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Transient boiling crisis induced by heat-load step pulses in a helium vertically heated natural circulation loop with static initial condition

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Boiling helium natural circulation loops are used as cooling system of some large superconducting magnets. Their thermalhydraulic behavior has already been studied quite thoroughly in steady state operation. However, the transient response of these systems remains up to date poorly studied, and transient boiling experiments in other fluids or heating configurations are difficult to extrapolate. In this work, an experimental study of helium natural circulation loops is conducted in which the system is excited by a step-pulse power wave function from a static initial condition (no power applied). The measurements of wall temperature on the heated section allowed the detection of boiling crisis onset during the transient. Different boiling crisis onset mechanisms could be determined from the dependence of the nucleate boiling lifetime on applied heat flux. The simultaneous analysis of thermal aspects and mass flow rate evolution allowed determining a semi-empirical local criterion based on the evolution of vapor fraction along the section for the prediction of transient boiling crisis.

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1. Introduction

Natural circulation is a cooling method with inherent safety features that make it attractive for application where the amount of power to be removed from the system is low enough to be dealt with by the spontaneously produced mass flow rate. As no pumping is required, the cold power to be removed is not unnecessarily increased, maintenance is quite simple as there are no mobile parts. Furthermore, cooling is available as long as gravity is present, improving safety.

This cooling scheme is used for large superconducting magnets, as are the cases of the CMS detector at CERN [1] or the spectrometer R3B-GLAD for GSI [2,3], where the coolant is *boiling helium*. The major concern of the cooling system is keeping the superconducting coils below its critical temperature everywhere, so as to avoid a (local) transition to the resistive state and a consequent magnet *quench*. This event is highly undesirable as, when the no longer superconducting strands dissipate the stored magnetic energy, it produces a huge energy deposition on the magnet in a very short time. It is thus important to understand how such a cooling system reacts to heat load transients, in order to know to what extent the temperature requirement can be fulfilled.

Large helium natural circulation loops have been studied before experimentally [4–6] and numerically [7,8] but the attention was focused on the description of steady state operation. The studies on transient boiling heat transfer in helium that can be found in the literature are mostly focused on small systems, or very narrow channels [9–11], too short pipes or pool boiling [12–15]. Although, qualitatively, it is expected to find similarities with already observed behavior, the extrapolation of the results of existing research is not easy, if even possible. Furthermore the particularities of helium, namely its low surface tension, low viscosity and low gas–liquid volume ratio arise the question about the validity of applying the results from other cryogens or conventional fluids. However, a vast background of observed phenomenology that could also take place in our particular system is given by these studies.

The starting point of this work was the study of steady state transition to boiling crisis, thoroughly presented in previous articles [16,17]. In this paper, we treat the problem of transient boiling crisis. Experiments were conducted on a natural circulation loop subject to power pulses and the response of the system was measured. A simple dynamic model was conceived with the aim of evaluating variables that are not measured. The overall objective was to identify and characterize the transition to boiling crisis that can take place in response to a heat load step pulse on the cooling section of the loop and understand what the key variables governing the observed phenomena are.

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Nomenclature

Acronyms

CHF	critical heat flux
DNB	departure from nucleate boiling
RHF	rewetting heat flux
SBC	stable boiling crisis
SNB	stable nucleate boiling
TBC	temporary boiling crisis

Symbols

α	void fraction
A	cross section (m^2)
D	heated section diameter (m)
ΔP	pressure difference (Pa)
γ	void fraction diffusion coefficient ($m^2\ s^{-1}$)
h	specific enthalpy ($J\ kg^{-1}$)
L	void fraction diffused length (m)
$\dot{m}$	mass flow rate (kg/s)
Ω	two-phase expansion rate (s^{-1})
P	pressure (Pa)
q	wall heat flux (W/m^2)
q_v	volumetric power (W/m^3)
ρ	density (kg/m^3)
r	radial coordinate (m)
t	time (s)
t_r	transit time (s)
u	velocity ($m\ s^{-1}$)
x	vapor mass fraction, quality
z	vertical position in the heated section (m)

Indexes

0	at the inlet
c	critical
f	final
g	saturated vapor
hs	heated section
i	initial
l	saturated liquid
lg	absolute difference between vapor and liquid
p	permanent crisis
s	quasi-steady state
t	temporary crisis

In this article, we will present the results and analysis in the case of the most violent solicitation conceivable, i.e. the application of a power step-pulse with a static initial condition in which no power is being applied on the loop. The more realistic, less violent situation in which the initial condition is given by an initial steady power and flow, and an increasing power step-pulse is applied, will be considered in a future article.

2. Description of the experiment

2.1. The experimental facility

The experimental facility consists of a natural circulation loop, depicted in Fig. 1, formed by a U-shaped tube at the bottom and a reservoir closing the loop at the top. The loop is filled with nearly saturated liquid helium at atmospheric pressure. Vapor is created in the test section, producing a column weight unbalance between the two branches and the apparition of a convective flow (indicated with arrows on the diagram). The full detail of all the components and instrumentation is presented in [16].

Two different test sections have been used in this work. Both are 1 mm thick, vertical, oxygen-free high purity copper tubes (OFHC, RRR = 145). Power is electrically provided by a spiral Manganin® heater glued on the external wall of the tube. The geometrical parameters of each test section are provided on Table 1.

Instrumentation allows measuring the following flow variables:

- *the mass flow rate* ($\dot{m}$) with a Venturi tube placed on the down-comer and a differential pressure sensor (Validyne model DP10-20).
- *the pressure drop on the test section* (ΔP_{hs}) with a differential pressure sensor (Validyne model DP10-22). Pressure taps are near the entrance at P1 and near the exit at P2.
- Wall temperature (T1 to T5): five Cernox™ CX-1050 SD temperature sensors are placed along the heated section to measure the wall temperature.

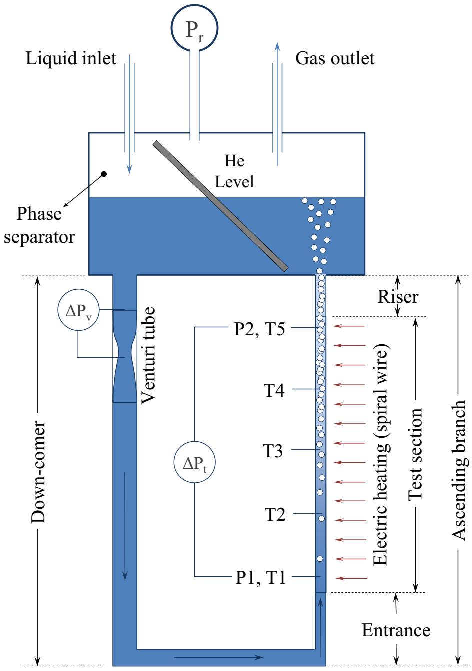

Fig. 1. The natural convection loop elements and main measured variables.

The pressure sensors are connected to the taps by gas-filled capillaries. They are placed inside the cryostat, in order to avoid heated capillary filtering effect on transient measurements. The sensing principle of these sensors is the displacement of a membrane that creates a disequilibrium in an inductance bridge. The voltage signal provided by their electronics is very linear with respect to the pressure difference. The calibration was done with the sensors immersed in liquid helium in a distinct experimental rig where the pressure sensitivity (voltage to pressure difference) was measured for the range of the experiment. The accuracy of this

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