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Effects of subcooling on downward facing boiling heat transfer with micro-porous coating formed by Cold Spray technique

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ABSTRACT

External reactor vessel cooling (ERVC) is an effective strategy to achieve in-vessel retention (IVR) of core melt in the reactor pressure vessel (RPV) under severe accident conditions. Among the available strategies, micro-porous coating technique has been known to enhance the thermal margin of the RPV. In this study, a new and versatile micro-porous coating technique applicable to commercial size reactors known as "Cold Spray" has been developed to coat a hemispherical test vessel. Quenching boiling experiments at different degrees of subcooling (10 °C, 5 °C, 3 °C, 1 °C, and 0 °C) were performed using bare and micro-porous coated vessels. Visual observations of the quenching process along with quantitative analyses of the boiling data were performed. It was found that the critical heat flux (CHF) limit varies significantly with the angular location at all subcooled conditions. Higher cooling rates and CHF limits were obtained with higher degrees of subcooling. A micro-porous coating formed by Cold Spray significantly improved the CHF limit compared to the bare vessel. In fact, nearly 90% enhancement was achieved using the Cold Spray coated vessel. CHF correlations for both bare and micro-porous coated vessel have been proposed capturing the effects of subcooling and angular variation along the outer surface of the hemispherical test vessels.

1. Introduction

Nuclear power is one of the existing energy resources that provides clean and reliable energy. Using nuclear energy resources, nuclear power plants (NPP) produce a significant portion of the total electricity worldwide with relatively small fuel costs and extremely low levels of pollution. Indeed, NPPs provide safe and consistent power with proper design and well controlled operating conditions. Nevertheless, radiation protection is one of the biggest concerns of existing NPPs. The multiple levels of protection for safekeeping the radioactive materials include the containment building, fuel pellet restraint of fission gases, cladding around the fuel rods, and so on. All hazardous materials are housed inside the reactor pressure vessel (RPV), which is within the containment building. Despite the presence of various safety features with multiple levels of defense, severe accidents can occur in NPPs under unexpected, extreme situations; the TMI-2 accident and more recently the Fukushima incident are two examples of severe accidents in nuclear reactors. With the ever-present possibility of such an event, it is crucial to develop a viable strategy for in-vessel retention (IVR) of the molten corium by maintaining the integrity of the lower head of the RPV, thus minimizing the risk of vessel, as well as an overall containment failure.

By flooding the reactor cavity with coolant water to submerge the entire RPV, radioactive molten corium could be contained within the reactor. This method, known as in-vessel retention (IVR) by external reactor vessel cooling (ERVC) allows for decay heat removal from the molten corium through the vessel wall by downward-facing boiling on the vessel outer surface. As the RPV is submerged, the water begins to boil which removes the decay heat from the molten corium. The feasibility of IVR-ERVC depends largely on the boiling crisis which bounds the rate of heat removal by downward-facing boiling of water on the vessel outer surface. Boiling crises occurs at a high wall superheat as the generated water vapor covers the heating surface such that the liquid can no longer reach the surface. This in turn causes the wall temperature to rise exponentially, leading to the melting of the RPV. The maximum heat transfer rate near the boiling crisis is the critical heat flux (CHF). The success of IVR significantly depends on the CHF limit for the downward-facing boiling process. In order to increase the thermal margin for cooling of the reactor vessel

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following a severe accident, it is therefore highly desired to develop methods to enhance the CHF limit.

In spite of the practical importance of downward-facing boiling, most of the research have only been conducted in the past 20 years. Important body of work includes the series of SULTAN experiments conducted by Rouge et al. [1,2] who investigated the effects of pressure, gap size, inclination angle, local quality, and mass flux on the critical heat flux (CHF). Rouge used a test section with a uniformly heated flat plate that could be inclined from a vertical to a horizontal position. It was reported that the CHF decreased almost linearly with the quality, with a positive influence of the mass flux at low qualities and a negative influence at high qualities. A decrease in CHF with increased inclination angle and a slight increase in CHF with increasing pressure were observed. Channel gap size variation had no effect on the CHF under saturated boiling conditions in the vertical position, and a limited positive effect was found under subcooled boiling conditions.

Brusstar et al. [3] performed an experimental study of subcooled, forced-convection boiling at high heat fluxes. During this study, the effects of subcooling and buoyancy orientation on the CHF with bubble residence times were investigated. The CHF corresponding to bubble residence time was constant which suggests that the heater surface orientation had no effect on the mechanism for dryout, despite vapor departure velocity and CHF with variation in orientation angle. Furthermore, the net rate of vapor generation was significantly reduced with an increase in the bulk liquid subcooling, such that bubble residence times at the CHF were independent of the subcooling. The energy per unit area leaving the heater surface during the bubble residence time was proposed as the CHF mechanism. A theoretical model was also developed by Brusstar et al. [4] for the CHF in pool and low-velocity forced convection boiling. The model described the combined effects of the heater surface orientation and flow on the CHF. Separate CHF correlations were proposed for upward and downward-facing surfaces.

A comprehensive study on downward-facing boiling and CHF phenomena on the outer surface of a hemispherical vessel using the Subscale Boundary Layer Boiling (SBLB) test facility at the Pennsylvania State University (PSU) was done by Cheung et al. [5–8]. Two configurations were explored in the facility, with and without a scaled thermal insulation structure surrounding the test vessel. For the case without an insulation structure, a significant spatial variation of the CHF was observed. The local CHF limit increased monotonically from the bottom center to the equator of the vessel, for both saturated and subcooled boiling. With an insulation structure, but still at the same heat flux level, more flow was induced along the vessel outer-surface compared to the case without insulation. Hence, the nucleate boiling heat transfer and CHF for the case with insulation were found to be consistently higher than those for the corresponding test without insulation. In addition, the insulation structure also affected the spatial variation of the CHF limit. For the case with insulation, local CHF no longer increased monotonically in the flow direction, rather, it decreased from the bottom center toward the downstream locations. This CHF pattern exhibited a minimum near the minimum gap of the annular channel, before it increased toward the equator of the vessel.

Theofanous et al. [9–11] employed five configurations at the ULPU facility at the University of California, Santa Barbara (UCSB) to perform a full-sized simulation of downward-facing boiling on the outer surface of a hemispherical RPV using a two dimensional copper plate with separately heated zones. Kim and Suh [12] and Kim et al. [13] conducted pool boiling experiments to examine the CHF on a one-dimensional downward-facing heating rectangular channel having a narrow gap at the Seoul National University (SNU). The experiments were performed with varying heater surface orientations from the downward-facing position (180°) to the vertical position (90°). Visualization of the boiling phenomena were conducted utilizing a high-speed digital camera. The CHF generally decreased with an increase in the surface inclination angle and a decrease in gap size. Using dimensional analysis, a correlation was developed for the CHF during natural convective boiling on the inclined, confined rectangular channels.

Jeong et al. [14] measured the CHF on the reactor vessel using a two-dimensional slice test-section. For these tests, a smaller flow channel area and heater width, but with a greater radius relative to the ULPU experiments were used. In general, a slightly lower CHF value than ULPU was obtained. However, a similar general trend of CHF with the mass flux was observed compared to ULPU. For mass fluxes higher than 200 kg/m^2, the experimental CHF data were well predicted by the SULTAN correlation [2]. Higher CHF was achieved with trisodium phosphate-added water. A similar study was done by Park et al. [15]. The CHF was measured on top of the reactor vessel lower head external wall using three test sections of a two-dimensional slice. A two-phase boundary layer analysis was performed through flow visualization. CHF correlations in terms of mass flux and exit quality were developed. Jeong et al. [14] Park et al. [15] also studied the effect of heater material and the combined effect of heater material and coolant additives on CHF for downward-facing curved surface.

More recently, Zhong et al. [16] performed saturated pool boiling experiments with three downward-facing pin fin surfaces in deionized water to enhance the CHF. Nucleate boiling heat transfer coefficients and CHF were measured at the inclination angles of 5°, 30°, 45°, 60°, and 90° (vertical). Higher heat transfer coefficients and CHF were observed for the pin finned surfaces over a plain surface. More importantly, the test data indicated 200% CHF enhancements at all inclination angles. Furthermore, the CHF increased with the number of fins per unit area and with the increase in fin height.

The combined effect of surface coating and surface orientation on nucleate and film boiling in R-11 was first investigated by Jung et al. [17]. Spray coating technique was used to deposit metallic particles on a mild steel plate. The coated surfaces showed two to three times the enhancement in heat transfer at constant heat flux as compared to plain copper surface as a result of increased surface roughness. Furthermore, the surface orientation effect was more significant at lower heat fluxes than at higher heat fluxes for both the coated and uncoated surfaces.

Chang and You [18,19] investigated the nucleate boiling heat transfer and CHF for both uncoated and micro-porous coated surfaces consisting of copper (1–50 μm) and aluminum particles (1–20 μm). Devcon Brushable-Ceramic epoxy was used as the binder and methyl-ethyl-ketone (M.E.K.) as the carrier. The coated heaters were cured in an oven for about an hour at 150 °C. For both coatings, ~80% reduction in incipient superheat, ~330% increase in nucleate boiling heat transfer, and ~100% enhancement in CHF over the corresponding values for the uncoated surface were obtained.

El-Genk and Ali [20–25] performed pool boiling experiments to investigate potential enhancement of critical heat flux (CHF) with PF-5060 dielectric liquid on microporous copper (MPC) surfaces. They performed both subcooled and saturated boiling and studied the effect of surface inclination angle. Coating thickness was varied as well, since the morphology and microstructure of the MPC surfaces changed with thickness. Inclination angle was varied gradually from fully upward to completely downward-facing configurations. The CHF increased as the thickness of the surface increased and/or the inclination angle decreased. Approximately 50% higher CHF was obtained in the upward-facing orientation relative to smooth Cu surface. For all surfaces, CHF values in the downward-facing orientation were found to be around 30% of

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