Proceedings of the Korean Nuclear Society Autumn Meeting
Seoul, Korea, October 1995

Saturated Boiling Heat Transfer of Freon-113 in Hemispherical Narrow Space and Implications for Degraded Core Coolability in Reactor Vessel Lower Plenum

Kwang-Hyun Bang
Pohang University of Science and Technology

Abstract

Saturated boiling heat transfer experiment in a hemispherical narrow space is conducted using Freon-113 to investigate an additional heat removal capability through a hypothetical gap between lower head and degraded core. The narrow space of 1mm consists of a 124mm-diameter heated stainless steel hemisphere and a glass outer vessel. Within the hemispherical narrow space large coalesced bubbles are produced and these bubbles rise in random direction, causing liquid flow in from the opposite side to fill the region. Such flow in random direction makes the flow field in the narrow space very chaotic and thus enhance heat transfer. The heat transfer coefficient is higher at lower angle and at higher heat flux. The present study shows that the liquid from upper region can effectively penetrate into the gap and augment the heat removal capability through the gap.

1. Introduction

For the thermal analysis of degraded core in reactor vessel lower plenum, it has been widely exercised to consider only two paths of heat transfer; boiling and radiation at the top surface and conduction through lower head. However, if the hypothesis of gap formation between the core and lower head due to the ductile characteristics of lower head material at high temperature is more likely, an additional heat removal capability through the gap could much enhance the coolability of the degraded core within the lower head, thus reduce the probability of ex-vessel progression of severe accident. Recently, some research programs[1,2] have been developed to investigate this inherent nature of degraded core coolability inside the lower head.

Although the information on boiling heat transfer in narrow space is little found in the literature, one valuable work is the one done by Ishibashi and Nishikawa[3]. They conducted a systematic investigation on the effects of gap size, heat flux, and fluid using a vertical narrow annulus consisting of a heating copper cylinder and a concentric glass tube. They reported the frequency of coalesced bubble rise which increases as heat flux increases or the gap size decreases.

The purpose of the present study is to experimentally simulate the boiling heat transfer through a hemispherical narrow space in a small-scale apparatus using a simulant fluid. Flow visualization is made to identify boiling behavior in the gap.

2. Experimental Apparatus

The experimental apparatus is designed to study saturated boiling heat transfer of low boiling temperature fluids in narrow space provided by two hemispherical surfaces facing downward, the inner surface being heated with an electric heater. The apparatus consists of the hemispherical test section, watt meter with variable transformer, coolant circuit for vapor condensation, visualization equipment, and data acquisition system. The overall layout is shown in Figure 1.

Since the visualization of boiling patterns in hemispherical narrow space is of main interest in this study, the test section is made of glass outer vessel and stainless steel inner vessel. The present design of the test section provides 1mm of narrow space with 0.5mm clearance due to the difficulty in fabrication of the glass vessel. The schematic of the test section is shown in Figure 2. The glass vessel is 200mm in height.

The inner vessel is made of a 124mm in diameter and 0.8mm think hollow stainless steel shell and the outer surface is polished. Inside the vessel, a 3.2mm in diameter and 2.4mm long sheathed cable heater is spirally coiled and located close to the inner surface. The heater capacity is 1kW. The vessel is then filled with mineral oil whose boiling point is around 175°C to enhance the uniformity of heat flux. To measure the surface temperatures of the inner surface, four T-type thermocouples are glued to the surface at the locations of 0, 30, 60, and 90 degrees measuring from the stagnation point of the vessel. Two more sheathed thermocouples are installed to monitor the mineral oil and boiling fluid temperatures. The inner vessel and the upper guide tube are joined with a cork gasket to minimize heat transfer to the upper structure.

The power to heater is regulated by a variable transformer and is measured by a digital watt meter. The temperature data are acquired and saved in PC data acquisition system. The visualization of the test section through a mirror is recorded by a video camera.

3. Results and Discussion

The saturated boiling experiment in a hemispherical narrow space was conduced using Freon-113 as working fluid. The boiling point of Freon-113 is 47.5°C. This makes such boiling experiment with simple instruments possible. However, in the present experiment the boiling of heating fluid such as mineral oil inside the inner vessel limited the heat flux, so the highest heat flux applied in this study was 1.5×10^4 W/m^2. In most tests, the temperature data indicated that the steady-state conditions were achieved.

3.1. Boiling Behavior

As the result of observing the boiling behavior within a hemispherical narrow space, a unique boiling pattern is distinguished when compared to the pool boiling case. First, Figure 3(a) shows the bubble behavior in pool boiling of spherical surface facing downward. This was conducted by raising the inner vessel by 50mm, so allowing large space at least in the lower part of the test section. The bubbles rise along the almost straight line in this case. However, as seen in Figure 3(b), which is the case of 1mm gap, the bubbles draw lines in a very chaotic pattern. Also, in the center region, there are a few of large coalesced bubbles. These coalesced bubbles rise in random direction. When such large bubble moves away, the liquid flows in from the opposite direction to fill the region. Such flow in random direction makes the flow field in the narrow space very chaotic. Such liquid inflow is identified by observing the bubble motion making a series of streamlines as seen in Figure 3(c). In this figure, the liquid flows in from the lower-left side.

The present observation of bubble behavior in a hemispherical narrow space is distinguished from the observation made by Ishibashi and Nishikawa[3] in a vertical narrow annulus consisting of two concentric cylinders. They reported the frequency of coalesced bubble rise which increases as heat flux increases or the gap size decreases. In this case the bubble rise is unidirectional, from bottom to top. However, in hemispherical narrow space the bubble rise is in random direction and the refilling liquid flows in from the opposite side. This makes the flow field very complex and any periodic behavior is hardly identified. Such turbulent flow filed must augment the boiling heat transfer in a hemispherical narrow space.

3.2. Heat Transfer

Figure 4 shows the temperature-time traces, indicating that the steady-state was achieved. In this figure, T_{S1} is at the stagnation point and T_{S4} is at right angle, and T_P for oil and T_L for Freon. It is seen that the surface was heated until Freon reached its saturation point, then as bulk boiling suddenly began the surface temperatures dropped rapidly and stayed at the steady-state values.

The temperature data of heating surface were reduced to heat transfer coefficients at the four locations under the assumption of uniform heat flux. Here the measured inner surface temperature can be assumed as the outer surface temperature without a significant error since the temperature drop across the thin wall (0.8mm) is less than 0.5°C ($\Delta T=q''t / k$). The resulting heat transfer coefficients are plotted in Figure 5 for three different heat fluxes. The heat transfer coefficient is higher at lower angle and at higher heat flux. This behavior agrees with the data in the literature[4]. However, the quantitative comparison was not possible due to the lack of data for this geometry. One notes that in the figure the heat transfer coefficients at right angle are almost same independent of heat flux. This may be attributed to the two facts; in this region convective heat transfer is more dominant due to higher vapor flow and heat flux is limited by the edge part of this particular geometry. Finally, the overall heat transfer coefficient in a narrow space is higher than that of pool boiling based on the present data, although any systematic investigation was not made due to the limit of the test section configuration.

3.3. Implications for Degraded Core Coolability in Lower Head

For the thermal analysis of degraded core in reactor vessel lower plenum, it has been widely exercised to consider only two paths of heat transfer; boiling and radiation at the top surface and conduction through lower head. However, if the possibility of gap formation between the core and lower head is more likely, the additional heat removal capability through the gap could much enhance the coolability of the degraded core within the lower head, thus reduce the probability of ex-vessel progression of severe accident. The present study of experimentally simulating boiling heat transfer through a gap in lower head shows that the liquid from upper region can effectively penetrate into the gap and augment the heat removal capability through the gap. To apply the present result to reactor case, however, one must note that the data are limited in mainly two factors; heat flux and geometric scale. Therefore, further investigation on these parameters with a careful experimental design seems in order.

4. Conclusion

The saturated boiling experiment in a hemispherical narrow space was conduced using Freon-113 to investigate an additional heat removal capability through a hypothetical gap between lower head and degraded core. The test section consists of a 124mm-diameter heated stainless steel hemisphere and a glass outer vessel, providing about 1mm gap. Visual observation shows a unique boiling behavior within the hemispherical narrow space. A few of large coalesced bubbles are produced and these bubbles rise in random direction, causing liquid flow in from the opposite side to fill the region. Such flow in random direction makes the flow field in the narrow space very chaotic and thus enhance heat transfer. The heat transfer coefficient is higher at lower angle and at higher heat flux. The present study shows that the liquid from upper region can effectively penetrate into the gap and augment the heat removal capability through the gap. The present data are limited in mainly two factors; heat flux and geometric scale. Therefore, further investigations on these parameters with a careful experimental design are desired to draw more concrete conclusion.

Acknowledgment

This work has been supported by POSCO's Basic Research Grant through Pohang University of Science and Technology.

References

(1) K.Y. Suh, "Lower Head Coolability and KAERI Programs," presented at the CSARP Meeting, Bethesda, Maryland, May 1995.

(2) K.J. Yoo et al., "A Study on the Establishment of Severe Accident Experimental Facility," Korea Atomic Energy Research Institute Report KAERI/RR-1481/94, 1995.

(3) E. Ishibashi and K. Nishikawa, "Saturated Boiling Heat Transfer in Narrow Spaces," Int. J. Heat Mass Transfer, Vol. 12, No. 8, pp. 863-894, 1969.

(4) K. Nishikawa and Y. Fujita, "Nucleate Boiling Heat Transfer and Its Augmentation," in Advances in Heat Transfer, Academic Press, Vol. 20, pp. 1-82, 1990.

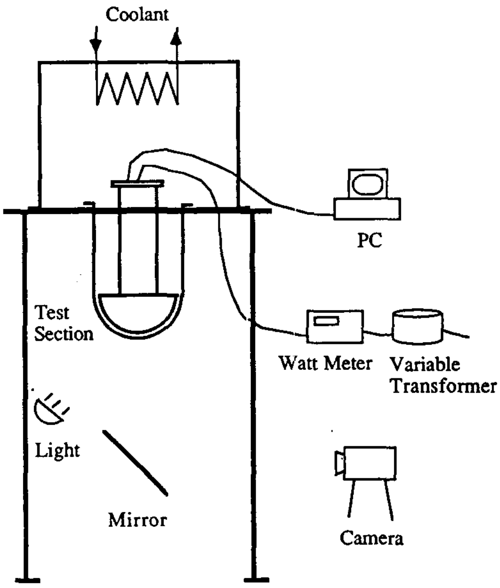

Fig.1. Experimental Apparatus

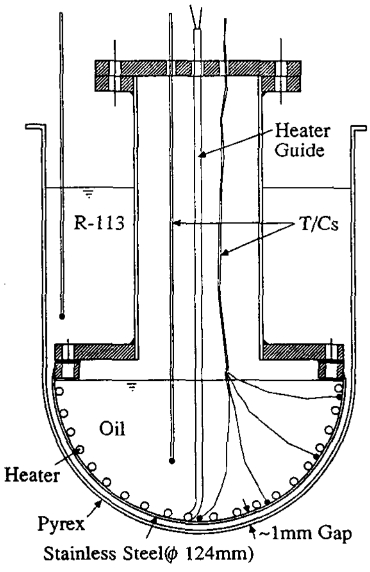

Fig.2. Test Section

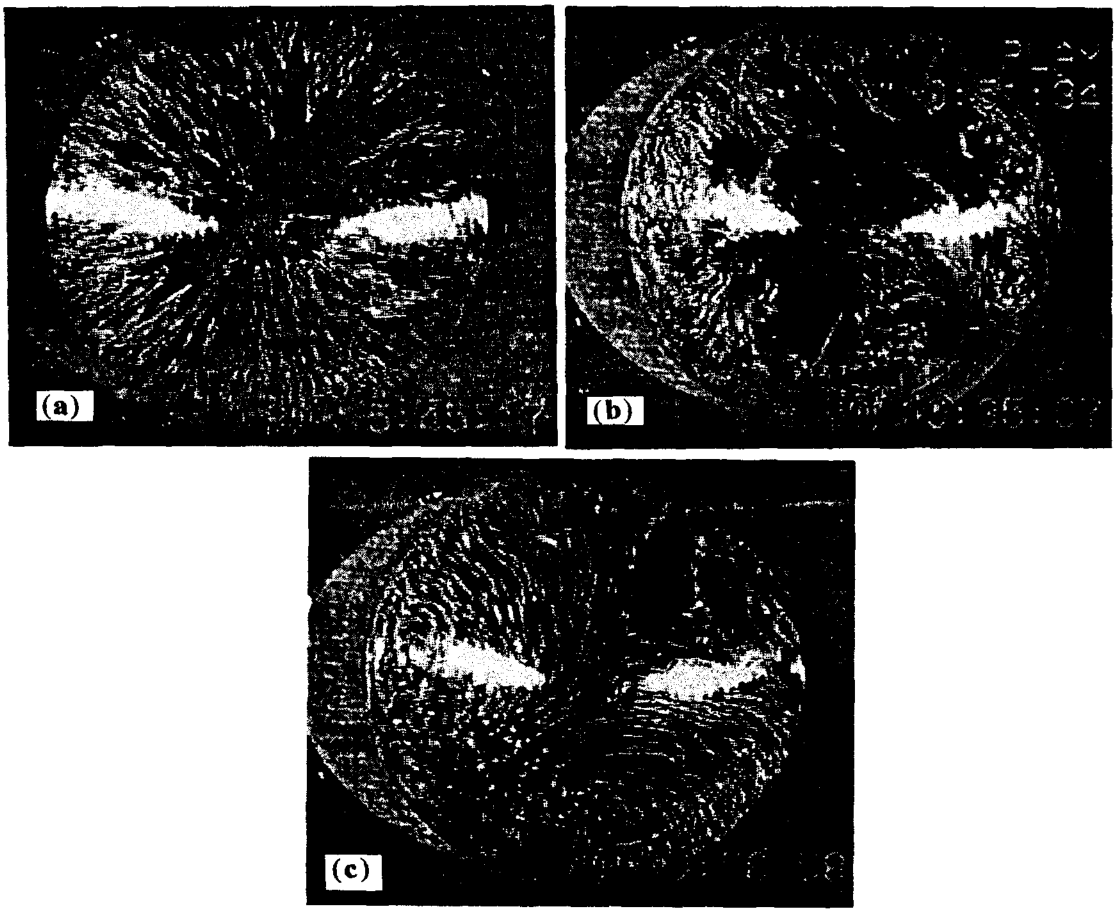

Fig.3. Boiling Behavior: (a) pool boiling; (b) narrow space (1mm); (c) bubble behavior on liquid inflow in narrow space

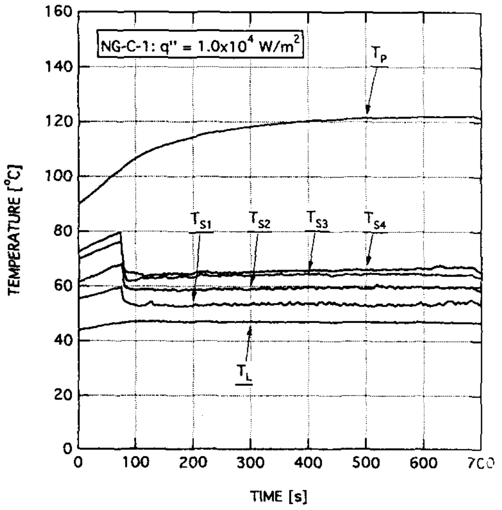

Fig.4. Temperature-Time Traces

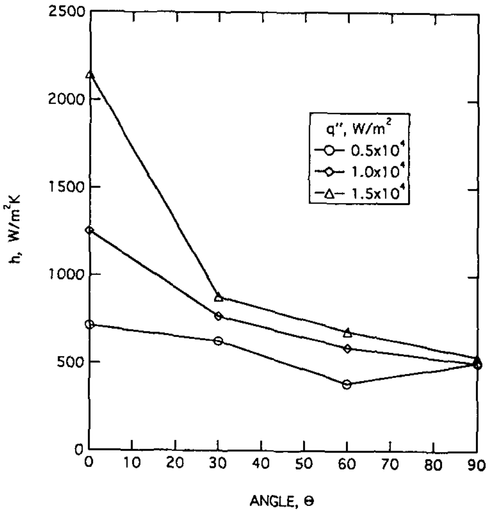

Fig.5. Heat Transfer Coefficients