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An analysis of interacting instability modes, in a phase change system

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ABSTRACT

This paper presents an analysis of the interaction of pressure-drop oscillations (PDO) and density-wave oscillations (DWO) for a typical NASA type phase change system. A transient lumped parameter model is developed for use in the analysis of the dynamics of this type of system. A compressible volume (e.g., an accumulator vessel) dynamics model was also developed and PDO/DWO interactions are investigated.

1. Introduction

The purpose of this paper was to analyze interacting instability modes in phase change systems, such as those used in nuclear reactors. This research has been motivated by the requirements of space exploration. In particular, an ambitious long range research program has been formulated by NASA for the human exploration and development of space (HEDS). This program includes the possible development of a lunar base and subsequent manned-missions to Mars. It has been found that one of the key enabling technologies which will be required to support the power, propulsion and life support aspects of these missions is the use of a phase change system in space (NRC, 2000). In particular, it appears that an on-board nuclear fission reactor, and an associated Rankine cycle energy conversion system, may be required to supply reliable power and propulsion for NASA's missions (NRC, 2000). This, in turn, implies that one must be able to reliably predict the performance of two-phase flows and phase change systems (e.g., boilers and condensers) in microgravity (i.e., $\leq 10^{-6}$ g) environments.

There is a need to develop a better understanding of the effect of gravity on many important multiphase phenomena, such as flow regimes, critical heat flux (CHF), pressure drop and phase change system stability (NRC, 2000).

This paper is focused on the development of the analytical capability required to analyze the effect of gravity on phase change system stability and the possible interaction of various system instability modes in typical phase change systems. In particular, we focus here on the analysis of the interaction of density-wave oscillations (DWO) and pressure-drop oscillations (PDO) in a typical experiment which could be performed both on earth and aboard the International Space Station (ISS). These types of interactions are of concern in NASA's proposed nuclear fission reactors, since any associated Rankine cycle energy conversion system will necessary be operating at low pressures to minimize weight.

Fig. 1 shows a typical test loop which was designed for use by NASA. The size of this test loop is appreciably smaller than a typical boiling system so that it can be tested aboard the ISS. Nevertheless, when properly scaled, the system instabilities are representative of much larger phase change systems. The geometry and operating parameters of the test section shown in Fig. 1 are given in Table 1.

Various thermal–hydraulic system instabilities have been observed in phase change systems. Typical instabilities are density-wave oscillations (DWO), flow excursions (i.e., Ledinegg instabilities), and pressure-drop oscillations (PDO). Both density-wave oscillations and pressure-drop oscillations are classified as dynamic instabilities whereas an excursive instability is normally classified as a static instability (Lahey and Moody, 1993). Kakac and Bon (2008) have done a comprehensive review of dynamic system instabilities, including when there may be interaction between DWO and PDO.

A density-wave instability can produce oscillations in the flow, which may either increase or decay in amplitude. These oscillations occur when a fluctuation in the subcooled inlet flow creates an enthalpy perturbation in the single-phase region of the heated channel, such that the boiling boundary begins to oscillate due to these enthalpy perturbations. As a consequence, these enthalpy perturbations induce quality and void fraction perturbations in the two-phase region of the test section. These perturbations cause, in turn, a perturbation in the two-phase pressure drop. If the total pressure drop across the heated channel is imposed (e.g., due to a parallel channel boundary condition), a perturbation in the two-phase pressure drop induces a feedback perturbation in the pressure drop of the subcooled (single-phase) region, which can either reinforce or attenuate the initial flow perturbation, and if in phase, may lead to a self-sustained DWO.

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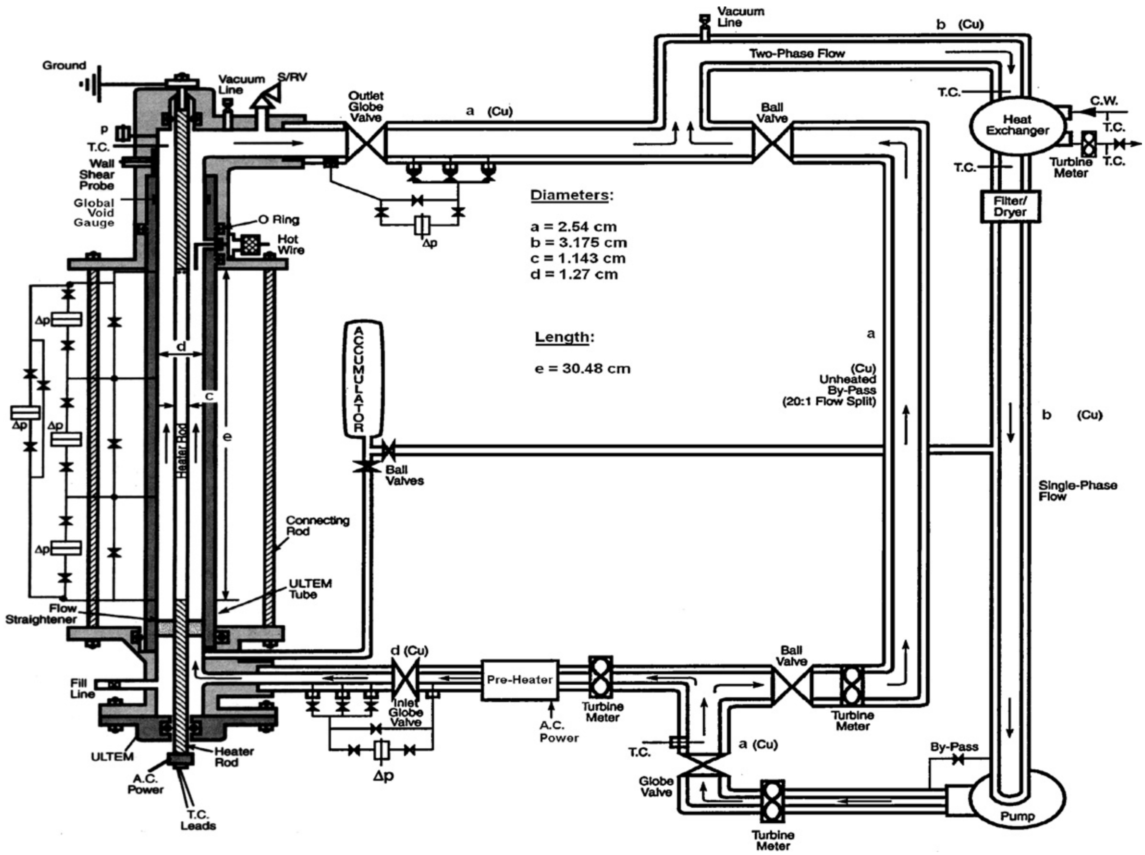

Fig. 1. Typical NASA test loop.

Non-periodic flow excursions arise from the interaction between the system's impressed head – flow characteristics and the hydraulic characteristics of the heated channel. An excursive instability may occur when trying to operate where the slope of the steady-state pressure drop versus flow curve of the heated channel is negative (e.g., region B to D in Fig. 2). We can only operate on this branch of the system's pressure-drop curve when the flow is forced by a suitable pump (e.g., a positive displacement pump). In general, when the slope of the pressure drop versus flow curve is negative, we may have an unstable fixed point, point A, which is a repeller (Strogatz, 1994). For an impressed constant pressure drop, fluctuations in the channel's flow will cause the flow to be repelled from this unstable fixed point to one of the two stable fixed points, or attractors (e.g., A′ or A″ when having the same pressure drop, as for a parallel channel boundary condition), depending on the sign of the perturbation. If the flow reaches the single-phase attractor (e.g., the stable fixed point, A′, in which the flow is single-phase liquid throughout the heated section) then the flow will be stable. In contrast, if the flow is sent to the two-phase attractor, A″, then the flow may operate at this fixed point or it may oscillate about it in the form of a DWO (Kakac and Bon, 2008; Yin et al., 2006).

A pressure-drop instability can produce oscillations which are somewhat similar to those found in density-wave oscillations, but at a different frequency, with the frequency based on the dynamics of the compressibility of the system. In particular, a compressible volume will result from the use of an accumulator, such as that shown in Fig. 1. During a pressure-drop oscillation (PDO), the flow may be diverted from entering the test section and will enter the accumulator. The increase of fluid in the accumulator volume compresses the gas in the accumulator, which after an over-compression, will later expand (actually over-expand), pushing fluid out of the accumulator and back into the inlet of the test section. These pressure-drop oscillations only occur for the case when, if the accumulator was coupled to the inlet of the test section, an excursive instability can occur.

Stenning et al. (1967) verified that a negative slope in the heater's pressure-drop characteristics was required for the pressure-drop oscillations (PDOs) to occur. These oscillations were associated with the presence of a compressible volume at the inlet of the heater. Kakac and Bon (2008) described a PDO as a flow oscillation that roughly traces the limit cycle EBCDE in Fig. 2. Stenning and Verizoglu (1965) and Maulbetsch and Griffith (1965) observed density-wave oscillations (DWOs) when operating on the EB branch of the system's operating

Table 1
Proposed ISS test section.

Fluid	FC-72
System pressure	300 kPa
Heated channel type	Annular
Hydraulic diameter	0.00127 m
Heated perimeter	0.03591 m
Channel area	2.407×10^{-5} m^2
Heated length	0.3048 m