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Inhibition of premature transient boiling crisis induced by heat-load step pulses in a helium natural circulation loop by dynamic initial condition

H. Furci *, B. Baudouy, A. Four

CEA de Saclay, DSM/Irfu/SACM, 91191 Gif-sur-Yvette, France

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ABSTRACT

Boiling helium natural circulation loops constitute a cooling option for large superconducting magnets. Their steady state thermalhydraulic behavior has already been studied quite thoroughly. However, the transient response of these systems has started being studied only recently. Although transient boiling experiments with other fluids or heating configurations exist, their findings are difficult to extrapolate to the case of natural circulation loops. In this work, we present the continuation of an experimental study on helium natural circulation loops. In this case, the system is excited by a stepwise power increase from a dynamic initial condition (a stable initial heat flux is applied). Boiling crisis onset during the transient was identified from the measurement of wall temperature on the heated section. The increase of the initial heat flux and the consequent initial flow increase have been found to have a partial or complete inhibiting effect on transient boiling crisis onset in the premature boiling crisis regime with respect to the static initial condition case. Behavior charts could be drawn on the initial-final heat flux plane. A general empirical criterion based on the evolution of vapor fraction along the section is provided for the prediction of boiling crisis onset by this mechanism.

1. Introduction

Helium natural circulation loops are the cooling systems of some large superconducting magnets, based on the advantages given by the absence of a pump in the hydraulic circuit. It is the case of the CMS detector at CERN [1] or the spectrometer R3B-GLAD for GSI [2,3]. In order to ensure that the temperature margins required for the safe operation of the superconducting magnets are fulfilled, a thorough knowledge of the steady state and transient dynamics regarding heat and mass transfer of these loops is highly valuable. The steady state of boiling helium natural circulation loops has already been studied extensively [4–10] but the transient behavior only preliminarily [11]. Previous works on transient heat transfer to boiling helium can be found in the literature [12–17], but these works focus mainly on small pool boiling systems (vertical or horizontal cylinders and flat plates). In no case is the problem of large natural circulation loops addressed.

This article is the second part of an experimental study of the transient behavior of a boiling helium circulation loop, with a special focus on the transition to boiling crisis. In our previous works [9,18], we treated in detail, respectively, the steady state heat transfer and the case of transients that start at a static initial condition, i.e. with no initial power applied on the loop and, therefore, no initial flow. The experiments in Ref. [18] are called hereafter 'type 0' experiments or transients. This is expected to be the most violent solicitation that one can imagine. This study highlighted the existence of different mechanisms initiating boiling crisis after a sudden power step-pulse. In particular, one of these mechanisms is directly linked to the evolution of cross-section average thermal-hydraulic parameters (vapor fraction or enthalpy) and is exclusively the consequence of the fact that the loop is operated with transient heat load and in natural circulation. It consists of an excessive vapor fraction increase before the arrival of a cold front that results from the onset of circulation. This mechanism, which we baptized 'linear regime', has been shown to be widely present in relatively large helium loops and capable of advancing the onset of boiling crisis with respect to the power limits found by reaching a given state increasing power quasi-steadily. We will call hereafter 'premature boiling crisis' the phenomenon by which the transient critical heat flux (CHF) is lower than that in steady state.

In this article we will present experimental results of similar experiments on the same setup, in which the initial condition is that of the system in dynamic equilibrium at a given power (lower than the final power applied). We call these experiments 'type 1'. This situation is more representative of a cooling system that undergoes a power increase incident while it was operating normally at a given steady power.

* Corresponding author at: CERN, CH-1211 Geneva 23, Switzerland.
E-mail address: hernanfurci@gmail.com (H. Furci).

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Nomenclature

Acronyms

CHF	critical heat flux
DNB	departure from nucleate boiling
NB	nucleate boiling
SNB	Stable Nucleate Boiling
SBC	Stable Boiling Crisis
TBC	Temporary Boiling Crisis

Roman

D	heated section internal diameter (m)
h	specific enthalpy (J kg^{-1})
L	heated section length (m)
$\dot{m}$	mass flow rate (kg s^{-1})
q	heat flux (except for sub-index v) (W m^{-2})
q_v	volumetric heat input (W m^{-3})
T	temperature (K)
t	time (s)
u	velocity (m s^{-1})
v	specific volume (m^3 kg^{-1})
x	vapor mass fraction
z	position along the heated section (m)

Greek

Ω	two-phase evaporation expansion rate (s^{-1})
ρ	density (kg m^{-3})

Indexes

0	at the inlet
c	critical
d	duration
f	final
g	saturated vapor
i	initial
inh	inhibition of crisis
l	saturated liquid
lg	difference between saturated liquid and vapor
lg	change from liquid to vapor phase
max	when maximum quality happens
p	permanent crisis
s	quasi-steady state
$t \leftrightarrow p$	from temporary to permanent crisis
t	temporary crisis

We feel that a more profitable reading of the current article can be achieved after having read the cited works [9,18]. This will allow the reader to compare the characteristics of type 1 transients to type 0 and to the steady state behavior of the loop. Also the terminology to classify the boiling crisis onset regimes has been introduced there.

2. Description of the experiment

2.1. The two-phase loop facility

The same experimental facility as in our previous works was used to do new experiments. We recall that this facility is a U-shaped loop with a liquid helium storage reservoir on top, with one of the two branches containing a roughly 1-m long vertical heated section of variable internal diameter, 6 (V06) or 10 (V10) mm. Wall temperature is measured at 5 points along the heated tube (called T1 through T5) at approximately equidistant positions, using Cernox temperature sensors. The total mass flow rate at the inlet is measured with a Venturi tube in the descending branch, and the pressure drop is measured on the heated tube. The technical details of the cryostat and instrumentation as well as the geometrical details of the loop are presented in Refs. [9,18]. The loop is filled with liquid helium and, with no power applied, the liquid is at 1 atm and 4.2 K, i.e. at non-pressurized saturated equilibrium condition. A scheme of the natural circulation loop is presented in Fig. 1.

The uncertainty for temperature differences on the same sensor is below 6 mK and 1% of the difference. Pressure drop measurements have an uncertainty of 3%, and the overall mass flow rate uncertainty of the Venturi flowmeter is around 4%.

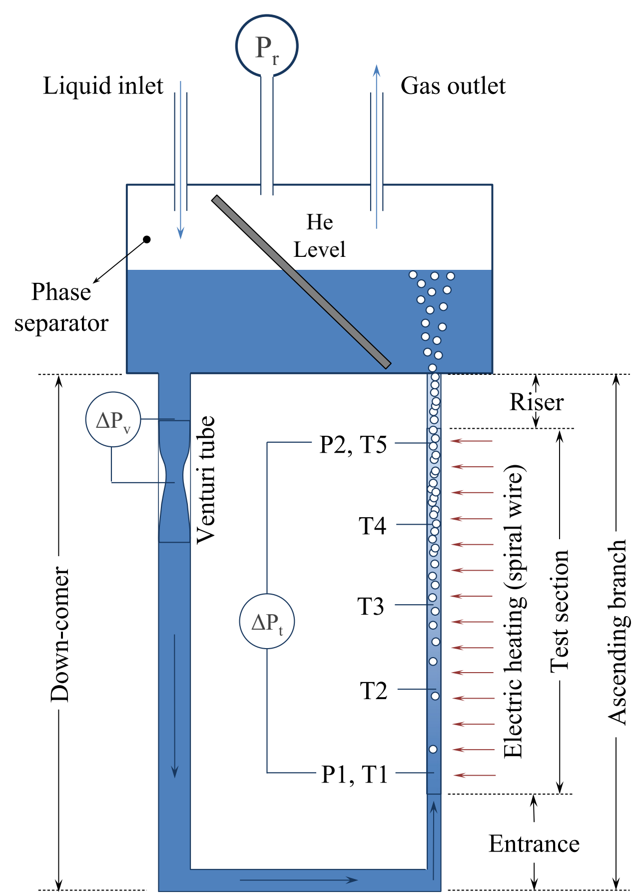

Fig. 1. Scheme of the natural circulation loop used in the experiments.

2.2. Measurement protocol

In our experiments, a transient is characterized by two parameters: the initial and the final heat fluxes applied on the vertical heated section, q_i and q_f. Initially the system is made to reach steady natural circulation equilibrium at $q = q_i$, and suddenly $q = q_f$ is applied in a stepwise manner. Data acquisition is set to record the conditions at $q = 0$ and $q = q_i$ and the time evolution since when q becomes equal to q_f. The measurements presented in this work can be classified into two types depending on the evolution of the injected power: