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Steady state boiling crisis in a helium vertically heated natural circulation loop – Part 2: Friction pressure drop lessening

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ABSTRACT

Experiments were conducted on a 2-m high two-phase helium natural circulation loop operating at 4.2 K and 1 atm. Two heated sections with different internal diameter (10 and 6 mm) were tested. The power applied on the heated section wall was controlled in increasing and decreasing sequences, and temperature along the section, mass flow rate and pressure drop evolutions were registered. The post-CHF regime was studied watching simultaneously the evolution of boiling crisis onset along the test section and the evolution of pressure drop and mass flow rate. A significant lessening of friction was observed simultaneous to the development of the post-CHF regime, accompanied by a mass flow rate increase, which lets suppose that the vapor film in the film boiling regime acts as a lubricant. A model was created based on this idea and on heat transfer considerations. The predictions by this model are satisfactory for the low quality post-CHF regime.

1. Introduction

Boiling crisis is a major concern in boiling cooling systems, as it implies a significant rise of wall temperature when wall heat flux exceeds a given critical heat flux (CHF), sometimes beyond admissible. The literature is rich in post-CHF heat transfer, however, the problem of hydraulic resistance has been less studied.

The present work is part of a research program on superconducting magnets cooling by two-phase helium natural circulation. Previous research on this field has been done [1–4] providing a detailed comprehension of heat and mass transfer and thermohydraulics, mostly in the pre-CHF regimes. The present article, divided in two parts, intends to complete the steady state study of helium natural circulation loops by analyzing in detail boiling crisis in these systems.

In Part 1, the wall temperature evolution on the heated section of the natural circulation loop has been studied thoroughly. This allowed the identification of CHF for different positions along the test sections, the characterization of the onset of boiling crisis and post-CHF heat transfer and the nature of the wall re-wetting hysteresis. During the onset of boiling crisis, a CHF anomaly was observed by which the post-CHF region advanced instantaneously a distance of around 30 cm towards the entrance of the test section. Furthermore, the nature of the re-wetting hysteresis was shown to depend on the previous occurrence or non-occurrence of this event. Reader is encouraged to refer to Part 1 for the details about the experiments, the definition of the geometry of the two test sections used (referred to as V10 and V06) and the positions of the temperature sensors (T1, T2, T3, T4 and T5) and pressure taps (P1 and P2).

In Part 2 we analyze the hydraulic effects of the crisis that can be inferred from the experimental results for mass flow rate and test section pressure drop obtained simultaneously to the temperature data analyzed in Part 1. Furthermore we study the validity of pressure drop predictions available in the literature and, finally, provide a new practical model to estimate the pressure drop in the film boiling (FB) regime based on heat transfer properties.

2. Natural circulation equilibrium

The mass flow rate, $\dot{m}$, in a natural circulation loop results from the balance of the driving gravity force and the opposing friction, liquid–vapor expansion and singular losses forces, added up on the whole circuit. In an open loop in steady state, it writes:

$$\underbrace{\Delta P_{gr,L}}_{>0,\propto u(q/\dot{m})} = \underbrace{\Delta P_{sing,L}}_{>0,\propto \dot{m}^2} + \underbrace{\Delta P_{fr,L}}_{>0,\propto \dot{m}^2} + \underbrace{\Delta P_{acc,HS}}_{>0,\propto \dot{m}q}, \tag{1}$$

where the proportionality rules are just approximated in order to illustrate the behavior of the system. The first index indicates the origin of the forces: *gr* gravity, *fr* friction, *sing* circuit singularities, *acc* acceleration due to expansion. The second index indicates on

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Nomenclature

Acronyms

CHF	critical heat flux
DFFB	dispersed flow film boiling
DNB	departure from nucleate boiling
FB	film boiling
IAFB	inverted annular film boiling
NB	nucleate boiling
RHF	re-wetting heat flux

Symbols

A	cross section area (m^2)
B	FB model parameter ($\mathrm{m}^{3/7}\ \mathrm{s}^{-3/7}$)
$\widetilde{B}$	non-dimensional FB model parameter
C	specific heat ($\mathrm{J\ kg^{-1}\ K^{-1}}$)
δ	film thickness (m)
D	diameter (m)
f	friction factor
G	mass flux ($\mathrm{kg\ m^{-2}\ s^{-1}}$)
g	gravity acceleration (=9.8 $\mathrm{m\ s^{-2}}$)
h	heat transfer coefficient ($\mathrm{W\ m^{-2}\ K^{-1}}$)
κ	Von Kármán constant (=0.41)
k	thermal conductivity ($\mathrm{W\ m^{-1}\ K^{-1}}$)
L	tube length (m)
$\dot{m}$	mass flow rate ($\mathrm{kg\ s^{-1}}$)
μ	viscosity ($\mathrm{kg\ m^{-1}\ s^{-1}}$)
P	pressure (Pa)
ρ	density ($\mathrm{kg\ m^{-3}}$)
q	heat flux ($\mathrm{W\ m^{-2}}$)
r	radial position variable (m)
s	coordinate along the loop pipes (m)
T	temperature (K)
τ	shear stress ($\mathrm{N\ m^{-2}}$)
V	velocity ($\mathrm{m\ s^{-1}}$)
v	specific volume ($\mathrm{m^3\ kg^{-1}}$)
x	quality
z	vertical coordinate on the heated section (m)

Indexes

1ϕ	one-phase
2ϕ	two-phase
AB	ascending branch
acc	fluid acceleration
DC	down-comer
eff	effective
f	at the film-liquid interface
fr	wall friction force
g	saturated vapor
gr	gravitational force
h	homogeneous bulk
HS	heated section
L	whole loop
l	saturated liquid
lg	absolute value of difference between liquid and vapor
sat	saturation
$sing$	circuit singularities (reductions, elbows, etc.)
sub	related to subcooling
w	at the wall

which loop component the quantities are integrated: L whole loop; HS heated section. $\Delta P_{gr,L}$ is the driving force of the loop, defined as:

$$\Delta P_{gr,L} = \int_L \rho\bar{g}\cdot d\bar{s} = \int_{DC}\rho_l g ds - \int_{AB}\rho(s) g ds. \qquad (2)$$

The new loop components are: DC down-comer; AB ascending branch. The function u (in the LHS term of Eq. (1)) is some monotonously growing function that reflects the diminution of density in the ascending branch as a function of exit quality: $x \propto q/\dot{m}$. Function u is rather linear for small x (as void fraction vs. x is too) and its slope diminishes for high x.

At low power, $\dot{m}$ increases rapidly as q increases in response to an important reduction of the average density of the ascending section, and the consequent transfer from the gravity term to the RHS terms to verify Eq. (1). Given that the void fraction (thus density) varies rapidly as a function of mass quality only at very low qualities, the increase of mass flow rate finally reaches a saturation, and eventually, at very high power, the variations of the terms $\Delta P_{fr,L}$ and $\Delta P_{acc,L}$, increasing with quality, dominate and can make equilibrium $\dot{m}$ diminish as the power increases.

From Eq. (1) we see that in natural circulation loops friction forces are highly influential in the determination of the steady operation point and the stability of the flow. If at a fixed heat flux, for some reason the friction term diminished appreciably, mass flow rate needs to increase to come back to an equilibrium; hence the importance of a good determination of friction factors in all heat transfer conditions.

3. Experimental observations on pressure drop during crisis

In Fig. 1 the experimental results are presented. We reproduce the temperature evolution plots already shown in Part 1 to make easier reference to them when necessary. In this opportunity, we focus on the evolution of mass flow rate ($\dot{m}$) and pressure drop on the heated section (ΔP_{tube}). The latter is calculated as P1–P2 (see Fig. 1 and Table 1 in Part 1). In order to eliminate possible systematic offset, we subtracted the measured value of pressure drop at zero power ($\Delta P_{tube}(q=0)$), theoretically equal to $\rho_l g(z_2 - z_1)$.

When we look at Fig. 1(c) and (d) the description presented in Section 2 is quite accurate for the pre-CHF part of the curves. However, when temperature evolution indicates the transition to FB, $\dot{m}$ increases gradually more than can be extrapolated from the pre-crisis behavior and it shows a strong correlation with the advancement of post-CHF region along the section. In fact, when the violent extension of FB to T2 and T1 takes place, a discontinuity is observed in $\dot{m}$, with an instantaneous increase.

Similar observations can be made about the evolution of the pressure drop variation, shown in Fig. 1(e) and (f). In the pre-CHF power region, the pressure drop on the section evolves differently according to the diameter of the section. For V10, the increase in power produces a diminution of the pressure difference. This means that the loss of density (negative) contribution is more important than the friction (and eventually acceleration) contribution(s). On the other hand, for V06, the increase of power produces positive pressure drop variation, indicating the predominance of friction on density change effects.

The trend suggested by the pre-CHF region does not apply once boiling crisis takes over the section. In both experiments, the pressure drop is lower than expected with an important slope break at sensibly the same heat flux at which the temperature sensor near the exit (T5) starts ‘firing’. In the case of V10 the slope before and after CHF are both negative, with the one above CHF being more pronounced. In the case of V06 the slope was positive before CHF and negative afterwards. There is a point at which a violent