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New pool boiling data for water with copper-foam metal at sub-atmospheric pressures: Experiments and correlation

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Abstract

Over the past decades, pool boiling heat transfer of water has been investigated extensively by many scientists and researchers at system pressures varying from atmospheric to near critical pressure. However, at sub-atmospheric pressures conditions there is a dearth of data, particularly when the vapour pressures are less than 10 kPa. The authors have conducted a detailed study of pool boiling of water in an evaporator where its system pressure was about 1.8 kPa. The heat flux for pool boiling was derived from an uniform radiant heaters up to 5 W/cm^2 (or a total heating rate of 125 W within an area of 25 cm^2), a region that is of interest for the cooling of CPUs.

Keywords: Pool boiling; Heat transfer correlation; CPU cooling

1. Introduction

Many theoretical and empirical correlations have been proposed for pool boiling of assorted working fluids over the past decades [1–6] and they have been used to estimate the heat transfer rates. One of the classical boiling processes of nucleate boiling is between a heated surface such as the plates, wires or single tube, etc., and a submerged liquid pool at saturation pressures. Such boiling phenomena have been studied with system pressures in the pressurized regimes up to the critical pressure and they have revealed that the main parameters affecting pool boiling are (i) local heat flux (q), (ii) saturation pressure (P), (iii) thermo-physical properties of the working fluid (namely c_p, k, σ, μ) and (iv) the characteristics of the boiling surface or materials. The basic pool boiling correlation hitherto that has withstood the test of time is the Rohsenow correlation [1]. Within the experimental uncertainty, it employs two coefficients to describe the broad range of nucleate pool boiling phenomena, namely (i) the exponent constant (n) in the dimensionless numbers and (ii) the surface characteristics constant, C_{sf}, as shown below

$$T_{\mathrm{w}} - T = \left(\frac{C_{\mathrm{sf}} h_{\mathrm{fg}} Pr_{\mathrm{l}}^{s}}{c_{\mathrm{pf}}}\right) \left[\frac{q''_{\mathrm{load}}}{\mu_{\mathrm{l}} h_{\mathrm{fg}}} \sqrt{\frac{\sigma}{g(\rho_{\mathrm{l}} - \rho_{\mathrm{g}})}}\right]^{n} \quad (1)$$

where q''_{load} denotes the local heat flux, Pr_{l} is the Prandtl number of liquid, σ and μ are the surface tension and the viscosity, the power index $s = 1$ for water and the other terminologies are the usual fluid properties.

Although the Rohsenow correlation is known to predict well for the pressurized situations, but its generic form is seldom recommended for system pressures that are sub-atmospheric. There is dearth of reliable data for pool boiling at low sub-atmospheric, corresponding to low saturation temperatures up to 10 °C or lower. The low temperatures are normally associated to cooling applications and thus, they receive much less attention as compared with the pressurized studies. For several types

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Nomenclature

A	surface area correction factor due pressure effect m^2
c_p	specific heat capacity J kg^{-1} K^{-1}
C_{sf}	a constant of Rohsenow correlation
g	gravitational acceleration m s^{-2}
h_{fg}	enthalpy of vaporization J kg^{-1}
k	thermal conductivity W m^{-1} K^{-1}
m	a constant (proposed correlation)
n	a constant (Rohsenow correlation)
P	working (sub-atmospheric) pressure Pa
PPI	pores per inch (or per 25 mm) –
Pr	Prandtl number
q''_{load}	heat flux at the evaporator W m^{-2}
T	temperature K
α	a constant of proposed correlation
μ	viscosity kg m^{-1} s^{-1}
σ	surface tension N m^{-1}
ρ	density kg m^{-3}
$\Delta T(=T_w - T)$	temperature difference K

Subscripts

l	liquid
g	gaseous
base	base area
atm	atmospheric
wetted	wetted area
w	boiling surface

of surface-fluid interface at sub-atmospheric conditions, Vachon et al. [2] reported that the C_{sf} and n for the pool boiling correlation varied widely as they could be influenced by fluid properties and pressures. In another experiment, Raben et al. [7], expounded on the gross effects of low pressure boiling heat fluxes on the wall. Similar studies have been conducted on saturated nucleate pool boiling of water at sub-atmospheric pressures [7,8] to identify the dominant energy transport mechanisms and to further understand the pressure effect on nucleate pool boiling. These studies were conducted at system pressures of about 4 kPa and higher, corresponding to saturation temperatures of 29–45 °C. They have attempted to correlate the pressure effect via the index term of the Prandtl number term i.e., the index s, in the Rohsenow correlation. However the predictive accuracy by using the s index exceeded the range of experimental uncertainty at low pressures as the Prandtl number effect is found to be non-linear. The pool boiling correlation of Cooper [9], which is based on the reduced pressure (working pressure divided by the reduced pressure) and surface roughness of boiling surface, covers the working pressure ranging from 22 kPa to 20.1 MPa for the pool of water. On the other hand, the pool boiling heat transfer is enhanced with porous material and convective heat transfer coefficient as a function wall superheat ΔT was calculated for the boiling of pure water at atmospheric pressure on different porous covering [10].

In this paper, the authors propose a slightly modified Rohsenow correlation to capture the low pressure effect on pool boiling of water. Both the pressure and area ratios, i.e., $\left(\frac{p}{P_{atm}}\right)^m$ and $\left(\frac{A_{wetted}}{A_{base}}\right)^\alpha$, are to be used in a multiplicative manner with the classical Rohsenow correlation. The variation of fluid properties at low pressures is fully captured by the non-dimensional parameters of the Rohsenow correlation and the reduction in the wall temperature at the same heat flux is accommodated by the proposed pressure ratio term. The validity of the proposed correlation is to be verified experimentally with measured data from two sources: i.e., (i) the pool boiling data of water of McGillis et al. [8] with tests conducted at two vacuum pressures of 4 and 9 kPa and (ii) the authors' own pool boiling experiments but measured at a lower pressures of 1.8 kPa. For comparative purposes, the reduced pressure correlation of Gorenflo [11] is also included where the pool boiling correlation is claimed to be valid from 11 kPa to 21.2 MPa and depends on surface roughness. In all these cases, the surface area exposed to the pool of water is identified for comparative purposes, defined here as the amount of liquid contact area to the base or foot-print area (where the heat flux is transmitted through to the pool of water) and this is used also as a reference for comparison between boiling surfaces.

2. Experiments

An evaporator, which is a part of an electro-adsorption chiller [12,13], is used to measure the temperature difference (ΔT) across the heating surface and the system saturation temperature. A copper-foam metal (5% density, 50 PPI, width 52 mm, length 52 mm and thickness 32 mm) is used as the boiling enhancement surfaces within a partially filled evaporator. Uniform radiant heat flux is delivered to the foam metal, placed within the evaporator, through a quartz window opening (transmittance wavelengths up to 2500 nm).

Fig. 1 shows the radiant energy delivery device which comprises an array of four electric heaters, projecting the IR energy through a four-sided tapered homogenize