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Influence of wall material on nucleate pool boiling of liquid nitrogen

Cristiano Bombardieri *, Chiara Manfletti

Institute of Space Propulsion, German Aerospace Center (DLR), 74239 Hardthausen, Germany

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ABSTRACT

The wall material thermal conductivity k is one of the surface characteristics that influences the pool boiling heat transfer curve. The growth rate of vapor bubbles and their frequency are mechanisms affected by the thermal conductivity. But the wall material k affects the nucleate boiling curve only in the case of a limited number of nucleation sites. Previous experiments in fact concluded that for a rough surface that has a larger number of vapor generating centers, the wall thermal conductivity does not significantly affect the nucleate pool boiling curve.

In this paper, nucleate pool boiling curves of saturated nitrogen under ambient pressure are experimentally obtained on a horizontal flat surface and the effect of three different wall materials (copper, aluminum, stainless steel) is evaluated. The tested surfaces are mechanically polished to avoid any roughness effect. Hysteresis behavior has been observed for the copper and aluminum surfaces, while the results for stainless steel are difficult to assess. The critical heat flux is also analyzed and compared by taking into account the thermal effusivity of the different materials. Finally, experimental results are compared against the most common empirical correlations for nucleate pool boiling heat transfer.

1. Introduction

Interest in boiling heat transfer of cryogenic fluids such as hydrogen, nitrogen, oxygen dates back to the ′50 and ′60 with the beginning of space activities and use of cryogenic propellants. The applications where cryogenic boiling occurs are numerous: chill-down of cryogenic tanks and pipelines, thermal control system of satellites, cryogenic phase-change heat exchanger, facilities for the production and use of cryogenic fluids (such as liquifiers, cryo-coolers and vaporizers).

Pool boiling heat transfer is a subject of extensive research worldwide. A large number of both theoretical and empirical correlations have been proposed to predict the pool boiling heat transfer curve. The nucleate pool boiling curve is dependent on many parameters, mainly related to the thermophysical properties of the boiling fluid and to the characteristics of the surface on which the pool boiling takes place. In particular the effect of the surface characteristics such as the thermophysical properties of the material, geometry, thickness, orientation, surface conditions (roughness, oxidation and even the boiling cycles), require further investigation [1].

Past investigations have shown that the thermal conductivity k and the thermal effusivity ε of the surface material play an important role.

In his work, Pioro [2] performed several experiments in order to evaluate the constants C_{sf}, r, s for the Rohsenow boiling correlation (Eq. (1)) for different fluid-material combinations, namely water, ethanol, R-11 and R-113 with copper, aluminum, brass and stainless steel.

$$\frac{c_{pf}\Delta T_{sat}}{h_{fg}} = C_{sf}\left[\frac{q}{h_{fg}\mu_f}\left(\frac{\sigma}{g(\rho_f-\rho_g)}\right)^{1/2}\right]^r Pr_f^s \qquad (1)$$

Pioro observed the differences among the tested materials, which are indeed taken into account in the value of the constants, while the slope of the boiling curve – $q \propto \Delta T^n$ – was not affected by the material.

Gogonin [3] analyzed several experimental data published by various authors focusing on the influence of the wall thermophysical properties on the critical heat flux (CHF). He concluded that the CHF depends substantially on the physical properties of both the boiling liquid and cooled wall and its geometrical parameters.

Numerical simulations performed by Mann et al. [4] showed that the influence of the wall thermal conductivity is small due to two compensating effects: a lower value of k decreases the local heat flux but it also leads to thinner liquid films in the micro region

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* Corresponding author: Tel.: +49 629828 732.
E-mail addresses: cristiano.bombardieri@dlr.de (C. Bombardieri), chiara.manfletti@dlr.de (C. Manfletti).

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Nomenclature

C_1, C_2	coefficients in Eqs. (8) and (9)
c_P	specific heat [J kg^{-1} K^{-1}]
C_{sf}, r, s	coefficients in Eq. (1)
g	gravity acceleration [m s^{-2}]
h_{fg}	latent heat of vaporization [J kg^{-1}]
k	thermal conductivity [W m^{-1} K^{-1}]
P	pressure [Pa]
Pr	Prandtl number [–]
R_a	arithmetic-average roughness [μm]
R_q	root mean square roughness [μm]
R_z	mean peak-to-valley height [μm]
q	heat flux [W m^{-2}]
T	temperature [K]
x	distance [m]

Greek symbols

$\triangle$	difference [–]
ε	thermal effusivity (or assimilability) [$\sqrt{\rho k c_P}$]
Λ	thermal effusivity ratio [–]
λ	Taylor instability length [m]
μ	viscosity [Pa s]
ρ	density [kg m^{-3}]
σ	surface tension [N m^{-1}]

Subscripts

f	fluid
g	saturated vapor
max	maximum
s	surface
sat	saturated
sf	surface-fluid
U	uncertainty
w	wall

Abbreviations

Al	aluminum
CHF	critical heat flux
Cu	copper
HTC	heat transfer coefficient
St.St.	stainless steel

which enhances heat conduction in the film and causes higher heat fluxes.

Another aspect to be considered is the effect of the surface roughness. A rough surface provides a high number of nucleation sites and therefore the influence of the wall thermal conductivity is less significant. However for the boiling of cryogenic fluids, the wall thermal conductivity affects the pool boiling curve even at moderate level of roughness, as cryogenic fluids wet the surface very well because their contact angles are close to 0. Therefore a surface that is rough for normal fluids can be considered smooth for cryogenics [1]. In his model to predict the CHF, Kandlikar [5] assumed a contact angle of 20 degree for cryogenic fluids on a copper surface, although no experimental measurements is available on contact angles for cryogenics.

Nucleate pool boiling of cryogenic liquids from ambient to near the critical pressure has been investigated by Kosky and Lyon [6] for oxygen, nitrogen, argon, methane and carbon tetrafluoride, and by Bewilogua et al. [7] for helium, hydrogen, and nitrogen.

The influence of the surface material on the pool boiling curve has been investigated by several authors [4,8–11] mainly with water and refrigerants, but very few studies are available for liquid nitrogen. Ackermann et al. [12] performed pool boiling experiments of nitrogen with copper, copper–nickel alloy (German silver) and aluminum surfaces under ambient pressure. No remarkable difference in the pool boiling curves was observed.

This paper presents the experimental nucleate pool boiling curves of saturated liquid nitrogen at ambient pressure for different surface materials, namely copper, aluminum and stainless steel. The surface tested is a mechanically polished horizontal flat plate.

In Section 2 the experimental apparatus is described and a detailed error analysis presented. Results are discussed in Section 3 and finally conclusions are drawn.

2. Experimental set-up

2.1. Apparatus

The apparatus used for the pool boiling experiments consists of a boiling vessel at the bottom of which the heating surface is mounted (Fig. 1). The boiling vessel is a stainless steel box insulated with 35 mm of low conductivity foam. The vessel features a quartz window for visual investigation of the boiling phenomenon. The heating surface is a 8 mm thick plate, mounted on a 20 mm thick copper block (Fig. 3). Size of the main components is detailed in Table 1. The copper block is heated at the bottom by a ceramic heater connected to an electrical power supply with output voltage of 150 V DC and a maximum current of 20 A for a maximum power of 3000 W. The heating power is provided by setting the V DC supply regulator by means of stepwise increases and decreases. The ceramic heater is a high temperature-pressed Si_3N_4 material and can withstand temperatures up to 1300 K. The copper block is used for heat flux measurements. Six thermocouples are mounted inside the copper block in two parallel rows (Fig. 2). The distance between the thermocouples is 15 mm horizontally and 12 mm between the rows. Table 2 shows the geometry of the installed thermocouples.

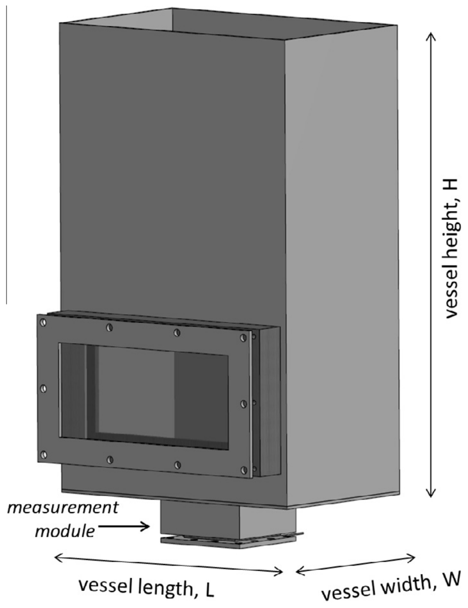

Fig. 1. Drawing of the vessel used for the experiments with the measurement module at its bottom.