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Strategy development of the experimental characterization for mixing characteristics inside reactor vessel for reactor transient condition

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1. Introduction

A mixing behavior of fluids having different property which is injected from the cold leg or DVI nozzle inside the downcomer and core is very important during a transient operation such as a reactivity insertion owing to the rapid boron concentration or overcooling transient. In pressurized water reactors (PWR), boron acid is added to the water coolant to compensate the excess reactivity of fresh fuel loadings. Due to different mechanisms or system failures, slugs of low borated water can accumulate in the primary cooling system. This can happen, e.g. as a consequence of a small break loss of coolant accident (SB LOCA), when coolant circulation is interrupted, steam produced in the reactor core is condensed in the steam generator, and a slug of low boron condensate will accumulate at the cold leg of the primary circuit. During start-up of coolant circulation after refilling the primary circuit with emergency cooling (ECC) water or by switching on the first main coolant pump (MCP), this slug will be transported into the reactor core causing a significant reactivity insertion by decreasing the amount of neutron absorber. The mixing of the deborated condensate with borated water in the reactor pressure vessel is in that case the only mitigative mechanism to prevent severe accident consequences.

The mixing is also relevant in overcooling transients, when the coolant temperature in one or more loops decreases, e.g. due to a leak in the secondary side steam system [1]. A strong decrease of the coolant temperature does also cause a reactivity insertion due to the enhanced moderation of neutrons. Mixing is relevant not only for nuclear safety, but also for structural integrity. In the case of LOCAs, cold ECC water will be injected into the hot primary circuit. When plumes of cold water get in contact with the reactor pressure vessel (RPV) wall, thermal stresses occur, which can be dangerous for the RPV integrity. Mixing is even of relevance for normal reactor operation, e.g. for determination of the coolant temperature distribution at the core inlet in the case of partially switched off MCPs.

As a recent license issue of the new reactors, the postulated deborated characteristics are considered as important scenarios. As an example, undesirable deborated water can be entered the reactor by an inadvertent CVCS operation, which can induce boron dilution in the core and then a criticality. The estimation of the arriving time to criticality without operation action is very important for the accident management. For the safety analysis, a perfect mixing assumption is usually adopted at the upstream of the core, in the meanwhile, the reactor inventory is assumed to be minimal value for conservatism, since it can lead the dilution effect more severely.

For such a thermal and hydraulic non-equilibrium mixing characteristics, several experimental and CFD analysis works have been performed past a few decades such as EU project FLOMIX-R. The ROCOM test program is a representative work as a model of the current study, which is a 1:5 scaled facilities representing different European reactor types: the Rossendorf coolant mixing model. [2]

Many CFD works to predict the multi-dimensional mixing behavior have been performed. In spite of the large amount of work performed like in FLOMIXR, there are still questions unanswered about the capability of CFD codes to model boron dilution transients and mixing in primary system in pressurized water reactors. [3]

- Mesh size dependency
- Faster and more accurate solvers and numerical schemes
- Necessity of the advanced turbulence model
- Better models of wall boundary layers
- Limitation of the fast transient condition

Current work is focused on the scratch for the experimental identification process of the non-equilibrium characteristics of the injected fluid at cold leg or DVI-nozzle in the downcomer and reactor core.

2 Setup Test Requirement

The thermal mixing behavior and boron dilution characteristics can be performed using same frame of test requirement since fundamentally, the mechanism is similar to each other. Three locations inside the pressure vessel are interested in respect of mixing of the injected coolant to the reactor.

- Azimuthal and depth directional mixing in the downcomer
- Mixing characteristics at core inlet
- Mixing characteristic at core outlet
- Flow split to the two hot legs of the injected flow to reactor

Based on the injection position, a cold leg and a DVI nozzle can be optionally selected. For example, the boron dilution induced by inadvertent operation of

CVCS, DVI nozzle injection should be investigated for the relatively new reactor after APR1400.

The channel geometry, where major reactor coolant should pass, should be preserved and appropriate scaling should be setup based on proper dimensionless parameters. Re and Eu numbers are usually considered important for the flow mixing similar to the flow distribution test. A 1/5 length reduced scale of prototype plant is widely adopted in the previous studies.

The inventory is very important for the boron dilution test. For conservatism, minimum boric acid water inventory is generally assumed in the safety analysis as a boundary conditions. However, a complete mixing is often assumed since the non-equilibrium degree cannot be addressed easily, which reduces the conservatism. To check the conservatism, the experiment should include a rationale inventory of the real plant has, including the volume of a part of cold leg and hot leg, and upper plenum. The solid volume in the core including core support structures should be considered properly.

The variation of the boron concentration at the core inlet at highest and lowest locations as well as average value are recommended to be measured along the time.

3. Experiment Method

3.1 Setup the Boundary Condition

Generally room temperature, pressure conditions would be fine for the flow mixing characteristic tests. The viscosity has significant variation over the room temperature range. A high temperature has advantage in respect of getting high Re number. A 60 ^oC of water temperature was used as working condition in the recent several literature, which condition is considered optimized in respect of Eu number analogy and a system maintenance. Gas can be used for the flow mixing test such as using SO_2 as a tracer material, which can be a possible option after checking the Re number range. A buoyancy effect due to the temperature difference can be simulated by a material having a different density like sugar. The flow rate can be widely selected. For the boron dilution, relatively low flow condition is interested, meanwhile, high flow rate may be required for the overcooling transient.

A tap water and demi-water can be an excellent combination for the continuous and tracer fluids since the two waters have more than hundreds times of conductivity difference, in general. It has an advantage of no required special waste disposal treatment.

3.2 Downcomer Mixing Characteristics

Fig. 1(a) and (c) shows an example of the instrumentation to get the impedance information at downcomer. In total, 64 points having azimuthally 16 points and 4 points in gap direction can give us a 2D concentration information of the injected coolant in the downcomer at specific elevation. The principle of the measurement is same as the instrumentation using a wire mesh sensor.

3.3 Core Inlet Mixing Characteristics

A special wire-mesh sensor, based on the measurement of the electrical conductivity can be used for the core inlet mixing characteristics. A wire mesh measuring system is widely utilized for a fine scale distribution of the different fluids including two-phase flow. They consist of two orthogonal electrode grids put into the measuring cross section. The wires of the first grid (transmitter electrodes) are supplied with short voltage pulses in a successive order. When a voltage pulse is given to a certain wire of the first grid, the individual currents, arriving at each of the wires of the second plane (receiver electrodes) are proportional to the local conductivity of the water at the crossing points between the corresponding transmitter and receiver electrodes. By positioning the cross-point at the center of the representative location of each fuel assembly, one can obtain the mixing characteristics of the injected different property fluid inside the reactor at fuel assembly wise nodes. Figure 2 shows a typical mixing characteristics in the core inlet measured by a wire-mesh system.

3.4 Hot Leg Split Ratio

The hot leg split ratio of the injected a cold leg flow can be achieved by a pipe area-averaged impedance sensor. Figure 3 shows a sample of the sensor applied for the previous experiment. Two arched sensors having 90^o central angle are attached at pipe inside surface contacting the working fluid. An AC or DC current is applied to each sensor to get the impedance information. Another pair of sensors can be designed with a 90^o rotated position to investigate the asymmetric effect of non-equilibrium flow mixing.

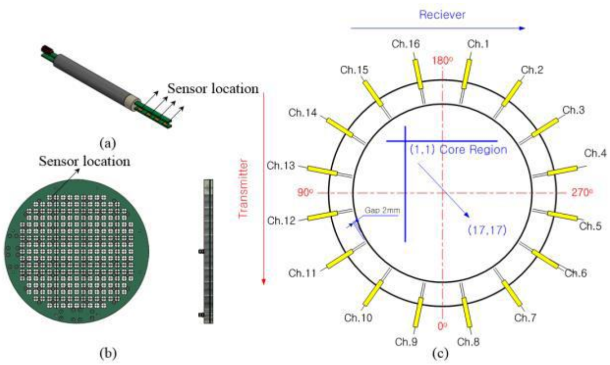

Fig. 1 Impedance Sensor for Core Inlet and Downcomer

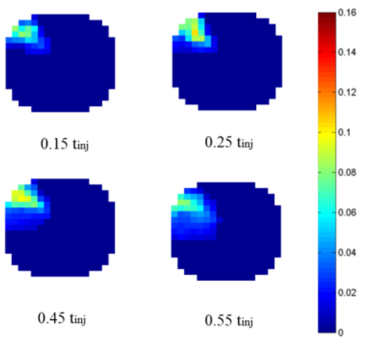

Fig. 2 Typical result of the core inlet mixing characteristics for intermediate flow velocity

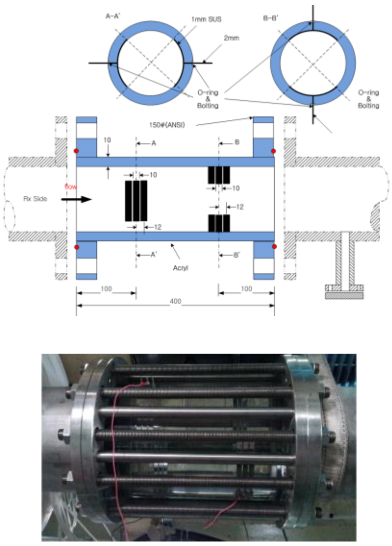

Fig. 3 Channel Averaged Impedance Sensor [4]

3.5 Calibration Process

The real impedance value can be converted from a calibration process. Because the impedance is affected significantly by the electric environment of the installed section, an in-situ calibration is recommended under a steady state operation over a coverage of the working impedance range and constant temperature. The reference value of the impedance is obtained using a reliable conductivity sensor.

4. Conclusion

In the present paper, a strategy of the experimental characterization for reactor mixing characteristics were studied for a fluids having different properties during a transient. The test requirement are being setup for the optimized scope and specification of the experiment.

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