Nuclear Engineering and Technology xxx (2016) 1—10

Available online at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Enhancement of Downward-facing Saturated Boiling Heat Transfer by the Cold Spray Technique

Faruk A. Sohag [a,*], *Faith R. Beck* [a], *Lokanath Mohanta* [a], *Fan-Bill Cheung* [a], *Albert E. Segall* [b], *Timothy J. Eden* [c], *and John K. Potter* [c]

[a] *Department of Mechanical and Nuclear Engineering, Pennsylvania State University, University Park, PA 16802, USA*

[b] *Department of Engineering Science and Mechanics, Pennsylvania State University, University Park, PA 16802, USA*

[c] *Applied Research Laboratory, Pennsylvania State University, University Park, PA 16802, USA*

ARTICLE INFO

Article history:
Received 19 January 2016
Received in revised form
28 June 2016
Accepted 26 August 2016
Available online xxx

Keywords:
Cold Spray
Critical Heat Flux Limit
Downward-Facing Boiling
In-vessel Retention
Microporous Coating

ABSTRACT

In-vessel retention by passive external reactor vessel cooling under severe accident conditions is a viable approach for retention of radioactive core melt within the reactor vessel. In this study, a new and versatile coating technique known as “cold spray” that can readily be applied to operating and advanced reactors was developed to form a microporous coating on the outer surface of a simulated reactor lower head. Quenching experiments were performed under simulated in-vessel retention by passive external reactor vessel cooling conditions using test vessels with and without cold spray coatings. Quantitative measurements show that for all angular locations on the vessel outer surface, the local critical heat flux (CHF) values for the coated vessel were consistently higher than the corresponding CHF values for the bare vessel. However, it was also observed for both coated and uncoated surfaces that the local rate of boiling and local CHF limit vary appreciably along the outer surface of the test vessel. Nonetheless, results of this intriguing study clearly show that the use of cold spray coatings could enhance the local CHF limit for downward-facing boiling by > 88%.

1. Introduction

Nuclear power is known to be a clean and reliable source of energy. With proper design, nuclear power plants provide safe and consistent power under well controlled operating conditions. However, from the Three Mile Island Reactor-2 accident to the recent nuclear incident in Fukushima, Japan, it is evident that severe accidents, although highly unlikely, can occur in nuclear power plants under unexpected, extreme situations. During a severe accident, the reactor core can melt down, with molten corium relocating downward into the bottom head. In order to contain the radioactive molten corium within the reactor, it is proposed to flood the reactor cavity with water to submerge the entire reactor pressure vessel (RPV). This method, also known as in-vessel retention (IVR), allows for decay heat removal from the molten corium through the vessel wall by downward-facing boiling on the vessel outer surface. The success of IVR depends on the

* *Corresponding author.*
E-mail address: fas153@psu.edu (F.A. Sohag).

http://dx.doi.org/10.1016/j.net.2016.08.005

critical heat flux (CHF) limit for the downward-facing boiling process. To increase the thermal margin for cooling of the reactor vessel following a severe accident, it is highly desirable to develop methods to enhance the CHF limit.

The concept of IVR by passive external reactor vessel cooling (ERVC) in a flooded cavity during severe accidents is a viable approach for retention of radioactive core melt within the reactor vessel. However, the feasibility of IVR-ERVC depends on the CHF distribution of the external bottom reactor vessel surface. Owing to the practical importance of this concept, much research has been done over the past 20 years. Theofanous and Syri [1], Theofanous et al [2], and Dinh et al [3] from the ULPU facility at the University of California, Santa Barbara, performed 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. From the five configurations that were built, the first three were designed for the AP600 and other two for the AP1000. Configuration I simulated downward-facing boiling on the external bottom center of the vessel covering the region $-30^\circ < \theta < 30^\circ$. Configuration II simulated a full scale reactor lower head from the bottom center up to the equator ($0^\circ < \theta < 90^\circ$), while Configuration III is similar to Configuration II, but with an added thermal insulation structure. The angular location θ is measured from the stagnation point. Although there was spatial variation of CHF with θ on the vessel, the insulation structure was found to have very little effect on the local CHF limit. Configuration IV had an integrated baffle and a total of 28 burnout experiments were performed with it. The baffle structure streamlined the flow path between the RPV surface and the insulation. Despite a sudden drop in the local CHF observed at the very top of the heated wall (90°), the baffle in Configuration IV improved the CHF from Configuration III. In order to overcome the exit phenomena found in Configuration IV, Configuration V was built with four major modifications over Configuration IV which improved the local CHF limits in the heater's upper region to 1.8 MW/m^2 and approached a value of ~2.0 MW/m^2 at 90°.

Chu et al [4] conducted a full scale, three-dimensional simulation of downward-facing boiling on the exterior surface of a RPV in the Cylindrical Boiling facility at Sandia National Laboratory. Using a torispherical reactor vessel, two types of steady-state heating experiments were carried out by heating the vessel using an array of radiant lamp panels. The bottom center was consistently at the highest temperature even though edge heat flux was higher than that at the center. The cyclic nature of the vapor dynamics and the resulting two-phase motion along the heating surface for downward-facing boiling were also visually observed.

Additional quenching experiments with a copper substrate were performed by El-Genk and Glebov [5] in saturated water using two test sections of different thicknesses. Boiling curves were derived at six locations on the bottom center region and then at a local inclination angle of 8.26° along the outer surface of the test section. The heat flux increased with increasing θ in the lower heat flux region and decreased with increasing values of θ at very high heat fluxes. Interestingly, the thickness of the copper heater had no effect on the observed CHF values. CHF occurred sequentially from the lower most to the highest positions in that order. As the thickness of the test section increased, the difference in time between subsequent CHF occurrences also increased.

Cheung et al [6–9] comprehensively investigated the downward-facing boiling and CHF phenomena on the outer surface of a hemispherical vessel. The vessel and its setup included conditions with and without surrounding insulation at the Subscale Boundary Layer Boiling (SBLB) test facility at the Pennsylvania State University. A significant spatial variation of the critical heat flux was observed with a monotonically increasing local CHF limit from the bottom center to the equator of the vessel under both saturated and subcooled boiling conditions.

Later, Dizon et al [10] investigated two different methods to enhance cooling of the APR1400 reactor vessel with insulation at the SBLB facility. The first method involved the use of an enhanced vessel-insulation structure to improve steam venting through the annular bottleneck channel between the RPV and the surrounding insulation. The second method involved the use of a microporous coating on the outer surface of the vessel to promote heat transfer during downward-facing boiling. A substantial increase in the local CHF limit was observed by both methods.

Yang et al [11–13] and Yang and Cheung [14] also investigated the viability of using microporous coatings to enhance local CHF limits under IVR-ERVC conditions by performing transient quenching and steady-state boiling experiments. The microporous coatings consisted of aluminum (Al) and copper coatings on Al and stainless steel (SS) vessels. The measured local boiling curves and CHF limits for the coated vessels showed substantial enhancement compared to the uncoated vessels. The steady-state boiling experiments also confirmed the durability of the microporous coatings after many cycles of heating and quenching.

Rainey and You [15] also investigated the effect of orientation and surface enhancement of nucleate boiling on flat surfaces made of copper. For these experiments, the surfaces were coated with diamond particles and it was demonstrated that surface orientation had no effect on the heat transfer for the coated surfaces. Furthermore, a large number of active nucleation sites, due to the coating, made the surfaces immune to variation in heater size. In a similar vein, Pranoto et al [16] studied various block and fin graphite configurations with increased nucleation sites and obtained enhanced heat transfer. Additional studies by El-Genk and Parker [17] found that porous graphite at different orientations gave rise to higher nucleate boiling heat transfer coefficients under both saturated and subcooled boiling conditions when FC-72 and HFE-7100 were used as the working fluid. A higher nucleate boiling heat transfer coefficient was observed for FC-72 compared with HFE-7100, with the values higher with increasing liquid subcooling.

More recently, Ho et al [18] investigated the effects of carbon nanotube (CNT) coated surfaces and surface orientation under saturated pool boiling conditions. Pool boiling was performed in FC-72 under atmospheric conditions for two surfaces; one surface was fully coated with CNTs and the other was patterned with an interlaced CNT coating. Both coatings were on top of a silicon substrate. A 42% increase in the average heat transfer coefficient was observed for both the coated and uncoated surfaces.

Please cite this article in press as: F.A. Sohag et al., Enhancement of Downward-facing Saturated Boiling Heat Transfer by the Cold Spray Technique, Nuclear Engineering and Technology (2016), http://dx.doi.org/10.1016/j.net.2016.08.005