al. [24] presented images of boiling water on a porous steel surface covered with a wire mesh. Ramaswamy et al. [25], using a fast camera (1500 frames per second), determined the bubble growth data for a silicon structure composed of interconnected mini-channels submerged in boiling FC-72. Pastuszko and Kaniowski [26] as well as Pastuszko [27] conducted visualization studies with narrow tunnel structures as well as with a transparent structured model of joined narrow tunnels with perforated walls. The visualization investigations aimed at identifying nucleation sites and flow patterns, and at determining bubble departure diameter and frequency.

E-mail address: tmprp@tu.kielce.pl.

https://doi.org/10.1016/j.ijthermalsci.2017.11.019
Received 23 May 2016; Received in revised form 19 July 2017; Accepted 20 November 2017
1290-0729/

Nomenclature

a	mesh aperture dimension, mm
a	thermal diffusivity, m^2/s
Bo	Bond number
$C_{1\text{-}2}$	growth period constant
c	specific heat at constant pressure, J/kgK
d	diameter, mm
f	frequency, Hz
g	acceleration due to gravity, m/s^2
HTC	heat transfer coefficient
h	micro-fin height, mm
i_{lv}	latent heat of vaporization, J/kg
Ja	Jakob number
L	capillary length, m
l	distance, m
MF	surface code (micro-fin)
MFM	surface code (micro-fin with wire mesh)
m	fin parameter, m^{-1}
n	nucleation site density, m^{-2}
p	pitch, mm
R	radius, m
q	heat flux, kW/m^2
s	distance between micro-fins, mm
T	temperature, K
t	time, s
w	width, mm

Greek symbols

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

Subscripts

0–1	waiting period
1–2	growth period
1,2, …, 8	thermocouple number
a	connected with mesh aperture
b	departing bubble
bs	base
Cu	structure material (copper)
ex	external
exp	experimental
l	liquid
m	mean
p	pore (opening)
s	smooth
sat	saturation
Sn	tin
th	thermocouple
theor	theoretical
tip	micro-fin tip
tun	tunnel
v	vapor
w	connected with tunnel width

Brautsch and Kew [13] showed images of boiling from a vertical mesh with the pore size of about 0.1 mm. In the case of immersed structures and during capillary rise, the bubbles were relatively small and the intermittent dry-out occurred within a wide range of heat fluxes. When q increased to about 140 kW/m^2, these small bubbles coalesced into vapor patches insulating the heater from the boiling liquid. At higher heat fluxes, completely dry mesh areas appeared. The same authors [28] described three areas of boiling from the surfaces with a single layer of mesh (boiling initiation, settled nucleate boiling, critical heat flux), based on visualizations of surfaces covered with four types of mesh (pore pitch from 0.508 mm to 0.127 mm).

Using 0.5 and 1.0 micro-fins with wire mesh covering was advantageous for water and FC-72 at low and medium heat fluxes, that is, below 150 kW/m^2 for water and below 30 kW/m^2 for FC-72. Compared to plain micro-fins, the heat transfer coefficient was about two times as high [2]. The purpose of this study was to extend the investigations in term of heat transfer coefficients for the MF and MFM with boiling ethanol, and to perform visualization study for the three working fluids.

This article is focused on the comparison between boiling efficiency of plain micro-fins and micro-fins with a wire mesh. The influence of the Bond number and dimensionless parameters on the heat transfer ratio at nucleate pool boiling were examined for 24 enhanced surfaces. The author of this paper proposed the simplified model for heat flux determination at pool boiling of water, ethanol and FC-72 on micro-fins surfaces with the sintered wire mesh. The model is based on the author's own experimental investigation and visualization studies and on the existing theoretical relationships.

2. Experimental setup

The diagram of the measuring unit is presented in Figs. 1 and 2a. The following modules constituted the laboratory station for determining boiling curves and heat transfer coefficients (Fig. 1):

1. main module (items 1–6, Fig. 2b);
2. vapor cooling and condensate recovery (item 7);
3. temperature measurement and data acquisition module (items 8–10);
4. power supply module (item 11);
5. visualization module (digital camera/digital video camera, item 12, Figs. 1 and 2a).

The visualization images were obtained using a high speed digital monochrome camera with CMOS sensor PHOT MV-D1024-160-CL (*Photonfocus*) with resolution of 1024x1024 pixels at 150 fps. The visualization was created at the image acquisition speed of 493 fps (at resolution 400 × 300).

The main module of the setup is shown in Fig. 2b. The cylindrical vessel is filled with the working fluid and mounted above the investigated surface with micro-fins. This surface is soldered to a 170 mm long copper heating bar with 45 mm in diameter. The cartridge heater (1500 W), 19 mm in diameter and 130 mm in length, was placed inside the cylinder. The insulation layer 200 mm in diameter was added to the outside of the cylinder. The level of the boiling fluid was maintained at about 45 mm above the top element of the specimen. The water-cooled condenser, operating at atmospheric pressure, kept constant the volume of the working fluid without the necessity of replenishment – the main module operated as a thermosiphon.

Prior to the measurement, the specimens were rinsed with ethanol and aged by heating for a few minutes at the heat flux of 200–300 kW/m^2.

To degas the surfaces, the heater was first supplied with the heat flux of about 300 kW/m^2 until the developed nucleate boiling was reached and then the supply of the same electric power continued for