Cryogenics xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics

Modeling of thermohydraulic transients in a boiling helium natural circulation loop

H. Furci *, B. Baudouy

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

ARTICLE INFO

Article history:
Received 20 October 2015
Received in revised form 12 January 2016
Accepted 30 January 2016
Available online xxxx

Keywords:
Helium
Transient
Modeling
Two-phase flow
Homogenous model

ABSTRACT

Boiling helium natural circulation loops are a cooling option for superconducting magnets. Previous studies on the field have provided a thorough understanding of their steady state behavior in all boiling regimes. Recent experimental research has lead to the understanding of their transient behavior. In particular, it highlights the impact of the thermohydraulic evolution of the circuit on the onset of transient boiling crisis, which represents a limitation of the cooling system. Hence, the need of modeling this aspect of these systems. In this work we present modeling options of two-phase helium loops departing from the homogeneous equilibrium two-phase flow model. Reasonable additional assumptions are introduced to obtain a simplified model and the effect of these assumptions is evaluated by comparison with the solution of the non-simplified equations system. These methods are compared to experimental data to analyze their success and limitations.

1. Introduction

Helium natural convection is the cooling scheme of some large superconducting magnets, such as CMS at the LHC for CERN [1,2] or R3B-GLAD for GSI [3,4]. This kind of cooling systems presents inherent advantages resulting from the absence of pump in the hydraulic system: no presence of mobile parts that require maintenance, the passive safety provided by the natural circulation of coolant and the benefit on the enthalpy balance at low temperature, that lowers the liquefaction power required.

Different aspects of this type of cooling system have been and continue being studied extensively [5–10]. The ensemble of these studies have provided a thorough comprehension of the heat and mass transfer phenomena in the diverse boiling regimes in the steady state. Nevertheless, the transient behavior of these loops in response to time-varying heat load still needs to be further studied.

The authors of the present work have started research on this line by experimental means. In the earlier work presented in Ref. [11] we have shown the occurrence of premature boiling crisis in transient conditions: when a final wall heat flux is attained in a stepwise manner, boiling crisis can take place at a lower heat flux than when reaching this condition in a quasi-steady power progression. Additional data and a more profound analysis have led to a better qualitative and quantitative understanding of the phenomena that determine the anticipation in terms of power of boiling crisis with respect to the quasi-steady case.

In this paper we tackle another aspect of the problem: the development of models and numerical tools that will enable the prediction of the behavior of these systems in response to unsteady heat load. These tools are necessary both for understanding the possibilities and limitations of present operating devices and for predicting possibilities and limitations in the case of future designs.

2. The experimental observations

Our findings on transient boiling crisis induced by a time-varying heat load motivated the modeling of the dynamics of natural circulation loops. We are not going to describe in much detail these results in this paper, but we are going to enunciate the key points that play a role and that should be taken into account in the models.

2.1. Brief description of the experiments

The experiments were conducted in a U-shaped natural circulation loop. This loop is placed inside a cryostat and filled with liquid helium, at atmospheric pressure (4.2 K boiling point). The loop is schematized in Fig. 1. It is formed by a top reservoir that acts as phase-separator, a descending branch on the left that acts as

* Corresponding author.
E-mail address: hernanfurci@gmail.com (H. Furci).

http://dx.doi.org/10.1016/j.cryogenics.2016.01.005
0011-2275/

Nomenclature

Acronyms
HEM homogeneous equilibrium flow model
ODE ordinary differential equation
PDE partial differential equation
RHS right hand side (of an equation)

Symbols
A cross section area (m^2)
D internal diameter (m)
e specific internal energy ($J\,kg^{-1}$)
$\tilde{e}$ specific energy $e + \frac{u^2}{2}$ ($J\,kg^{-1}$)
$\mathbf{e}_s$ unit vector in the s direction
f friction factor
G integral of momentum ($kg\,m^{-1}\,s^{-1}$)
g gravity acceleration (9.8 $m\,s^{-2}$)
$\mathbf{g}$ gravity acceleration vector ($m\,s^{-2}$)
h enthalpy ($J\,kg^{-1}$)
Ω two-phase expansion rate (s^{-1})
p pressure (Pa)
q heat generation rate ($W\,m^{-3}$)
ρ fluid density ($kg\,m^{-3}$)
s curvilinear space variable (m)
sg sign function
t time (s)
u velocity ($m\,s^{-1}$)
v specific volume ($m^3\,kg^{-1}$)

Indexes
0 at the entrance of the heated section
d down-comer
e adiabatic entrance of the ascending branch
ext. external to the loop, i.e. in the phase separator
f liquid subcooled phase
fr friction
g gas saturated phase
h heated section
in at the inlet of the down-comer
L over the whole loop (for integrals)
l liquid saturated phase
lg difference between phases (absolute value)
out at the outlet of the riser
r adiabatic riser
sing. singularity in the circuit
u horizontal section of the U-shaped loop

down-comer and an ascending branch on the right. The ascending branch has a section that can be heated by an externally glued wire, thus producing vapor and driving the flow. Temperature was measured at 5 points along this heated section to study the heat transfer regimes, as well as the total mass flow rate in the descending section (with a Venturi flow meter) and the pressure drop on the heated section, allowing to study hydraulic properties of the flow.

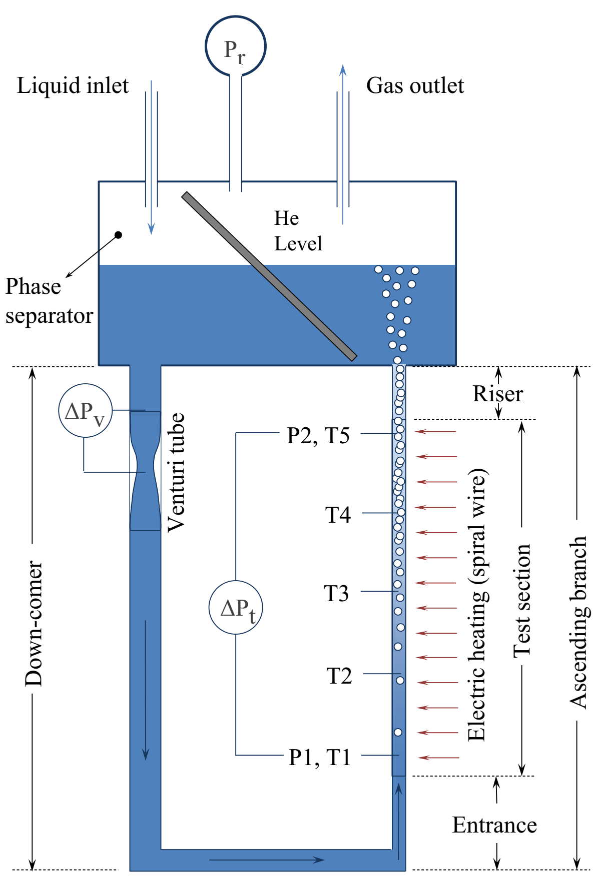

Fig. 1. Diagram of the experimental loop.

2.2. Observations concerning boiling crisis

The transient experiments that interest us consisted of exciting the system with a step power pulse on the heated section and observing the evolution of the measured variables. In particular, great efforts were devoted to the study of those transients that present boiling crisis, i.e. temperature excursions significantly above the typical values of nucleate boiling (NB) heat transfer regimes.

Earlier work [11] showed that boiling crisis during transients induced by a sudden increase of power can take place (temporarily) at lower final values of heat flux than in steady state. Further experiments and data analysis allowed us to determine that the physical mechanism producing the onset of crisis in these cases is of a different nature than that in steady state. Boiling crisis in these cases can be explained by an initial two-phase expansion stage in which the vapor fraction overshoots its final stable value. This happens before the natural circulation starts by gravity unbalance and promotes a cold front from the entrance of the heated section towards its exit. If sufficiently high vapor fractions are reached, liquid contact can get lost completely, producing a boiling crisis. It has been appreciated that the evolution of the thermohydraulic variables (enthalpy, vapor fraction, fluid velocity, etc.) and their interactions play a major role on this type of crisis. The simultaneous usage of our empirical observations and a reliable model of the aforementioned evolution would enable the prediction of the onset of transient crisis. It is in this context that we try to conceive models capable of simulating the thermohydraulic evolution of a helium natural circulation loop to dynamic heat load.

3. Modeling approach

We took as a starting point for the modeling of a two-phase flow helium natural circulation loop the equations of the 1D time-dependent homogeneous equilibrium flow model (HEM). This is justified by the fact that previous research indicates that

Please cite this article in press as: Furci H, Baudouy B. Modeling of thermohydraulic transients in a boiling helium natural circulation loop. Cryogenics (2016), http://dx.doi.org/10.1016/j.cryogenics.2016.01.005