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Steady state boiling crisis in a helium vertically heated natural circulation loop – Part 1: Critical heat flux, boiling crisis onset and hysteresis

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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. The same loop was used in two experiments with different heated section internal diameter (10 and 6 mm). 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 recorded. The values of critical heat flux (CHF) were found at different positions of the test section, and the post-CHF regime was studied. The predictions of CHF by existing correlations were good in the downstream portion of the section, however CHF anomalies have been observed near the entrance, in the low quality region. In resonance with this, the re-wetting of the surface has distinct hysteresis behavior in each of the two CHF regions. Furthermore, hydraulics effects of crisis, namely on friction, were studied (Part 2). This research is the starting point to future works addressing transients conducing to boiling crisis in helium natural circulation loops.

1. Introduction

A large number of technological devices, either high temperature systems or cryogenic facilities, are cooled by natural circulation loops driven by boiling. The main advantages of this cooling method are its inherent safety features, the absence of mobile components in the circuit and the minimum level of required maintenance for assuring its well-functioning.

Within the frame of superconducting magnet cooling systems and techniques, research on helium natural circulation loops has recently been motivated by the Compact Muon Solenoid (CMS) magnet for the Large Hadron Collider (LHC) at CERN [1] and later by the R3B-GLAD spectrometer for GSI [2,3]. Several (mainly experimental) works have addressed the problem of the helium natural circulation loop from different points of view in steady state [4–7]. The experiments were performed on a 2-m high loop that intends to simulate a real magnet cooling system. These works addressed primarily the heat and mass transfer in nucleate boiling regime in this type of system for large heated section diameters (10 and 14 mm i.d. tubes). Nowadays, our efforts are focused on studying, on the same experimental facility, the transient dynamics of these systems with the aim of better understanding how they would respond face to sudden heat load depositions.

A major concern in boiling cooling systems is that of *critical heat flux* (CHF): a sudden deterioration of the wall heat transfer in the heated section takes place when powers exceeds a certain value, leading to too high temperatures on the wall. In the case of superconducting materials, this temperature rise could entail the loss of superconducting state.

Most of the literature about boiling crisis is focused on determining values and correlations for the CHF in steady state. However, few of the correlations contain helium data [8,9] and few experimental works to our knowledge study this phenomenon in liquid helium. Generally it is done in narrow tubes (1 or 2 mm) [10,11]. Furthermore, the existing correlations are in many cases not able to predict properly the CHF values all along the heated section due to physical reasons as pointed out by Groeneveld [12].

The study of transient boiling crisis in helium is mostly focused on systems with imposed flow or very narrow channels [13–16]. Moreover, even if CHF predictions were accurate for the steady state, experimental evidence exists that the values of CHF in transient regime can differ significantly from those determined in steady state [17].

As a part of our current research program, we published preliminary results that we obtained on transient heat transfer in a helium natural circulation loop [18]. Our attention was

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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 rewetting heat flux

Symbols
D internal diameter (m)
G mass flux (kg m^{-2} s^{-1})
h heat transfer coefficient (W m^{-2} K^{-1})
L_v vaporization latent heat (J kg^{-1})
q heat flux (W m^{-2} s^{-1})
ρ density (kg m^{-3})
σ surface tension (N m^{-1})
T temperature (K)
z position from the inlet (m)

Indexes
c critical
g saturated vapor
l saturated liquid

concentrated on the problem of boiling crisis during the transients. We believe that for a more fruitful analysis of the experimental data on transients, a more detailed understanding of the onset of boiling crisis and its hysteresis [19] in steady state in this kind of systems is necessary.

In this work we present the results of experiments that were conducted on a cryogenic natural circulation facility. It consists of a 2-m high liquid helium system, with relatively large diameter heated tubes (6 and 10 mm internal diameter). In Part 1 we present the thermal aspects of boiling crisis, namely, the CHF evolution along the heated section, the ability of available correlations to predict it and the nature and properties of the boiling crisis hysteresis. In Part 2 we present a very particular hydrodynamical effects of boiling crisis on the helium flow: the lessening of friction pressure drop. This work constitutes a stepping stone to the study of the onset of boiling crisis in the system in the case of a power transient that will be published in near future works.

2. Description of the experiment

The experimental facility consists of a U-shaped natural circulation loop inserted in a cryostat under ground level. The loop, schematically represented in Fig. 1, is composed of four main elements:

- The *down-comer*: A non-heated tube of 4 cm in diameter and around 1.2 m in length. In steady operation the fluid moves downwards inside this component and in liquid phase. It constitutes the helium supply line.
- The *test section*: An electrically heated tube that can be removed from and changed in the circuit. In steady operation the fluid moves upwards inside this component in two-phase flow. It simulates the cooling tubes of a device that are in contact with the component to be cooled. Vapor is produced at the wall of the tube, and the consequent diminution of density of this branch drives the flow.
- The *riser*: A non-heated tube downstream the test section that conduces the two-phase mixture up to the same or higher level than the down-comer entrance level, back into the phase separator.
- The *phase separator*: A reservoir at the top of the loop that receives the gas–liquid mixture leaving the ascending branch through the riser. The vapor and liquid separate simply by gravity. Liquid can be recirculated to the down-comer and gas can exit the system to avoid pressurization. The internal volume of the reservoir is about 50 L and it is 30 cm high.

The down-comer and the test section are connected by a horizontal tube, in such a way that all the tube elements form a U-shaped circuit connected to the phase separator at its bottom.

The cryostat is a 2-m deep well with a concentric liquid nitrogen reservoir all around, acting as a first thermal barrier. Vacuum is created inside in order to eliminate conduction and convection heat transfer from the exterior onto the loop. Additionally there is an internal aluminum thermal radiation shield, cooled by the helium vapor produced in the loop.

The natural circulation loop is attached to the top flange of the cryostat, which fully supports its weight and vacuum seals the

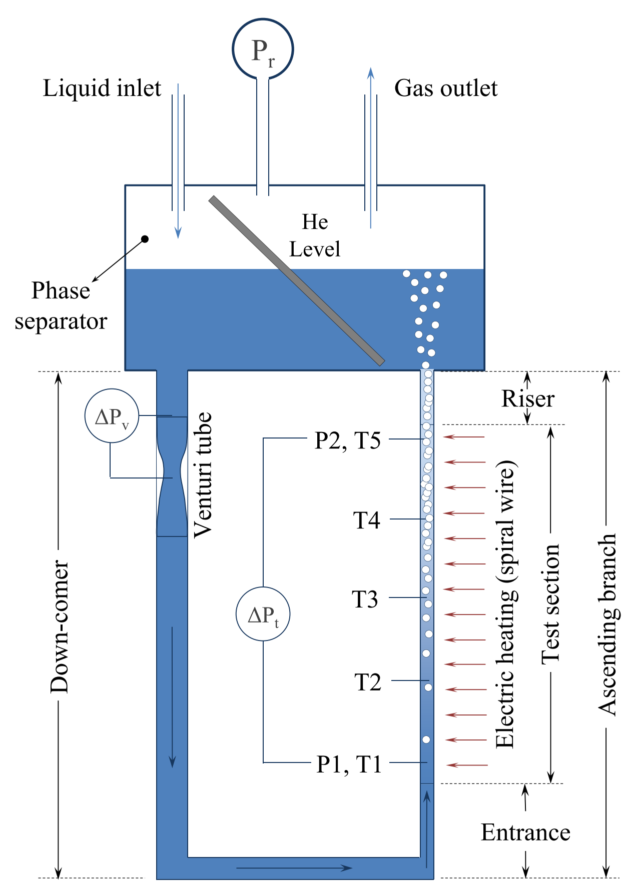

Fig. 1. The natural convection loop elements and main measured variables.