Appearance of pressure shocks in subcooled flow boiling at a slightly inclined channel subjected to upper surface

Uiju Jeong [a] and Sung Joong Kim [b*]
[a]*KHNP Central Research Institute, 1312 70-gil Yuseong-daero, Yuseong-gu, Daejeon 34101, Korea*
[b]*Department of Nuclear Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Korea*
**Corresponding author: sungjkim@hanyang.ac*

1. Introduction

The Fukushima accident was an accident in which AC power was lost for a long period in the nuclear power plant. At that time, as most NPPs under operation used active components for their safety functions, several reactor units in Fukushima could not maintain their cooling function. Of course, the emergency diesel generators (EDGs) were prepared for the AC power loss, but they were not working due to flooding caused by a large tsunami. As a result of the Fukushima accident, some advanced NPPs have attracted more attention because they do not rely on active systems to mitigate accident consequences by introducing passive safety systems, e.g. AP1000 and ESBWR. In Korea, development of such advanced reactor is underway, which is called as iPower.

Among the passive safety systems, the focus of this study is the ex-vessel core catcher cooling system. This cooling system was designed for retention and cooling of the corium ejected from the failed reactor vessel for NPPs, such as EU-ABWR, VVER, ESPWR, and EU-APR. These systems have a common feature which utilized boiling to remove residual heat generated from an ejected corium. Boiling occurs at the bottom wall which is designed to be inclined at around 10 degree from the horizontal plane to facilitate vapor venting. This is why we chose 10 degree for the inclination of the cooling channel subjected to upper heating surface in the present study.

Violent behavior of subcooled boiling was observed in the present work. Owing to a downward-facing heater surface, departed bubbles slide along the surface in the form of vapor slug. The bubbles naturally congregated above the surface and grew up to a large one via an active bubble coalescence process. The violent behavior comes from rapid condensation of the large vapor slug. Such rapid condensation causes a local flow reversal and pressure oscillation with frequent pressure shocks. The aim of this study is to examine the pressure shock phenomenon visually and quantitatively, and to predict its influence on the cooling mechanism of the real system of large-scale.

2. Experiment

2.1 Test section

In the test section design, a stable formation of large vapor slug even at a moderate heat flux level was a key factor. Accordingly, heater length and width were determined as 216 mm and 108 mm, respectively. This criterion was set to simulate the prototype core catcher cooling channel, which has a large heated surface. Figure 1 presents some sectional views of the test section in which stud structures are installed in the coolant channel, but the studs were eliminated in the present study.

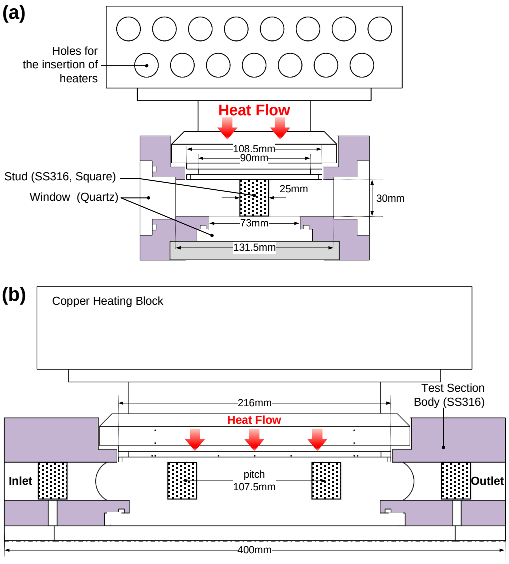

Fig. 1. Sectional views of the test section.

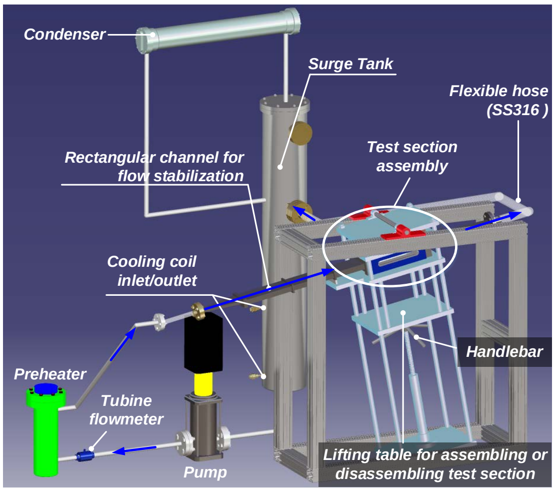

Fig. 2. 3D drawing of the forced convective water boiling loop

2.2 Boiling loop

The water boiling loop is shown in Fig. 2. The bubble condensation induced pressure shock (BCIPS) phenomenon was observed and analyzed by visual observations using a high-speed camera system. A high-speed gauge pressure transducer with a sampling rate of 1000 Hz was used for measurement of dynamically changing pressure.

3. Result

3.1 Visual observation on the pressure shock

Initiation of the pressure shock was defined as appearance of peak pressure exceeding 1 bar (gauge pressure). The specific value of 1 bar was determined by considering the thermodynamic state of water and the wall superheat. This is because the physical connection between the pressure increase and bubble dynamics is considered to be an important factor in the subcooled boiling. For water at atmospheric condition, an increase in pressure of 1 bar leads to increase in the saturation temperature by 20 ^{o}C. Such degree of temperature increase is close to the wall superheat at CHF level. This means that when the pressure buildup is initiated, vapor mass will be condensed and also the bubble nucleation process will be suppressed.

As shown in Fig. 3, the pressure shock and corresponding flow reversal were captured in the subcooled boiling experiment.

Representative behavior of the pressure shock when it is initiated is presented in Fig. 4. The pressure shock can be characterized by a pulse-shaped pressure increase and subsequent decrease even below the atmospheric pressure. Such deep pressure alleviation may cause the bubble growth process to be explosive, accordingly immediate formation of a large vapor slug.

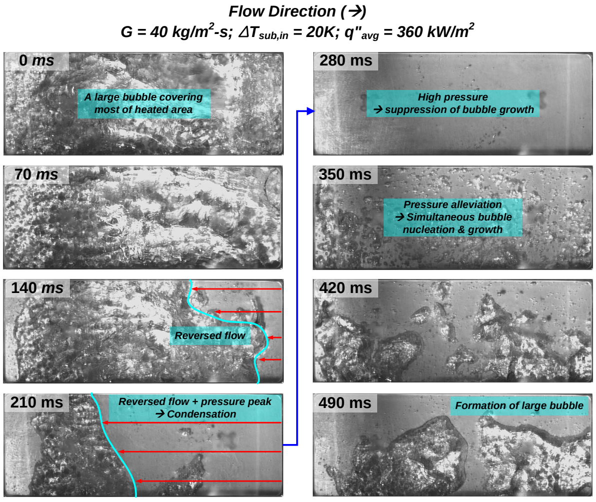

Fig. 3. Bubble behavior when the flow reversal and the accompanying pressure shock occur

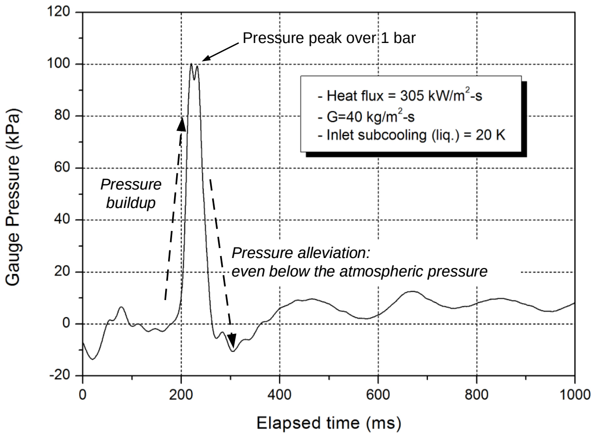

Fig. 4. Representative behavior of the pressure shock

3.2 Quantification of the pressure shock

The initiation conditions for the pressure shock are plotted in Fig. 5 to judge whether the boiling process proceeds stably or not for a given condition. The experimental data for the initiation were produced for various degrees of liquid subcooling and mass fluxes.

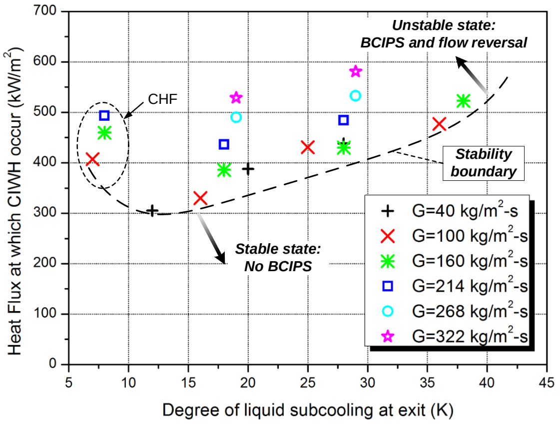

Fig. 5. Stability map at various mass flux, subcooling.

Beyond a specific degree of subcooling of 12 K, the subcooling increase brings out the stabilizing effect on the pressure shock regardless of mass flux. Also, it was found that the boiling crisis occurred instead of appearance of pressure shock when the subcooling is below 8 K. This means that minimum degree of the liquid subcooling required for occurrence of pressure shock is a value between 8 and 12 K. The most influential factor in the shock initiation was found to be the flow velocity, stabilizing the violent behavior. Reduction of size of vapor slug was found to bring out the smaller pressure shock.

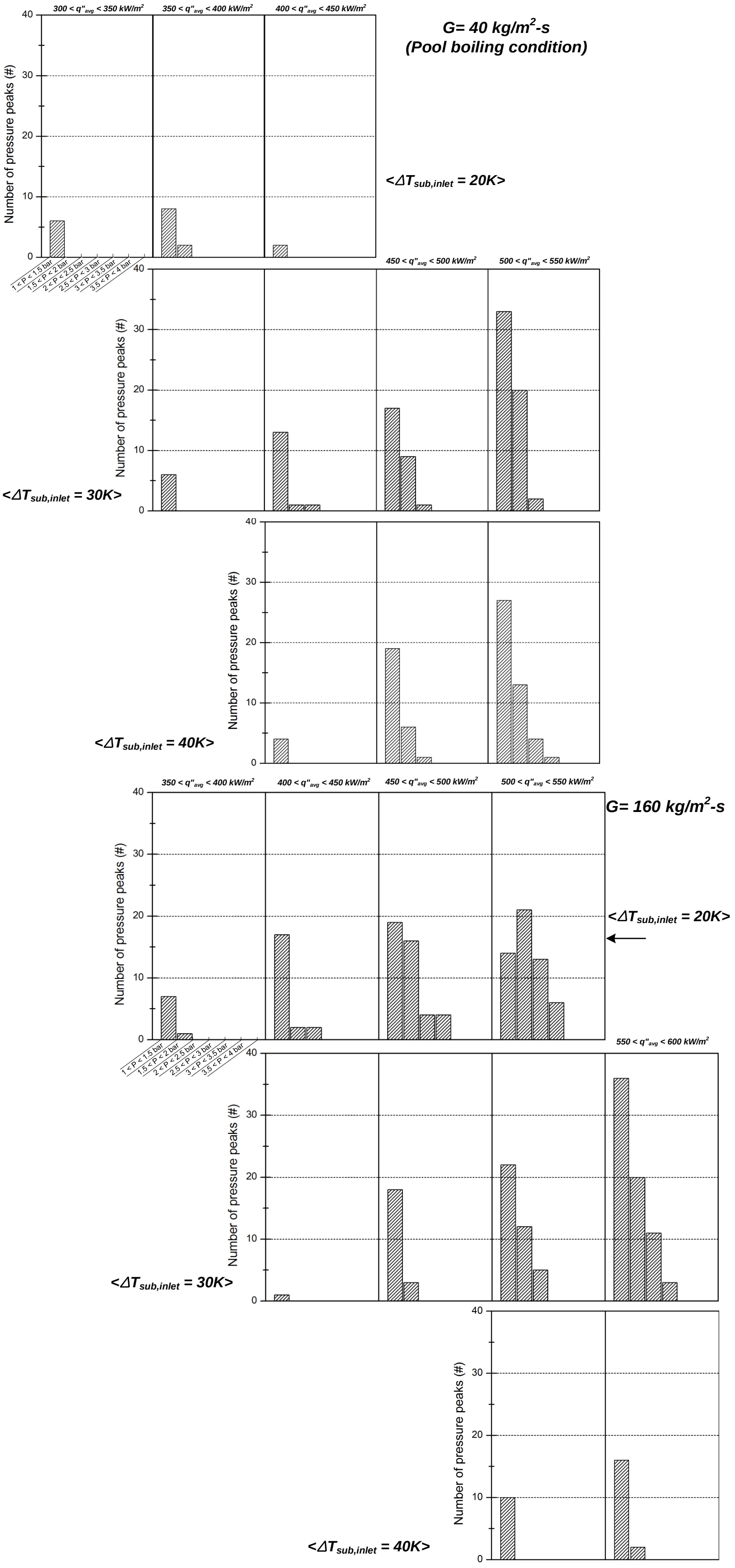

Fig. 6. Change in population distribution of pressure shocks with variation of subcooling and heat flux level at mass fluxes of 40 and 160 kg/m^2-s; amplitude of the pressure shocks were divided into six groups.

Figure 6 presents the change in population distribution of pressure shock, ranging from 1 to 4 bar of gauge pressure. In each case, the number of pressure shocks, shown in the figure, was counted from the pressure data recorded for 3 minutes. Major outcomes can be summarized as below:

- The higher heat flux level, the more frequent and higher pressure shock
- Increase in liquid subcooling generally lowered both amplitude of the shock and frequency
- The maximum amplitude of the shock was measured as 3.74 bar at subcooling of 15 K and mass flux of 100 kg/m^2-s.
- The maximum frequency of the shock was measured as 0.4 sec^{-1}

Formation of a large vapor slug is regarded as a key to understand the parametric analysis involved in the above major outcomes. Obviously, increase in heat flux level results in thicker thermal boundary layer in the vicinity of a heated surface, accordingly denser active nucleate site. The increase in vapor generation brings out either larger vapor slug or more frequent formation of it. According to Griffith (1997) [1], strength of the pressure shock is proportional to volume of vapor slug which undergoes condensation. In this way, it can be physically explained that the heat flux level has a proportional relation with frequency and amplitude of pressure shock.

There are two opposite mechanisms through which liquid subcooling affects the pressure shock. First mechanism is described below as one intensifying the shock. During the condensation process, the higher degree in subcooling of surrounding liquid can cause a more rapid change in liquid velocity at the vapor/liquid interface. This is because the vapor pressure should drop to the saturation value associated with the subcooled temperature. That is, increase in liquid subcooling can raise the pressure shock via intensification of pressure gradient over the liquid/vapor interface. Second mechanism mitigates the pressure shock shock with increase in subcooling. An increase in liquid subcooling will decrease the net rate of vapor generation via addition of sensible energy and increased amount of condensate at the interface between vapor bubble and subcooled liquid in bulk region. As a result, size of the vapor slug get smaller due to reduced amounts of vapor mass.

According to experiments by the present works, it was confirmed that the second mechanism is a dominant mechanism at least in the present study. As the subcooling increases, the appearance frequency and amplitude of the pressure shock remarkably decrease.

3.3 Influence of the shocks on cooling capability

It is expected that the pressure shock will appear in the large-scale system according to experimental works from the present study. More strictly speaking, the shock can occur if the prototype system is operated in the unstable region, presented in Fig. 5. In case of the small-scale experiment, like the present work, the pressure shock has been found to be effective for delay of the boiling crisis, showing favorable influence regarding the cooling limit. The favorable influence comes from a fact that vapor slug hovering on a heated surface can be condensed efficiently by the pressure shock and the violent flow reversal. The pressure shock and the flow reversal bring out a substantial increase in saturation temperature and violent mixing of subcooled water with vapor layer, respectively.

On the other hand, the pressure shock can negatively affect the cooling process of the large-scale cooling channel, e.g. the prototypical core catcher cooling system. Violent mixing right after the shock can promote the condensation considerably, but space under its influence is limited only near the region where the shock occurs. This is because, the jet-like reverse flow would make highly turbulent motions and accordingly lose its kinetic energy rapidly to surrounding fluids flowing in the opposite direction. Thus, the flow reversal and mixing process are expected to have limited contribution to positive effects for large-scale applications. Furthermore, the bulk flow characteristic will be degraded by the pressure shocks via both frequent appearance of the reversed flow and suppression of bubble, which provides a buoyancy force.

4. Concluding remarks

In the present study, pressure oscillation appeared in subcooled flow boiling at the inclined channel subjected to upper heating surface has been investigated and identified as geysering phenomenon. Geysering produces the pressure shocks and rapid flow reversal frequently. It was revealed that the inclined cooling channel with large diameter, large and flat heated surface facing downward is susceptible to the condensation induced pressure shock phenomenon for subcooled boiling situation. The highest amplitude of the pressure shock was measured as 3.74 bar. This means that the pressure shock cannot affect the structural integrity of the cooling system, but can affect bulk flow characteristics and bubble dynamics along the heater surface.

REFERENCES

[1] P. Griffith, Screening reactor steam/water piping systems for water hammer, NUREG/CR-6519, U.S. Nuclear Regulatory Commission, 1997.