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Investigation of Downward Facing CHF with Water-based Nanofluids for IVR

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INTRODUCTION

In-Vessel Retention (IVR) through External Reactor Vessel Cooling is a severe accident management measure that is power limiting to the Westinghouse AP1000 due to critical heat flux (CHF) at the outer surface of the vessel. Increasing CHF by altering the coolant would increase safety margin at current design power or allow for higher power. Modification to current design would not require significant changes to the containment and systems [1].

Research at MIT has demonstrated that CHF of water on a heated metal surface can be increased from 30% to 100% with the introduction of nanoparticles at low concentrations. Research has measured enhanced CHF in both pool [2,3] and force convective [4,5] boiling. Alumina and water nanofluid has shown the best enhancement and long-term stability in solution.

Conceptual implementation could involve storage tanks of high concentration nanofluids installed in containment (Fig. 1). Once IVR strategy has been initiated with flooding of the vessel support cavity with water from the In-Vessel Refueling Water Storage Tank, nanofluids would be released to mix as the natural circulation sets up along the gap between the vessel and the insulation on the vessel cavity.

DESCRIPTION OF THE ACTUAL WORK

To measure CHF for the conditions relevant to IVR in the AP1000, a two-phase flow loop has been built (Fig. 2). The test section has hydrodynamic similarity to the AP1000 insulation/vessel gap and allows for all angles that represent the bottom surface of the reactor vessel. Research competed herein has measured CHF for varied conditions of angle, pressure, mass flux, fluid type and surface material.

Downward inclination angles are from 0° (horizontal) to 90° (vertical). Pressure range is 1 to 5 atmospheres absolute and bounds the AP1000 containment design limit. Mass fluxes in the test section range from 500 to 1500 kg/m²·s. Working fluids studied are de-ionized water and alumina nanofluids (<0.01% volume). Surface materials are stainless steel 316L and SA508, which is the vessel material.

RESULTS

Results indicate 35% to 116% enhancement in CHF for conditions expected for IVR (Fig. 3). The CHF enhancement is higher, as a percent, in low flow conditions and in downward facing geometry with inclination angle of less than 60°. As expected, for a given fluid, CHF increases for increasing mass flux and pressure. Angular dependence of CHF is inversely proportional to mass flux and nearly disappears at a mass flux of 1500 kg/m²·s. At a given mass flux, CHF is nearly linear with angle increasing smoothly from downward horizontal position to maximum at vertical.

Water only cases were compared to studies done at the Sultan facility in France [6] and UCSB [7] and show similar trends and levels.

Results support utilizing alumina based nanofluid during IVR to improve margin to CHF for the AP1000.

REFERENCES


Fig. 1 – Conceptual application of nanofluid to AP1000 IVR

Fig. 2 – Schematic of flow boiling loop (left) and photo of variable inclination test section (right)
Fig. 3 – CHF data versus mass flux and inclination angle for water and alumina nanofluids at atmospheric pressures.