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Visualization experiments on the geyser boiling-induced instability in vertical circular tube at low-pressures

Lili Tong [a,*], Jinbo Chen [a], Xuewu Cao [a], Shengxing Yang [a], Shiliang Liao [a], Jian Deng [b], Wei Zeng [b]

[a] School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China
[b] Nuclear Power Institute of China, Chengdu 610041, PR China

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ABSTRACT

The geyser boiling in a vertical circular tube with an inner diameter of 32 mm is experimentally investigated with water under system pressure, in which the heat flux and system pressures are in the ranges of 0–7.96 W cm^{-2} and 0.1–0.4 MPa, respectively. The test channels consist of three parts: a heated channel section installed downstream, a nonheated middle channel section and an elevated water tank installed upstream. The process of the geyser boiling is observed by visualization, which can be characterized by a quiet phase, an explosive eruption of vapor and refilling of subcooled liquid, including four typical flow patterns, namely, bubbly, slug, churn and annular flow. The results show that the geyser boiling occurs obviously below 0.12 MPa, but the intensity of the geyser eruption becomes lower, when the system pressure is increased, and the fluid temperature is affected by system pressure. The intermittent flow and boiling disappear when the system pressure is raised beyond the threshold, which may be helpful to suppress the intermittent flow instability during the water injection in nuclear reactor at accidents.

1. Introduction

Natural circulation or water injection under gravity as a heat removal mode is being considered as passive safety features in the innovative nuclear reactor designs, particularly in the new generation of pressurized water reactor, such as AP1000 and ABWR, due to its inherent physical mechanism for reliable heat removal under accident conditions based on passive principles (Jain et al., 2010; Kozmenkov et al., 2012; Lakshmanan and Pandey, 2009). However, in a system using natural circulation or water injection under gravity where pressure and thermal power are relatively low as the main driving force of cooling water, various kinds of thermal hydraulic instabilities might be induced (Watanabe et al., 2008). And a particular interesting phenomenon in natural circulation systems is the geyser boiling-induced instability. The term "geysering" refers to violent explosion of vapor due to overheated liquid which are generally followed by reentering of the subcooled liquid. Under certain thermal conditions, a large amount of liquid is periodically vaporized and propelled from the heating section to the subcooled section with a significant velocity. This fast-moving liquid result in oscillating heat transfer and strong pressure fluctuations, and the reverse reentering fluid produces a water hammer or shock, which may damage the container and channel wall under an extreme case (Lin et al., 1995).

Geyser boiling is a thermal nonequilibrium phenomenon and assumes greater significance particularly at low-pressures, which has been observed mostly in a variety of closed end, vertical columns of liquid, heated at the base (Durga Prasad et al., 2007). The whole process is explained as occurring in four different parts: boiling delay, superheating boiling, explosive eruption of vapor and liquid refilling. Fig. 1 shows a representation of the geyser boiling phenomenon in a vertical tube. The mechanism can be explained as follows (Paniagua et al., 1999; Aritomi et al., 1993). In vertical channels, bubbles are generated and gradually a large slug of bubbles is formed as a result of the overheating, which grows due to decrease in the hydrostatic pressure head. The superheated water in the channel closed at the bottom vaporizes and then explosive eruption occurs, when large quantity of vapor mixed with liquid is propelled towards the upper subcooled liquid, and the condensed liquid refills the channels and restores non-boiling conditions.

Casarosa et al. (1983) investigated the "geyser effect" experimentally in a two-phase thermosyphon facility using water at gauge pressures between 0.03 and 1.0 bar and with heat fluxes between 2.0 and 15.0 kW m^{-2}, in which the process of boiling occurs with bubbles of large diameter at low pressure is observed. The intensity of the geyser effect reduces with increase of the

* Corresponding author. Tel./fax: +86 21 34205495.
E-mail address: lltong@sjtu.edu.cn (L. Tong).

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pressure in the condenser until the effect disappears, in which it is pointed that at low pressure (less than 0.15 bar), the overheating between wall and fluid is unaffected by variations in the specific thermal flux, which means that the geyser effect may occur even at the low values of thermal flux. Kuncoro et al. (1995) experimentally investigated the mechanism of the geyser in a closed two-phase thermosyphon as the system pressure is varied from 3.4 kPa to 47 kPa for water, in which it is observed that degree of superheat changes with system pressure, with lower pressures usually resulting in a higher degree. The results are consistent with those given by Niro and Baretta (1990). Watanabe et al. (2008) experimentally investigated the thermal hydraulic instabilities such as geyser in vertical multicombined channels under natural circulation conditions, in which it is observed that the intermittent type of geyser tends to be suppressed as the system pressure increases and the stable region of the system in higher-heat-flux conditions hardly depends on the system pressure. Chiang et al. (1994) experimentally investigated the effects of system pressure on the occurrence of geyser, in which it is observed that a large bubble covering the entire flow cross section is relatively difficult to be formed with an increase in the system pressure, that is, geyser is suppressed by increasing system pressure. It is supposed that this instabilities hardly occur when system pressure are higher than 0.5 MPa. However, their investigation is limited up to the system pressure of 0.2 MPa only. In addition, Inada and Yasuo (1992), Masuhara et al. (1993), Tong et al. (2014) and Chen et al. (2014) have also performed small scale experiments to demonstrate this phenomenon, and these experiments illustrated that the geysering-mode oscillations could occur at low pressures and low flows under certain thermal hydraulic conditions.

The current investigation shows that the mechanisms and characteristics of geyser boiling are widely diverse dependent upon the system configuration and operating conditions such as system pressures or the thermal transport conditions. And it is the difference of system configuration that directly resulted in different input thermal conditions in the test facility. Thus, the resulting geysering phenomenon can be further classified into two types: Griffith's type and Aritomi's type according to the difference in input thermal conditions (Watanabe et al., 2008). Griggith (1962) studied geysering in a vertical heated channel under non-flow-circulation conditions, which concluded that a superheat is required for vapor burst during geysering process explained as follows. A large bubble generated by superheated liquid in the heated section rises and grows due to a decrease in the hydrostatic head, as it moves toward the exit. The bubble is mixed with subcooled liquid in an upper plenum and is condensed therein. As a result, the pressure in the channel rapidly decreases, and then subcooled liquid reenters the channel. This process is repeated periodically. Aritomi et al. (1992) experimentally investigated geysering in vertical twin parallel heated channels under both natural and forced circulation conditions, which is concluded that if large slug bubbles just exist in the parallel channels instead of bubbles generated by superheated liquid, geysering could be induced in the parallel channels.

The objective of this study is to experimentally clarify the transport mechanisms of this flow oscillation in a test facility with a vertical heated section with no circulation. During the loss of coolant accidents in nuclear reactors, the temperature and pressure affect the heat removal from the reactor core by natural circulation or water injection under gravity. Therefore it is worth to investigate the pressure effect on the behavior of geyser boiling under such conditions. In this paper the pressure effect is experimentally investigated to understand the flow instability mechanism in the geyser boiling process, induced by superheating a long vertical tube with a closed lower end under the pressure with the range of 0.1–0.4 MPa.

2. Experimental apparatus

In order to investigate the geyser boiling instabilities in vertical channels, an experimental facility "intermittent flow and boiling in a heated vertical channel" (IFBHVC) is established, shown in Fig. 2a, which consists essentially of a heated section, a vertical riser section and a water tank. The heated section consists of four electric heated rods embedded in an SUS-304 stainless steel tube with an inner diameter of 50 mm and an outer transparent boron silicon glass tube with an inner diameter of 50 mm, as shown in Fig. 2b. The use of glass tube allows visual observation of flow patterns. The heated rods have a length of 0.60 m (10 mm O.D., 1.0 mm thick), and only the upper 0.40 m part is uniformly heated. The heated power is provided by a D.C. 220 V power supply unit which can control the active power ranges of each heated rod, in which the maximum power input is 4.0 kW. The riser section is made of SUS-304 tube with an inner diameter of 32 mm and the length of 1.80 m. The upper water tank is a shell-tube design having a total height of 0.80 m with a total volume of 0.1 m^3, which provides the subcooled water under refilling conditions. The system pressure is controlled by a pressure control system composed of a nitrogen container, a pressure regulating valve and a relief valve to supply pressurized nitrogen. The entire loop, except for the visual section is insulated by thermal insulation layer made of centrifugal glass wool to minimize heat loss. The heat loss due to natural air convection from the uninsulated section is estimated

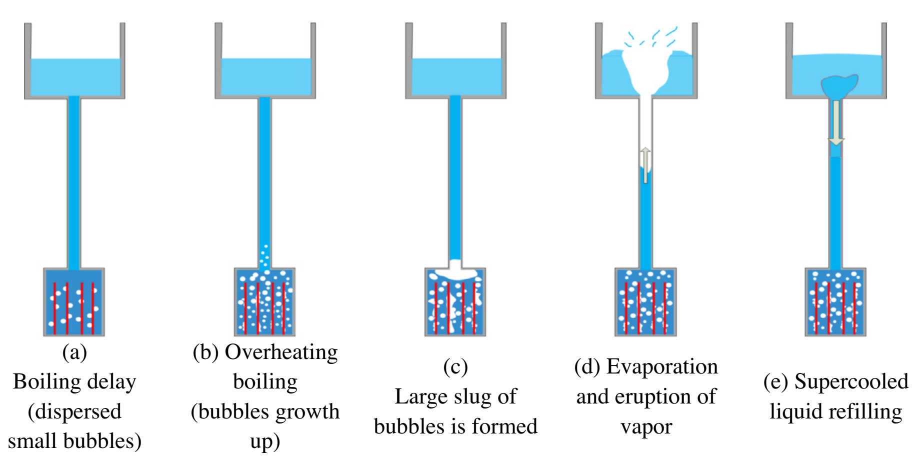

Fig. 1. Fluid transport during geyser boiling process.