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Experimental study of low pressure pool boiling of water from narrow tunnel surfaces

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ABSTRACT

This article aims at studying pool boiling of water at sub-atmospheric pressure which takes place on narrow tunnel structures (NTS). This kind of surface consists of multiple horizontal and vertical channels that can remain open, or be covered with perforated copper foil. The structures were immersed under 5, 28.7, and 86.2 mm of distilled water. The range of saturation pressure range was 0.75–4 kPa (corresponding to a temperature range of 2.8–28.9 °C), and that of imposed heat flux was 0.25–3 W/cm^2. The process of bubble creation and detachment, the bubble departure diameters and the frequencies were analyzed for three different NTS structures. Visual observations were complemented by measurements of temperatures and pressures, which were used to determine heat flux, superheat, and heat transfer coefficients.

The boiling curves at sub-atmospheric pressure were shifted towards higher superheats in comparison to atmospheric pressure (this in agreement with the literature). NTS surfaces reduced this negative effect. Indeed, the NTS structures enhanced with perforated copper foil substantially improved heat transfer at low pressures, i.e. they increased the heat transfer coefficient and the bubble departure frequency.

1. Introduction

Among cooling technologies, the systems using water as primary refrigerant are particularly interesting. These include adsorption chillers (gas-solid process) and absorption chillers (gas-liquid process), such as lithium bromide. Refrigeration by means of sorption systems answers recent environmental regulations, but most of existing devices are either medium or high capacity units with low efficiency and large thermal mass. To raise efficiency, reduce the investment cost and improve compactness of sorption cooling systems, the size of heat exchangers must be reduced. In particular, evaporator is the component which needs to be improved. Yet, experimental results on boiling at higher pressures can not be extrapolated to low pressures [1], and the studies on low pressure heat exchangers suitable for sorption systems are scarce [2]. They are usually focused on basic designs and surface types (e.g. flat surface or tube bundle).

The aim of the present article is to report the results of an experimental investigation of the behavior of pool boiling of water at sub-atmospheric pressure (0.75–4 kPa, corresponding to a temperature range of 2.8–28.9 °C) on complex surfaces made of Narrow Tunnel Structures. NTS-es have been introduced and tested by Pastuszko et al. [3–6]. This kind of surface consists of narrow horizontal and vertical channels, either opened or covered with perforated foil. The design combines boiling enhancements caused by subsurface tunnels and by fins with subsurface tunnels. Pastuszko et al. analyzed boiling of several refrigerants under atmospheric conditions (including water) and observed that NTS surfaces improved heat transfer coefficients (HTC) in comparison to plain surfaces.

To check the suitability of these structures in such conditions, bubble creation on three different surfaces (described as NTS-1, NTS-2, and NTS-3) was recorded using a high speed camera. Bubble departure diameters and frequencies were determined on the basis of recorded material. Visual observations were supplemented with temperature and pressure measurements that allowed to

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Nomenclature

d	Diameter m
f	Frequency Hz
h	Height m
H	Water level m
HTC	Heat transfer coefficient W m^{-2}K^{-1}
N	Number of bubbles –
p	Pressure Pa
P	Pitch m
R	Radius m
s	Fin pitch m
t	Time s
T	Temperature K
w	Width m
q	Heat transfer density W m^{-2}
Greek	
δ	Length m
Δ	Difference –
Δh_{l-v}	Latent heat of vaporization J/kg
ΔT	Temperature difference K
ΔZ	Distance between the thermocouples m
λ	Heat conductivity W m^{-1} K^{-1}
ρ	Density kg m^{-3}
σ	Surface tension J m^{-2}
Subscripts	
base	Base
d	Departure
f	Fin
ns	Nucleation site
p	Pore
sat	Saturation
tc	The upper-most thermocouple
tun	Tunnel
tunH	Horizontal tunnel
wall	Wall
v	Vapor

determine the heat flux, the wall superheat, and the resulting heat transfer coefficients.

2. Sub-atmospheric boiling environment

2.1. Bubble dynamics

Subatmospheric pressure influences the dynamics of bubble growth. Schnabel et al. [7], Giraud et al. [8,9], McGillis et al. [10] and Chan et al. [11] observed the formation of much larger bubbles as a result of increased surface tension and larger buoyancy forces. Larger departure diameters result in a longer bubble departure time and thus in a decrease in the bubble departure frequency, as described by the empirical correlation developed by McGillis et al. [12]:

$$t_d = 0.266(1000p)^{-0.565} \tag{1}$$

Subatmospheric conditions and the induced specific thermophysical properties also affect bubble nucleation. As a matter of fact, the minimal nucleation site radius and minimal superheat can be related to the thermophysical properties by the following equation:

$$\Delta T_{sat} = \frac{1.6\sigma T_{wall}}{R_{ns}\rho_v \Delta h_{l-v}} \tag{2}$$

This equation derives from the Clausius-Clapeyron equation and equation of the static bubble equilibrium [12]. Finally, all these specificities in the bubble behavior also have consequences in terms of wall superheat: the departure of a larger bubble produces a much larger wake of subcooled liquid, and the sudden removal of superheated liquid leads to wall temperature fluctuations, which were also reported in the previously cited references.

2.2. Filling level

Giraud et al. [8] showed that non-homogeneity of the saturation temperature and pressure influences sub-atmospheric boiling process and for this reason the filling level must be taken under consideration.

The filling level induces hydrostatic pressure gradients in liquid. Pioro et al. [13] determined that during pool boiling of water at atmospheric pressure for levels higher than 2 mm the impact of filling level is negligible. At 2 mm the dominant mechanism of heat transfer changes from conduction to the latent heat transfer and forced convection induced by bubble flow.

Schnabel et al. [7] and McNeil [14] showed that at sub-atmospheric pressure, the influence of the filling level is large. Schnabel et al. analyzed nucleate boiling of water at 2 kPa for two different filling levels: 10 and 20 mm. They reported that the amount of heat flux transferred through the heater wall doubles for the same superheat if the filling level increases from 10 to 20 mm. Giraud et al. [9] studied the influence of liquid level on bubble nucleation at a single artificial nucleation site and under pressure between 1.2 and 3 kPa. The experiments showed that the wall superheat remains constant at low liquid levels (3–20 mm). For high liquid levels (50–200 mm) both wall temperature and instantaneous heat flux oscillate. Those oscillations are caused by large temperature gradients in the liquid bulk which is mixed by escaping detached bubble. The effect is further amplified due to the difference of saturation temperature between the top and the bottom of the liquid bulk (9 K for 100 mm filling level, see Fig. 1).

2.3. Heat transfer coefficient

Heat transfer coefficient (HTC) during pool boiling at sub-

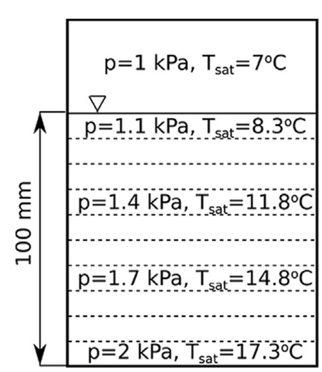

Fig. 1. Non-homogeneity of saturation temperature T_{sat} in a 100 mm deep pool of water.