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Effect of in-core instrumentation mounting location on external reactor vessel cooling

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ABSTRACT

The effect of in-core instrumentation (ICI) mounting location on the application of in-vessel corium retention through external reactor vessel cooling (IVR-ERVC), used to mitigate severe accidents in which the nuclear fuel inside the reactor vessel becomes molten, was investigated. Numerical simulations of the subcooled boiling flow within an advanced pressurized-water reactor (PWR) in IVR-ERVC applications were conducted for the cases of top-mounted ICI (TM-ICI) and bottom-mounted ICI (BM-ICI), using the commercially available computational fluid dynamics (CFD) software ANSYS-CFX. Shear stress transport (SST) and the RPI model were used for turbulence closure and subcooled flow boiling, respectively. To validate the numerical method for IVR applications, numerical simulations of ULPU-V experiments were also conducted. The BM-ICI reactor vessel was modeled using a simplified design of an advanced PWR with BM-ICI; the TM-ICI counterpart was modeled by removing the ICI parts from the original geometry. It was found that TM-ICI was superior to BM-ICI for successful application of IVR-ERVC. For the BM-ICI case, the flow field was complicated because of the existence of ICIs and a significant temperature gradient was observed near the ICI nozzles on the lower part of the reactor vessel, where the ICIs were attached. These observations suggest that the existence of ICI below the reactor vessel hinders reactor vessel cooling.

1. Introduction

In-vessel corium retention through external reactor vessel cooling (IVR-ERVC) is a management strategy for severe accidents in light-water reactors (LWRs). The concept of the IVR strategy consists of flooding the reactor cavity with water to cool the reactor pressure vessel (RPV) and ensuring the retention of core debris within the vessel. However, the presence of in-core instrumentation (ICI) beneath the reactor vessel may be important in determining the success of the IVR strategy in bottom-mounted ICI (BM-ICI) systems, even when reactors have sufficient thermal margin to remove decay heat from the molten debris in the vessel. The penetration nozzle connecting the ICI to the RPV is the most vulnerable to attack by molten core materials during severe accident. Conversely, the top-mounted ICI (TM-ICI) approach, which has no penetration, may be advantageous in mitigating severe accidents. TM-ICI also enables more efficient supplying of cooling water from the in-containment refueling water storage tank (IRWST) than the BM-ICI geometry does, because of the reduced flow resistance arising from the simpler geometry of the inlet region of the cooling water loop.

Computational fluid dynamics (CFD) is useful for understanding two-phase flow dynamics in nuclear engineering applications. In the present study, the commercially available CFD software ANSYS-CFX was used to simulate subcooled flow boiling during an IVR application. Numerical simulations for ULPU-V experiments were conducted to verify subcooled boiling flow in IVR application. ULPU is an experimental facility at the University of California at Santa Barbara (UCSB), designed to assess the coolability limits of IVR devices in the Westinghouse AP600 and AP1000 reactors. The facility offers a full vertical-scale representation of the entire cooling flow loop between the RPV and the reflecting thermal insulation. Electrical heaters provide thermal loading at the copper block using heat flux profiles measured in the UCSB ACOPO facility as a function of the polar angle (Dinh et al., 2003). Among several ULPU experiments, experiment run No. 4 for configuration V of ULPU-2400 was simulated, for which the previous computational and experimental results are available.

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Nomenclature

A_W	fraction of area influenced by bubbles
Cp_{RV}	reactor vessel specific heat
d_W	bubble diameter at detachment
f	bubble generation frequency
h_C	single-phase convection heat transfer coefficient
h_Q	quenching heat transfer coefficient
H_{LG}	latent heat for bulk evaporation or condensation
k	turbulent kinetic energy
$\dot{m}_W$	evaporation mass flux at wall
N	nucleation site density
Q_C	heat flux due to single-phase convection
Q_E	heat flux due to evaporation
Q_{RV}	heat applied at reactor vessel during IVR-ERVC
Q_Q	heat flux due to quenching
Q_{tot}	external heat flux applied to heated wall
T_L	cooling liquid temperature
T_{RV}	reactor vessel temperature
T_W	wall temperature
V_{RV}	reactor vessel volume
ε	turbulent kinetic energy dissipation
ρ_G	vapor density
ρ_{RV}	reactor vessel density
η_{IVR}	cooling efficiency of IVR-ERVC
ω	specific turbulent kinetic energy dissipation

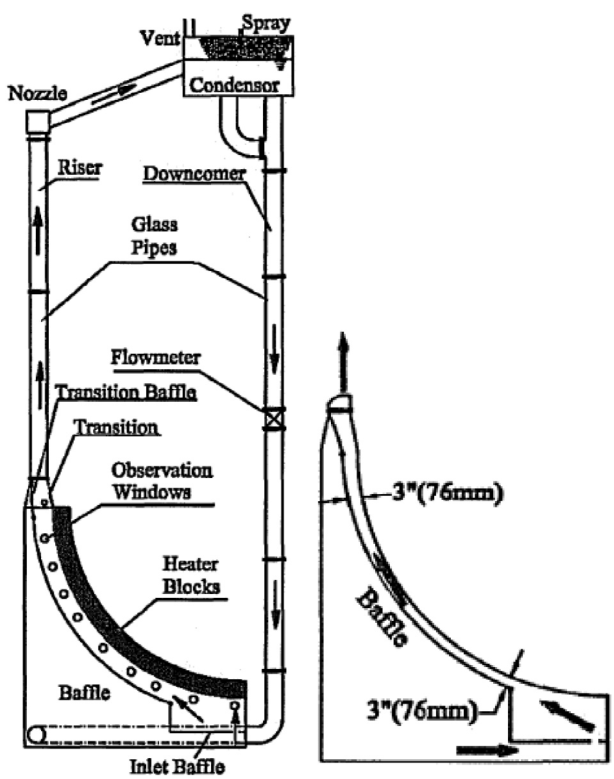

Fig. 1. Schematic of the ULPU-2000 configuration V, run No. 4 (Dinh et al., 2003).

Table 1
Grid parameters and liquid velocities at downcomer.

Grid	Nodes	Elements	Liquid velocity at downcomer
C	88,112	42,199	-4.62×10^{-1} m/s
M	107,590	51,726	-4.70×10^{-1} m/s
F	187,366	90,799	-4.63×10^{-1} m/s

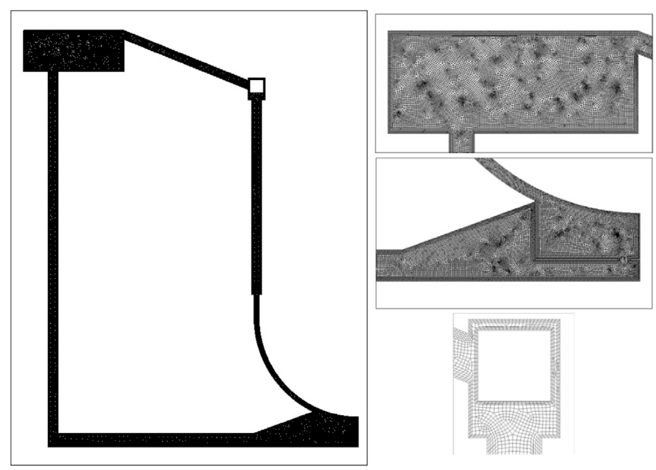

Fig. 2. Computational grid M.

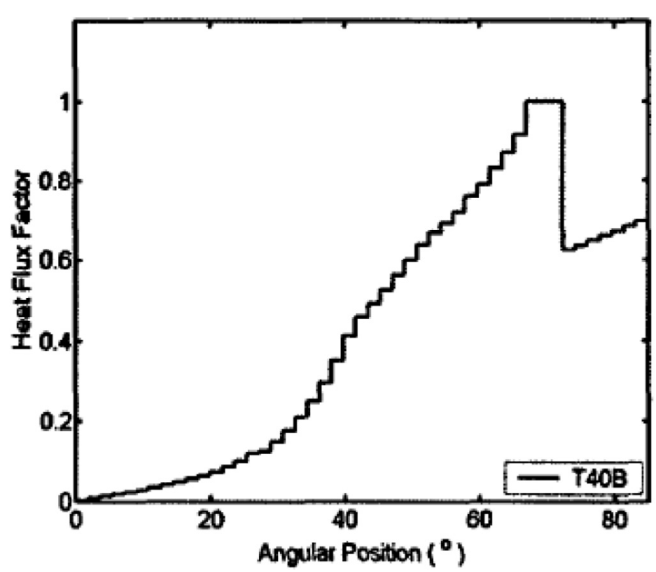

Fig. 3. Angular dimensionless heat flux profile (Dinh et al., 2003).

2. Numerical methods

2.1. RPI subcooled flow boiling model

Among the varied multidimensional theoretical approaches for subcooled boiling, two-fluid modeling is the most widely used. This consists of a dispersed phase (vapor bubbles) and a continuous phase (liquid flow) and is based on averaged transport equations. In averaging, the interpenetrating continua assumption is used, where each phase is assumed as a continuum filling the