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Subcooled pool film boiling heat transfer from small horizontal cylinders at near-critical pressures

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ABSTRACT

Experimental results for subcooled pool film boiling on small horizontal cylinders at near-critical pressures are presented. Experiments were performed with CO_2 was the test liquid and platinum wires (25.4, 76.2 and 100 μm diameter, D) as the test heaters. The pressure (P), liquid subcooling (ΔT_{sub}) and bulk liquid temperature (T_b) were varied parametrically. For the range of parameters investigated, the heat transfer coefficient (h) was found to be proportional to $D^{-0.5}$. Because the dependence of h on D varies, a criterion has been developed to predict a priori what this dependence would be any given situation. Subcooled pool film boiling heat transfer coefficient data have been correlated. The correlation developed predicts almost all the experimental data from the current study to within ±10%. The strength of the new correlation is that it is applicable to a much wider range of experimental conditions (including level of gravity) and fluids as demonstrated by the fact that it predicts all of the data reported in the literature to within ±20%. Visual observations during experiments showed that the transitions in film boiling patterns are a function of the dimensionless cylinder diameter.

1. Introduction

Pool film boiling heat transfer on horizontal cylinders has been extensively studied. Bromley [1] was the first to develop a theoretical model for saturated film boiling on horizontal cylinders, based on boundary layer analysis of the vapor film surrounding the cylinder. Later, Berenson [2] applied the Taylor instability theory to a horizontal surface and developed a semi-empirical correlation to predict the heat transfer coefficient during saturated pool film boiling. Breen and Westwater [3], investigated the effect of cylinder diameter on film boiling heat transfer and found out that neither model resulted in good agreement with experimental data when the cylinder diameter (D) was very small, or was comparable to the most dangerous wavelength for a flat plate ($\lambda_{dF} = 2\pi\sqrt{3}l_o$), where l_o is the characteristic length $\left(\sqrt{\sigma/g(\rho_{l,sat} - \rho_{v,sat})}\right)$. Most of the early studies of film boiling on horizontal cylinder focused on saturated liquids at pressures (P) close to the atmospheric. These studies have been reviewed by Clements and Colver [4], and Kalinin et al. [5].

The influence of pressure on film boiling from microscale cylindrical heaters was reported in [6–14]. The studies [10,13,14] showed that when P approached P_c (critical pressure), an increase in P led to a decrease in the heat transfer coefficient (h). This behavior was attributed to the large variations of the fluid properties close to the critical point, particularly the thermal conductivity (k) and the specific heat capacity (c_p), as illustrated by Fig. 1(a). This figure shows the variation of thermodynamic properties of CO_2 with temperature, for $P = 6.99$ MPa ($T_{sat} = 301.77$ K). Fig. 1(b) shows the variation of the surface tension (σ) as a function of T_{sat}. Note that σ goes to zero as T_{sat} approaches T_c. Visual observations [7,9,11,12] during saturated film boiling heat transfer of CO_2 from small cylinders, showed three distinct modes of vapor removal, namely: (1) discreet bubbles departing from the vapor–liquid interface, (2) formation of vapor columns and (3) rise of a vapor sheet above the wire. Transition between these three modes occured with increase in heat flux (q) or wall temperature (T_w). As reported in [14], for small D and high P, standard correlations [1,3] were unable to accurately predict h. This lead Pitschmann and Grigull [8] and Nishikawa et al. [15] to develop semi-empirical correlations for a wide range of D and P. The predictions from these correlations showed good agreement with experimental data [9,13,14].

Few experimental studies have focused on the effect of subcooling on film boiling from horizontal cylinders. Results reported in [10,16,17] showed that q (or h) increases with increase in liquid subcooling ($\Delta T_{sub} = T_{sat} - T_b$), for given wall superheat ($\Delta T_w = T_w - T_{sat}$), P and D.

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Nomenclature

A	heater surface area, m^2
c_p	specific heat at constant pressure, J/kg K
D	diameter, μm
g	gravitational acceleration, m/s^2
Gr	Grashof number, Eq. (2)
h	heat transfer coefficient, W/m^2 K
h_{fg}	latent heat of vaporization, J/kg
i	enthalpy, J/kg
Ja^*_{sub}	modified Jakob number for the subcooled liquid, $(i_{l,\text{sat}} - i_{l,b})/h_{fg}$
Ja^*_{sup}	modified Jakob number for the superheated vapor film, $(i_{v,f} - i_{v,\text{sat}})/h_{fg}$
k	thermal conductivity, W/m K
L	wire length, μm
l_o	characteristic length, $\sqrt{\sigma/g(\rho_{l,\text{sat}} - \rho_{v,\text{sat}})}$
Nu	Nusselt number, $Nu = hD/k_v$
Nu_P	Nusselt number predicted from Pitschmann and Grigull's correlation, Eq. (3) [8]
P	pressure, MPa
Pr	Prandtl number, $Pr = \mu_v c_{p,v}/k_v$
Pr^*	modified Prandtl number, Eq. (4)
q	heat flux, W/m^2
Q	total energy transferred, W
R	heater resistance, Ω
Ra^*	modified Rayleigh number, Eq. (4)
T	temperature, K
ΔT_w	wall superheat $T_w - T_{\text{sat}}$, K
ΔT_{sub}	liquid subcooling $T_{\text{sat}} - T_b$, K
U	speed of rise of the vapor or liquid dripping velocity, m/s
$\dot{V}$	volumetric flow rate per unit length, m^2/s
We	Weber number, Eq. (11)

Greek symbols

α	absorptivity
δ	vapor layer thickness, m
ε	emissivity
λ	wavelength, m
λ_d	most dangerous wavelength, m
μ	dynamic viscosity, Pa s
ρ	density, kg/m^3
σ	surface tension, N/m
σ_{sb}	Stefan–Boltzmann constant, $W/m^2 K^4$

Subscripts

b	bulk conditions
c	critical state
e	earth
f	film temperature, $T_f = (T_w + T_b)/2$
F	flat plate
p	constant pressure
rad	radiation
sat	saturation
sub	subcooled
w	wall temperature

Superscript

*	reduced

To the best of the authors' knowledge, the study by Simoneau and Baumeister [10] is to date the only one in which systematic investigation of subcooled pool film boiling on horizontal cylinders, at very high pressures, has been carried out. Sakurai et al. [18–22] conducted an extensive study of subcooled pool boiling for a broad range of fluids, liquid subcoolings ($0 \leqslant \Delta T_{\text{sub}} \leqslant 50$ K), pressures ($0.053 \leqslant P \leqslant 1.96$ MPa, $0.005 \leqslant P^* \leqslant 0.54$), wall superheats ($\Delta T_w \leqslant 700$ K) and cylinder diameters ($D \geqslant 300$ μm). Based on their data, they developed a semi-empirical correlation for subcooled pool film boiling heat transfer from horizontal cylinders.

Studies of saturated film boiling at pressures close to the critical pressure show that analytical models and correlations developed for normal pressures ($P \ll P_c$) are no longer applicable when P approaches P_c. This is due to the large variation in fluid properties. Additionally, no experimental data is available for subcooled film boiling from cylindrical heaters at near-critical pressures. As a result, our understanding of the coupled effects of pressure and liquid subcooling on during film boiling from horizontal cylinders is limited. Hence, the goal of this study is twofold: (i) to further our basic understanding of subcooled pool boiling heat transfer phenomena at near-critical pressures and to extend the current experimental database, and (ii) based on the experimental data, develop a correlation for subcooled pool film boiling heat transfer to carbon dioxide at near-critical pressures.

2. Experiments

2.1. Experimental setup

The experimental apparatus is identical to the one used in [23]. It consists of a horizontal wire mounted in a high pressure cylindrical vessel (stainless steel 316, height = 100 mm, ID = 41.3 mm). To enable visual observation, four single-crystal sapphire windows (diameter = 38.1 mm) are provided on the high pressure vessel. Visualization of the flow was accomplished using a high speed (Fastec HR) camera. A schematic of the experimental apparatus is shown in Fig. 2.

In the experiments, the bulk fluid temperature was controlled by circulating a water-ethylene glycol mixture through channels provided within the vessel's walls. A recirculating chiller was used to control coolant temperature. The pressure inside the vessel was measured with a bourdon pressure gage (Ashcroft Type 1082) and a digital pressure transducer (Omega DPG7000-5K), while the temperature of the bulk fluid was measured with a K-type thermocouple and a four-wire RTD probe (Omega P–M ultra precise immersion RTD).

Bone dry CO_2 was the test fluid. Filling and pressurization of the test chamber was performed using a manual high pressure generator (HiP 62-6-10). Platinum (99.99% pure) was the wire material, since its temperature dependant electrical resistance is well known. The resistance of the wire was measured using the four-wire resistance measurement technique. Two of the wires were used to connect the heater to the DC power supply, while the other two wires were used to measure the voltage drop across the heater wire. This voltage drop was measured using a digital multimeter (Keithley 2100). The current supplied was calculated based on the voltage drop measured across an external high precision shunt resistor. Fluid properties were calculated using the REFPROP software from NIST [24].

2.2. Experimental procedure

Prior to each test run, the pressure vessel was filled with CO_2 at room temperature. With the cylinder still connected to the test chamber, the vent valve was opened to purge the vessel of any