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Jet impingement model for system analysis code to enhance mixing behavior prediction in downcomer during DVI line break accident

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ABSTRACT

Advanced Power Reactor of 1400 MWe (APR1400) adopts a Direct Vessel Injection (DVI) system that injects Safety Injection (SI) water directly into the reactor vessel downcomer during accidents. As the DVI nozzles are directly attached to the reactor vessel downcomer, complex thermal-hydraulic phenomena occur in the downcomer region. Recently, in the International Standard Problem (ISP) No. 50 exercise, the phenomena of Emergency Core Cooling (ECC) water mixing in the upper downcomer during the DVI line break accident observed in Advanced Thermal-hydraulic Test Loop for Accident Simulation (ATLAS) test were highlighted in terms of the prediction capability of the system analysis codes. Thus, to validate the results from the ATLAS study independently, an additional experimental study was performed with an integral effect test facility, Seoul National University Facility (SNUF), to observe the mixing behavior in the downcomer during a DVI line break accident. According to the SNUF test results, the ECC water mixed vigorously in the downcomer annulus. However, the temperature difference in the azimuthal direction was predicted by a system analysis code, Multi-dimensional Analysis Reactor Safety (MARS). In the MARS calculation, the momentum flux terms are set to zero for the junction between the one-dimensional volume and three-dimensional cell of the MultiD component because the axial and radial velocities are marginal in the large three-dimensional region. However, if the nozzles are attached to the downcomer with a thin gap, the axial and radial velocities are significant when the incoming orthogonal flow through the nozzles impinges against the downcomer wall. It was necessary to consider the momentum flux terms induced by the impinging flow, and to do so, an appropriate jet impingement model, for incorporation in the system analysis code, MARS, was developed in this study. To develop the jet impingement model, Computational Fluid Dynamics (CFD) calculations were carried out, and the jet impingement model was formulated based on the CFD calculations under various conditions. The momentum flux term resulting from the jet impingement phenomenon was correlated with the diameter of the nozzle, downcomer gap size, and incoming flow velocity. This model was applied to MARS by considering the momentum flux term for the junctions connected to the cell of the MultiD component. The modified MARS incorporating the jet impingement model was validated with the test results from the SNUF and ATLAS, and the analysis results exhibited reasonable agreement with the test data.

1. Introduction

Advanced Power Reactor of 1400 MWe (APR1400) is an advanced Pressurized Water Reactor (PWR), and it adopts a Direct Vessel Injection (DVI) system that injects Safety Injection (SI) water directly into the reactor vessel downcomer, instead of using a Cold Leg Injection (CLI) system, as a new SI feature. However, as the DVI nozzles are directly attached to the reactor vessel downcomer, complex thermal-hydraulic phenomena occur in the downcomer region.

To understand the overall system behavior in the reactor under various accident conditions, the Korea Atomic Energy Research Institute (KAERI) has been operating an integral effect test facility, Advanced Thermal-hydraulic Test Loop for Accident Simulation (ATLAS), for APR1400 (Baek et al., 2005; Choi et al., 2006). A series of experiments have been conducted to investigate the sensitivity of the system behavior to the DVI line break sizes (Choi et al., 2009; Choi et al., 2011). Among the DVI line break scenarios, a DVI nozzle break accident simulating 50% of the cross section breakage was selected for the Organization for Economic Cooperation and Development (OECD)/ Nuclear Energy Agency (NEA) International Standard Problem (ISP)

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Nomenclature

d	diameter [m]
Fr	Froude number
g	gravitational acceleration [m s^{-2}]
l	length [m]
P	pressure [Pa]
r	r-direction, radial coordinate measured from the stagnation point [m]
Re	Reynolds number
s	height of downcomer [m]
T	temperature [K]
t	downcomer gap size [m]
u	x-direction velocity [m s^{-1}], local mean velocity in the radial direction [m s^{-1}]
$\bar{u}$	x-direction average velocity [m s^{-1}]
V	velocity of incoming flow [m s^{-1}]
v	y-direction velocity [m s^{-1}]
$\bar{v}$	y-direction average velocity [m s^{-1}]
w	z-direction velocity [m s^{-1}]
$\overline{w}$	z-direction average velocity [m s^{-1}]
x	x-direction
y	y-direction
z	z-direction, axial coordinate measured from the impingement wall [m]

Greek letters

α	void fraction
θ	θ-direction
ρ	density [kg m^{-3}]

Subscripts

0	initial value
a	ambient water in downcomer
g	gas
in	incoming flow
K	upward volume
L	downward volume
m	mean value
R	scaling ratio

exercise No. 50 (OECD/NEA, 2012). In the ISP-50 exercise, the reproduction of the Emergency Core Cooling (ECC) water mixing phenomena in the upper downcomer observed during the test was highlighted as an indicator of the prediction capability of the code. According to the synthesis of this benchmark problem, it was determined that the code's prediction capability of three-dimensional downcomer mixing phenomena was not satisfactory in a majority of calculations. In the experiment, the cold ECC water was vigorously mixed with the hot inventory in the downcomer. However, this vigorous and instant mixing was not reproduced appropriately by the system analysis codes and the temperature difference in the azimuthal direction was predicted in the downcomer region adversely.

This multidimensional behavior in a downcomer annulus can influence the mixing of inlet coolant with the asymmetric temperature gradient during a transient period such as a Steam Line Break (SLB) accident as well as the ECC water mixing with the DVI mode. Rupturing a steam line in one of the loops causes an increase in steam flow from the broken secondary system. The increased heat removal induces a temperature drop in the primary system for the loop with a rupture. Then, it results in a highly asymmetric coolant temperature in each loop, and the temperature distribution in the azimuthal direction can be observed in the lower downcomer. If the coolant in the lower downcomer is not mixed, it can cause a challenging problem with a highly asymmetric power distribution in the core due to a negative Moderator Temperature Coefficient (MTC). In accordance with an analysis performed to develop an advanced integrated modeling/simulation tool named Virtual Environment for Reactor Applications (VERA) (Montgomery, 2014) in Consortium of Advanced Simulation of Light water reactors (CASL) program, an asymmetric core inlet temperature distribution (480 K in the high temperature region and 458 K in the low temperature region) during the SLB accident resulted a highly asymmetric core power distribution (Kucukboyaci et al., 2015). The high power assemblies were clustered in the broken loop section of the core, and the hot assembly factor was approximately 7.2. Therefore, it is important to estimate the mixing effect of the coolant water in the downcomer which has different temperatures driven from the broken and intact side.

The current system analysis codes are presumed to have a limitation in predicting multidimensional liquid phase mixing behavior in a downcomer annulus reasonably, although the mixing phenomena in the downcomer can influence safety analyses significantly as described above. Motivated by this, the present experimental and analytical research study has been performed to understand the mixing behavior in reactor downcomer.

The objective of this study was to investigate the liquid phase mixing behavior in downcomer annulus of reactor. In particular, it was focused upon understanding the cause of inaccurate prediction of azimuthal temperature distribution in downcomer by system analysis code, and upon improving the capability of the codes to predict mixing behavior in downcomer. To achieve this objective, an additional experiment was performed. Since an aspect ratio of the ATLAS downcomer is approximately 6.0, the coolant mixing phenomenon can be distorted (KAERI, 2009). Thus, an integral effect test facility, Seoul National University Facility (SNUF) which has an aspect ratio approximately 2.0 (Kim et al., 2003, Kim et al., 2005, Lee et al., 2008) was utilized for the test. The test data were predicted using a system analysis code, Multi-dimensional Analysis Reactor Safety (MARS)-KS 1.3 (KINS, 2016), and a model referred to as the jet impingement model, which was developed as part of this study by utilizing a Computational Fluid Dynamics (CFD) software, STAR-CCM+, was implemented into the system analysis code for a realistic prediction of the ECC mixing in the downcomer. The test results of the SNUF and ATLAS were used to evaluate the improved performance of MARS incorporating the developed jet impingement model.

2. Integral effect test for mixing behavior in downcomer

2.1. Description of SNUF

The SNUF is an integral loop test facility designed to simulate the primary and secondary loops of APR1400 (Kim et al., 2003; Kim et al., 2005; Lee et al., 2008). A schematic of the SNUF is illustrated in Figs. 1 and 2. The scaling factors for length and area in the primary system are 1/6.4 and 1/178, respectively. The geometrical configuration of the reactor vessel in the SNUF is equivalent to that in APR1400, which consists of two hot legs and four cold legs. The test vessel contains 150 heaters to simulate the core decay heat. The maximum total operational power of these heaters is approximately 180 kW. The maximum operational pressure is 0.8 MPa.

2.2. Need for the experiment with SNUF

Regarding the mixing behavior in the downcomer, it is critical to preserve Froude numbers in accordance with the ROCOM buoyance