CRITICAL HEAT FLUX FOR DOWNWARD-FACING BOILING ON A COATED HEMISPHERICAL VESSEL SURROUNDED BY AN INSULATION STRUCTURE

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Received February 7, 2006

An experimental study was performed to evaluate the effects of surface coating and an enhanced insulation structure on the downward facing boiling process and the critical heat flux on the outer surface of a hemispherical vessel. Steady-state boiling tests were conducted in the Subscale Boundary Layer Boiling (SBLB) facility using an enhanced vessel/insulation design for the cases with and without vessel coatings. Based on the boiling data, CHF correlations were obtained for both plain and coated vessels. It was found that the nucleate boiling rates and the local CHF limits for the case with micro-porous layer coating were consistently higher than those values for a plain vessel at the same angular location. The enhancement in the local CHF limits and nucleate boiling rates was mainly due to the micro-porous layer coating that increased the local liquid supply rate toward the vaporization sites on the vessel surface. For the case with thermal insulation, the local CHF limit tended to increase from the bottom center at first, then decrease toward the minimum gap location, and finally increase toward the equator. This non-monotonic behavior, which differed significantly from the case without thermal insulation, was evidently due to the local variation of the two-phase motions in the annular channel between the test vessel and the insulation structure.

KEYWORDS : Downward Facing Boiling, Critical Heat Flux

1. INTRODUCTION

Nuclear reactors are built to produce clean energy and operate safely throughout the lifetime of the reactor. Nevertheless, under certain unfavorable circumstances, severe accidents could occur in nuclear reactors although the probability for such occurrence is extremely low. One key severe accident management (SAM) strategy that has been adopted by some operating nuclear power plants and proposed for some advanced light water reactors (ALWRs) is the so-called in-vessel retention (IVR). One viable means for IVR is the method of external reactor vessel cooling (ERVC) by flooding of the reactor cavity during a severe accident. With water covering the lower external surfaces of the reactor pressurized vessel (RPV), nucleate boiling would be the prevailing regime if the wall heat flux from the corium is below the CHF limit for downward-facing boiling on the vessel outer surface. With the decay heat being removed from relocated corium through the vessel wall by downward facing boiling on the vessel outer surface, the latter could be maintained near the saturation temperature of the coolant to assure the integrity of the vessel.

In many nuclear power plants such as the Korean Advanced Power Reactor APR1400, the reactor vessel is surrounded by a thermal insulation structure that forms a hemispherical annular flow channel with the vessel. As boiling of water takes place on the vessel outer surface, the vapor masses generated on the surface would flow upward through the annular channel under the influence of gravity. Because of the vapor motions, liquid water would be entrained in the flow, thus resulting in a buoyancy-driven upward co-current two-phase flow in the channel. It has been shown by Cheung et al. [1,2] that the local critical heat flux (CHF) limit can be significantly affected by the resulting two-phase flow. Furthermore, the effect on the local CHF limit of an enhanced design of the insulation, which features streamlining local flow conditions around the bottleneck location in the annular channel, has been shown to be positive according to the study of Cheung et al. [3,4].

Another effective means for enhancing the local boiling rate is the use of micro-porous layer surface coating on the outer surface of the vessel, which has been experimentally explored by Dizon et al. [5]. Micro-porous layer surface coatings are extra-thin porous coatings with layer thicknesses that are less than the superheated liquid layer thickness needed for activation of the cavities during the nucleation. According to Dizon et al., the use of an aluminum micro-porous layer surface coating could result in local CHF enhancement of 42% to 112% for different angular location along the vessel wall. In the study of Yang and Cheung [6], the physical mechanisms behind the CHF enhancement were found to be due to capillary pumping action on the liquid supply flow, increased number of nucleation sites, extended heat transfer surface area and the availability of the vapor escape paths from the porous coating to the liquid pool. However, the works of Dizon et al. [5] and Yang and Cheung [6] considered only the case without thermal insulation structure. It is not clear what would the effect of the thermal insulation be since the induced buoyancy-driven upward co-current two-phase flow in the channel could have a strong influence over the local boiling heat transfer and the local CHF limits.

In this study, the feasibility of using an enhanced insulation structure and vessel coating for improving ERVC was assessed experimentally as part of the joint United States/Korean International Nuclear Energy Research Initiative (I-NERI) program. Steady-state boiling experiments were performed in the Subscale Boundary Layer Boiling (SBLB) test facility using an enhanced vessel/insulation design for the cases with and without vessel coatings. The objectives were to determine the separate and the combined effects of the enhanced insulation structure and the vessel coating. Note that the present ERVC enhancement strategy took advantage of modifying the flow dynamics both globally and locally. Globally, this was accomplished by the use of an vessel/insulation configuration that streamlines the two-phase motions and facilitates the process of steam venting through the bottleneck in the annular channel. Locally, this was accomplished by applying a micro-porous layer coating on the vessel outer surface to promote downward facing boiling.

2. EXPERIMENTAL METHOD

2.1 Enhanced Insulation Structure and Surface Coating

Figure 1 shows the enhanced thermal insulation design for APR1400 with indication of the annular flow channel

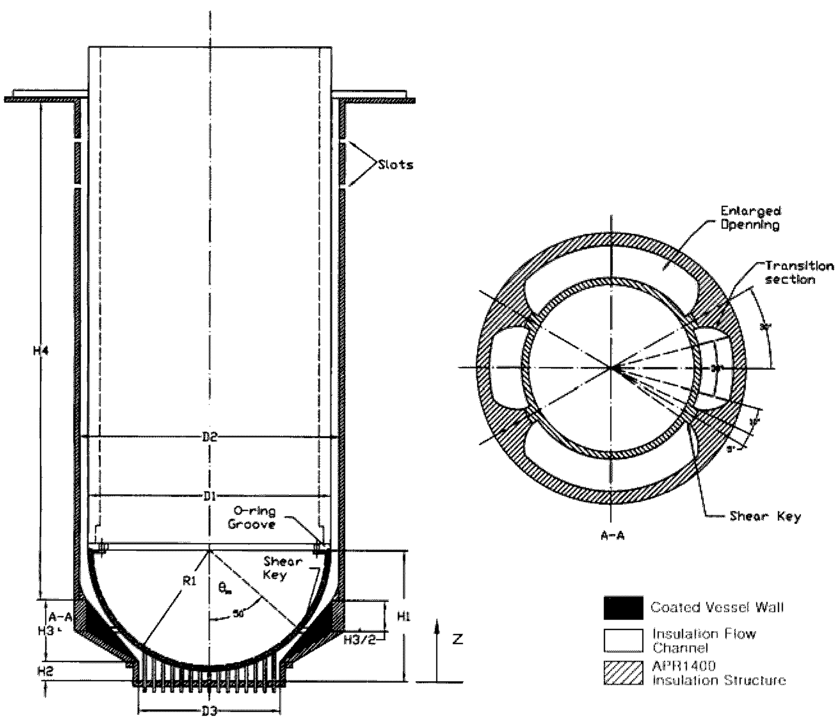


Fig. 1. Approximated Fluid Segment in Numerical Cell (3-dimensioncal case)

that is formed between the insulation and the reactor vessel. Note that there is a bottleneck between the reactor vessel and the insulation structure in the minimum gap location near the shear key position. The present insulation structure has the enhanced design proposed by Cheung et al. [3.4], which uses a non-uniform gap size for enlarging the bottleneck by opening the space available for steam venting in the circumferential locations away from the shear key positions. According to Cheung et al. [3,4], by enlarging the minimum gap at circumferential locations away from the four shear keys, the pressure drop through the bottleneck could be reduced appreciably. As a result, more flow would be induced when subjected to the same downward facing boiling conditions, which in turn leads to a higher CHF limit.

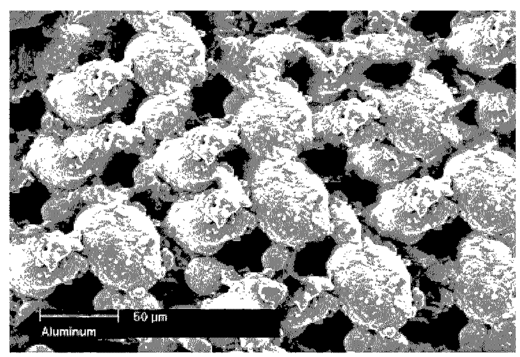
An extensive characterization study of the micro-porous layer surface coating that has been considered for use in full-scale reactors was performed by Dizon et al. [5]. Different compositions of the coating material were evalu-ated in order to obtain a mixture with desirable qualities. Sample surfaces were coated, and then examined using an optical microscope and a scanning electron microscope to determine the microstructure formed (see Fig. 2). Different painting techniques, including drip, brush, and spray painting, were tried. Durability and adhesion tests were then done to study the performance of each of the resulting coatings. Dizon et al., found that the aluminum micro-porous layer surface coating appears very steady and durable throughout a series of durability tests including abrasion, scratch, adhesion and boiling. Based on the spray coating method developed by Dizon et al. [5], the test vessel was coated with aluminum micro-porous layer coating for use in the present steady state boiling experiments.

2.2 Subscale Boundary Layer Boiling (SBLB) Test Apparatus

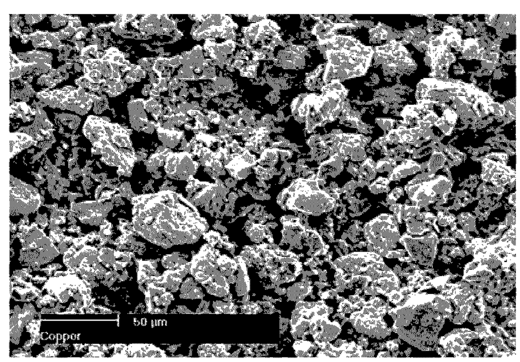
The test facility (see Fig. 3.) employed for this study consisted of a water tank with a condenser assembly, a heated hemispherical test vessel surrounded by a scaled insulation structure, a data acquisition system, a photographic system, and a power control system. The test vessel has a diameter of 0.305m. The water tank was designed to conduct boiling experiments under simulated ERVC conditions. The size of the water tank was chosen to accommodate hemispherical vessels of diameters up to 0.381m and to minimize the effect of recirculation motions created by the boiling process. The tank contained large viewing windows for observation, video-taping and photo records, and was equipped with three immersion heaters with a total power of 36kW for preheating the water to a desired temperature. The test vessel comprised two main parts: a heated hemispherical lower head simulator and a non-heated cylindrical upper portion. Groups of cartridge heaters were used to deliver power input to the lower head.

The data acquisition system, capable of monitoring 32 thermocouple signals with a sampling rate of up to twenty per second, was specifically calibrated for use in boiling experiments. An ACPC-16 board was installed in a computer. The ACPC-16 board had 16 analog inputs and 16 digital input/output channels. An additional ACPC-16 board could also be installed in the PC to give a total of 32 analog inputs. The ACPC-16 board had resolution capacities in the range of 12 to 16 bits, equivalent to 0.024% and 0.0015% of full scale, respectively. The board had six voltage ranges that could be set according to the sensor used.

To carry out the control strategy, a control routine was created using the computer program Quicklog. This routine started by collecting the temperatures of the vessel wall at several desired locations. These temperatures were then compared to a set point value of 250° C, which was much higher than the expected wall temperature that was characteristic of nucleate boiling in water. Wall temperature higher than 250 °C could have only been due to the occurrence of the CHF. Under normal operating conditions, the vessel wall temperature would be less than 250° C and the digital I/O channel connected to the solid state relay would be closed. This allowed the high voltage side of the solid state relay to stay closed until the desired power was delivered to the vessel. When a wall temperature greater than 250° C was detected, the digital I/O channel became open. As a



Aluminum Coating



Copper Coating

Fig. 2. SEM Photos of Aluminum and Copper Micro-porous Layer Coatings

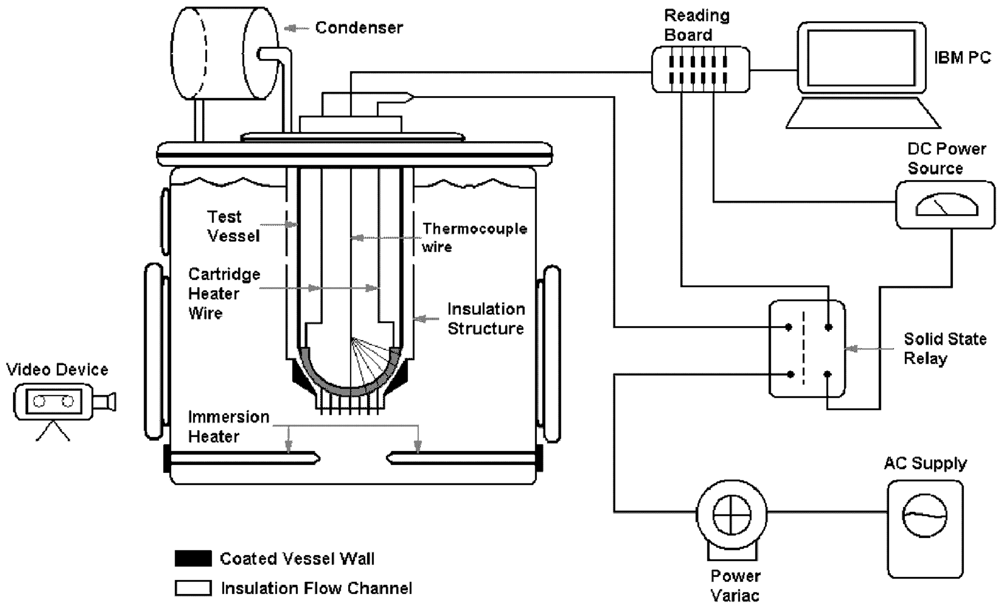


Fig. 3. Overall Schematic Diagram of the SBLB Test Apparatus

result, the low voltage side of the solid state relay was not powered anymore and the power supply to the heaters was discontinued, which prevented any further substantial increase in the vessel wall temperature as the CHF limit was approached. Based upon the procedure outlined by Haddad [7] and Liu [8], the uncertainty in the temperature measurements was estimated to be ± 0.38°C. For heat flux levels above 0.1 MW/m^2, the uncertainty in the heat flux measurements was estimated to be ± 7%. Some selected experiments were repeated to confirm the reproducibility of the data.

2.3 Steady State Test Procedure

Figure 4 shows the steady state boiling experimental procedure that is employed in this study. Before a run, the tank was first filled with water to the desired level. A pump was then used to circulate the water through a high-performance filter. This helped prevent water from becoming feculent during the heating process and also removed the particles within the water that would precipitate later. Then the immersion heaters were turned on to heat the water to a prescribed temperature. If the temperature fell below the desired value during an experiment, one of the heaters was turned on again to bring the water temperature back up. Before power was supplied to the groups of cartridge heaters inside the vessel, the water was given time to become completely quiescent to minimize the circulatory motion caused by immersion heaters. In these tests, the water in the tank was maintained at the saturation temperature. The power supply cables and the thermocouple wires were then connected to the adjustable power suppliers and the data acquisition system, respectively. Each power supply circuit for a group of cartridge heaters was equipped with a multimeter that allowed the voltage across and current

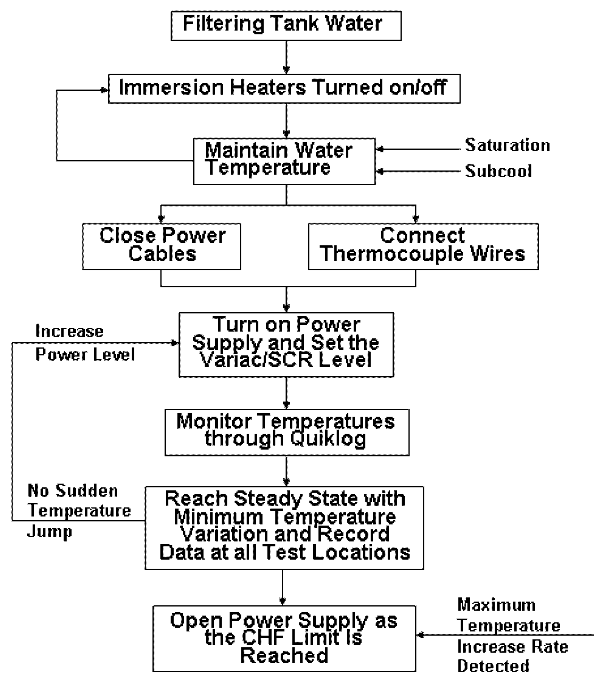


Fig. 4. Steady State Boiling Test Procedure

through the adjustable power suppliers to be measured. Next, the power sources to the adjustable power suppliers were turned on and the variac and/or SCR were set to deliver the desired heat flux level. At the same time, the temperatures at various locations inside the vessel wall were monitored on the computer screen using the data acquisition program Quicklog. Once steady state conditions were reached, the program Quicklog was used to record the steady state temperatures at various locations of the vessel wall and store them into a file for analysis.

At high heat flux levels, it was observed that large vapor slugs were generated on the heating surface. The insulation structure also tended to vibrate due to the strong upward motions of the two-phase mixture inside the flow channel. Although the water tank was well sealed, the sound of vibration of the insulation structure and vaporization of water could still be heard outside. When the wall heat flux was approaching the local CHF limit, the temperature would increase abruptly with large and violent vapor slug covering the vessel lower head. At this point, the control routine would be initiated to shut down the power supply once a sudden jump in the wall temperature was detected.

Whenever it was decided to video tape the boiling process, a high speed video camera system was turned on after the desired steady state conditions had been reached. Then, the lighting was adjusted until a satisfactory image of the flow was obtained. The boiling process was also photographed directly using a digital camera and was then stored on the computer. Two types of steady state boiling tests with the enhanced thermal insulation structure were conducted, one using plain test vessels whereas the other using coated vessels. By comparing the results obtained in these two types of tests, the separate effect of vessel coating could be determined.

3. RESULTS AND DISCUSSION

Nucleate boiling data for the case with and without micro-porous layer coating were measured under saturated boiling conditions at various locations along the vessel outer surface by performing steady state boiling tests in the SBLB test facility. For both cases, the test vessel was surrounded by the enhanced insulation structure depicted in Fig. 1.

Figures 5-9 compare the nucleate boiling data obtained from the steady state boiling tests at locations from the vessel bottom center up to the 75° location. In these figures, the local boiling heat fluxes are plotted against the local wall superheats at different angular positions. As can be seen from these figures, the nucleate boiling rate and CHF limit for the case with micro-porous layer coating are consistently higher than those values for a plain vessel at the same angular location. This observation is similar to the results reported by Dizon et al. [5] for the case without an insulation structure. The enhancement in the local CHF limits and nucleate boiling rates are mainly due to the micro-porous layer coating that increases the local liquid supply rate toward the vaporization sites on the vessel surface. This improved liquid supply rate contributes to the delay of local dryout at a given location.

According to Dizon et al. [5], for a coated test vessel without an insulation structure, the local boiling curve for the nucleate boiling regime tended to shift upward and to the right as the angular position was increased from the bottom center toward the equator of the test vessel. In other words, for a given wall superheat, a higher nucleate boiling rate would be obtained in a location downstream of the

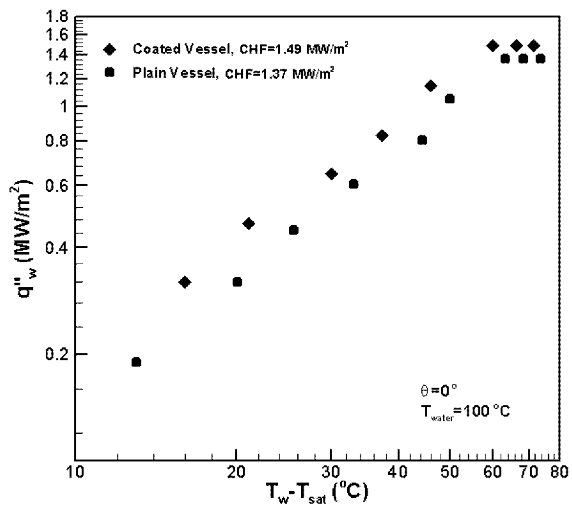


Fig. 5. Comparison of the Nucleate Boiling Data Obtained at the Bottom Center Location

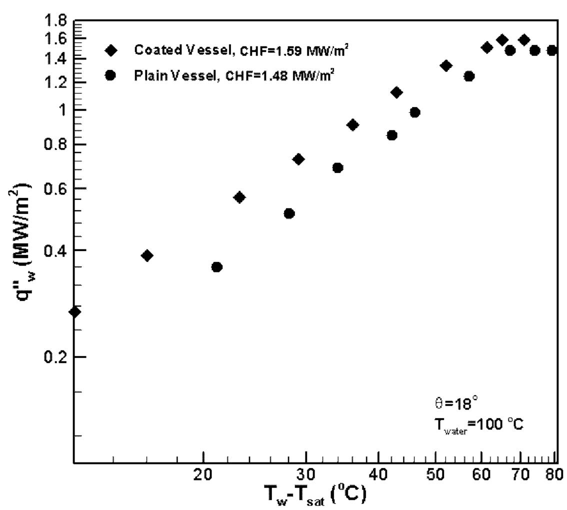


Fig. 6. Comparison of the Nucleate Boiling Data Obtained at the Downstream Location (18°)

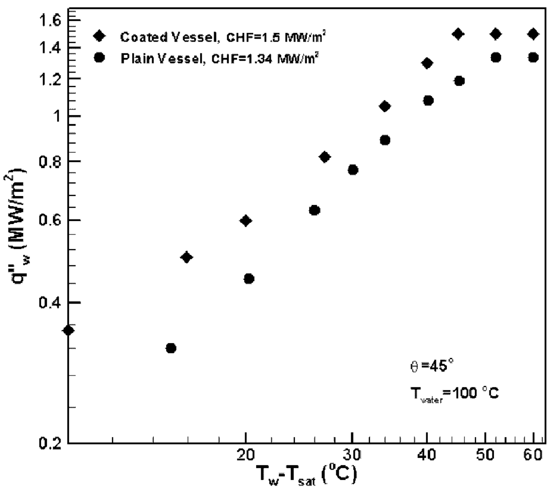


Fig. 7. Comparison of the Nucleate Boiling Data Obtained at the Downstream Location (45°)

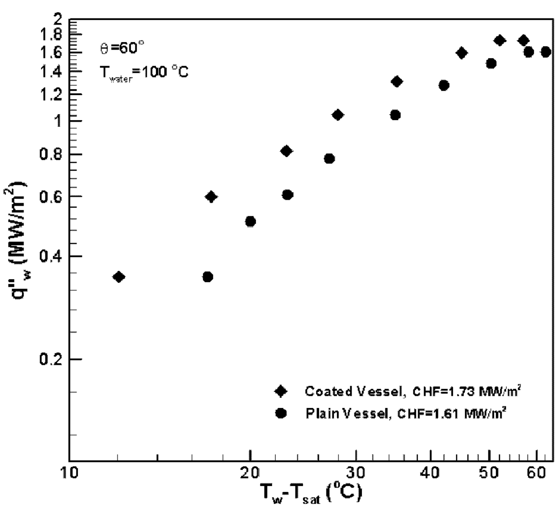


Fig. 8. Comparison of the Nucleate Boiling Data Obtained at the Downstream Location (60°)

bottom center. However, the same wasn't observed for the case with thermal insulation. By comparison of the steady state boiling data obtained at various angular positions, it can be seen that for the case with an insulation structure the nucleate boiling rates do not exhibit a monotonic trend. This behavior could be due to the effect of the non-uniform gap geometry of the flow channel on two-phase motions, which may have great impact on the local boiling heat transfer.

For the case with thermal insulation, the local CHF limit tended to increase from the bottom center at first, then decreased toward the minimum gap location, and finally increased toward the equator (see Fig. 10). This non-monotonic behavior is evidently due to the local variation of the two-phase motions in the annular channel between the test vessel and the insulation structure.

Based on the CHF data obtained for both the coated and plain vessels with thermal insulation, empirical correlations were made to describe the variation of the local CHF on the vessel outer surface. Results are presented in the following correlations, where the CHF values are in MW/m² and the angular position $\boldsymbol{\theta}$ is in radians. Taking into account the variation of the cross-sectional flow area along the flow channel, CHF correlations are developed for three separate regions as described below.

In the bottom center region of the channel where $0<\theta<0.3142$ (18°), the experimental results gave rise to the following CHF correlations:

Plain Vessels

$$\left(q''_{CHF}\right)_{Plain} = (1.37 + 0.3501\theta)\,(\mathrm{MW/m^2}) \qquad (1)$$

Coated Vessels

$$\left(q''_{CHF}\right)_{Coated} = (1.49 + 0.3183\theta)\ (\mathrm{MW/m^2}) \qquad (2)$$

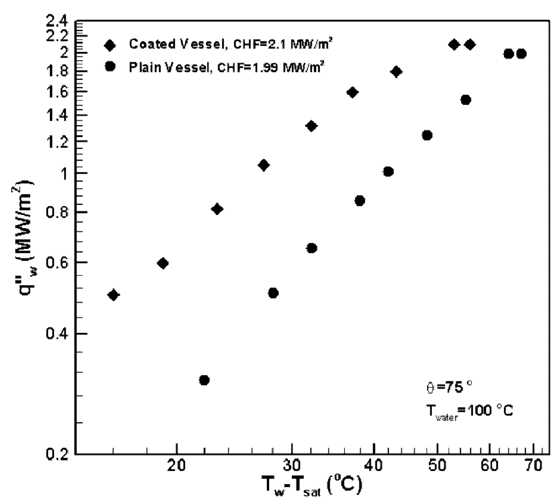


Fig. 9. Comparison of the Nucleate Boiling Data Obtained at the Downstream Location (75°)

In the convergent region covering the upper exit of the inlet section up to the minimum gap location where $0.3142<\theta<0.7854$ (45°), the experimental results gave rise to the following expressions:

Plain Vessels

$$\left(q''_{CHF}\right)_{Plain} = \left(1.5734 - 0.29510\theta\right)\left[1 + 0.0925\left(\theta - 0.3142\right)^{1/3}\Delta T_{sub}\right] \qquad (3)$$

Coated Vessels

$$\left(q''_{CHF}\right)_{Coated} = \left(1.65 - 0.191\theta\right)\left[1 + 0.0925\left(\theta - 0.3142\right)^{1/3}\Delta T_{sub}\right] \quad (4)$$

where $\Delta T_{sub} = T_{sat} - T_{water}$. The term ΔT_{sub} accounts for the subcooling effect on the local CHF limit.

In the divergent region covering the upper part of the channel beyond the minimum gap location where $0.7854 < \theta < 1.5708$ (90°), the experimental results gave rise to the following expressions:

Plain Vessels

$$\left(q''_{CHF}\right)_{Plain} = \left(1.19 - 0.43930\theta + 0.80250\theta^2\right) \left[1 + 0.0746\left(1 - 0.573\left(\theta - 0.7854\right)\right)\Delta T_{sub}\right] \quad (5)$$

Coated Vessels

$$\left(q''_{CHF}\right)_{Coated} = \left(1.65 - 0.99310\theta + 1.02130\theta^2\right) \left[1 + 0.0746\left(1 - 0.573\left(\theta - 0.7854\right)\right)\Delta T_{sub}\right] \quad (6)$$

Aside from the nucleate boiling data and CHF limits, there were also distinct differences in the observed hydrodynamic behavior between the plain and coated surfaces. For a coated hemispherical vessel, the bubbles were generated at a higher frequency compared to that for a plain vessel. Thus, a vessel with micro-porous surface coating would give rise to a shorter boiling cycle. Such enhanced boiling cycle explains the increased nucleate boiling rate for a coated vessel because more latent heat of vaporization could be transferred per unit time from the reactor surface. For a plain vessel, a large vapor slug covering the entire bottom center area was observed at high wall heat flux levels. However, for a coated vessel, the vapor bubbles generated in the bottom center region did not tend to agglomerate. This behavior could be due to the availability of vapor escape paths provided by the porous cavities of the coating. Although vapor bubbles tended to disperse on the coated vessel, a higher boiling site density resulted in a higher rate of heat removal, i.e., higher boiling rate.

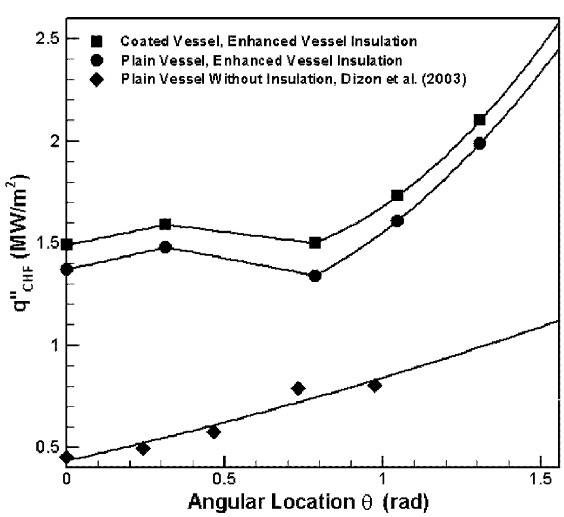


Fig. 10. Variations of the Local CHF Limits Along the Vessel Outer Surface

4. CONCLUSIONS

Based on the results obtained in this study, the following conclusions can be made:

1. The nucleate boiling rates and the local CHF limits for the case with micro-porous layer coating are consistently higher than those values for a plain vessel at the same angular location. The enhancement in the local CHF limits and nucleate boiling rates is mainly due to the micro-porous layer coating that increases the local liquid supply rate toward the vaporization sites on the vessel surface.
2. For the case with an insulation structure the nucleate boiling rates do not exhibit a monotonic trend, i.e., the local boiling curve does not shift upward and to the right monotonically with increasing angular position. This behavior could be due to the effect of the non-uniform gap geometry of the flow channel on the two-phase motions which could have important impact on the local boiling heat transfer.
3. For the case with thermal insulation, the local CHF limit tended to increase from the bottom center at first, then decrease toward the minimum gap location, and finally increase toward the equator. This non-monotonic behavior is evidently due to the local variation of the two-phase motions in the annular channel between the test vessel and the insulation structure.
4. For a coated hemispherical vessel, the bubbles were generated at a higher frequency compared to that for a plain vessel. Such enhanced boiling cycle explains the increased nucleate boiling rate for a coated vessel because more latent heat of vaporization could be transferred per unit time from the reactor surface.
5. For a coated vessel, the vapor bubbles generated in the bottom center region did not tend to agglomerate. This behavior could be due to the availability of vapor escape paths provided by the porous cavities of the coating. Although vapor bubbles tended to disperse on the coated vessel, a higher boiling site density resulted in a higher rate of heat removal, i.e., higher boiling rate.
6. Depending on the angular position, a local CHF enhancement of 200% to 330% over a plain vessel without insulation could be achieved using an enhanced insulation structure with vessel coatings. It appears that ERVC with the use of vessel coatings and an enhanced insulation structure could provide sufficient cooling for high-power reactors such as APR1400.

ACKNOWLEDGMENTS

This work was performed under DOE contract number DE-AC07-99ID13727. The authors are grateful for the financial support by the U.S. Department of Energy and the Korean Ministry of Science and Technology as part of the K-INERI program.

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