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Methodology Development for 3D Analysis of Spray Cooling in a NPP containment using OPENFOAM

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1. Introduction

During an accident accompanied by a core damage in a nuclear reactor, a large amount of steam and hydrogen can be released into containment of nuclear reactors. The pressure inside the containment can increase substantially, and the integrity of the containment may be threatened, such as Fukushima nuclear power plant accident. In order to prevent overpressures in steam break event, a spray cooling system in the upper part of the containment is an effective method to reduce the stress on containment walls and prevent its damage by condensation of the steam in containment. However, the concentration of hydrogen in a mixture can be increased, and it can be badly affected to a probability of hydrogen explosion.

Hydrogen behaviors during a severe accident in an NPP containment strongly depend on various phenomena [1]. Implementation of all the models for each phenomenon in a single code makes it complicated to run for long-term accident scenarios. To resolve important phenomena by changing models and correlations, a conservative but best-estimate approach requires repeated simulations. They also need validation works with separate effect tests. So, a new analysis code is needed, which is cost-effective for heavy use and manageable for improvement and addition of numerical and physical models and correlations. An analysis tool for hydrogen behavior in a containment is under development based on the OpenFOAM [2] library which supplies modularized numerical and physical models by using classes and namespaces.

The present work concerns the interaction of an internal water spray used at the top of the containment in order to reduce the steam partial pressure, under air-steam mixtures conditions. The module for the simulation of spray cooling is under development based on the Euler-Euler approach using OpenFOAM[3]. The module is validating by comparing the analysis results with TOSQAN[4] experiment.

2. Development of numerical methods

2.1 Spray modeling

In the Euler-Euler approach, the gas and the liquid (droplet) phases are modelled with separate flow-field. The Euler equations of mass, momentum, energy can be employed for each phases. The gas and the dispersed droplet phases interact each other and exchange momentum, thermal energy and mass. reactingTwo-PhaseEulerFoam in OpenFOAM[2], which is an open-source CFD code, is a solver for a system of two compressible fluid phases with a common pressure, but otherwise separate properties. The basic algorithm of the solvers is pressure-based semi-implicit method (SIMPLE and/or PISO) with non-staggered arrangement of variables on a computational mesh. The unsteady terms are discretized by 1st order Euler or 2nd order backward scheme. But current simulations are mostly conducted by using 1st order Euler scheme.

The phase system is run time selectable and can optionally represent different types of momentum, heat and mass transfer. In this version, we select interfacecompositionPhaseChangeSystem in reacting TwoPhaseEulerFoam to consider interfacial heat and mass transfer between a number of phases according to an interface composition model. There are also several models for the interaction terms.

We develop the model to simulate the spray system, such as the droplet temperature, velocity, and droplet size, etc. Also, to simulate the spread of spray system, we used the turbulentdispersion model in phasesystem.

2.2 Benchmark problem: TOSQAN experiment [4]

The TOSQAN experiment program have been created to simulate typical thermal hydraulic conditions representative of a severe accident in the reactor containment. The several spray tests were performed in hot conditions to analyze the heat and mass transfer between spray droplets and gas mixtures [4]. In this study, the test No. 101 was selected as the benchmark test, because the test No.101 is the reference test with air-steam mixture (A-S)

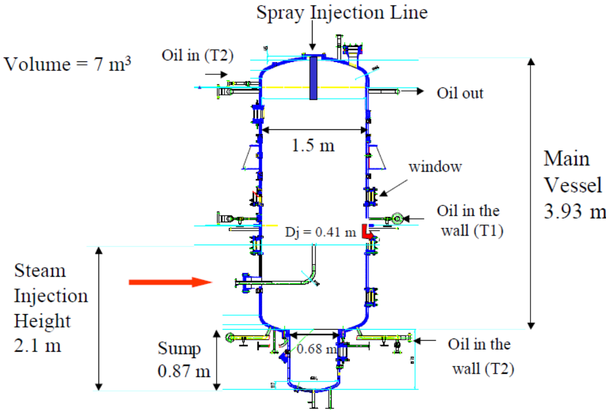

Fig. 1. Overview of the TOSQAN facility [4]

The TOSQAN facility shown in Fig. 1 consists of a closed cylindrical vessel into which steam gases can be injected through a vertical pipe located on the vessel axis. The spray is injected on the vessel axis, 70 cm from the top of the facility. They measured the temperature, pressure and the steam volume fraction in the vessel.

TOSQAN test presented consist of a water spray injection into the enclosure, which is initially filled with an air-steam mixture, the walls having already reached their nominal temperature. A vessel depressurization is observed and a final equilibrium is reached. Measurements which are pressure and temperature are performed during the depressurization and during this final equilibrium.

2.3 Preliminary analysis

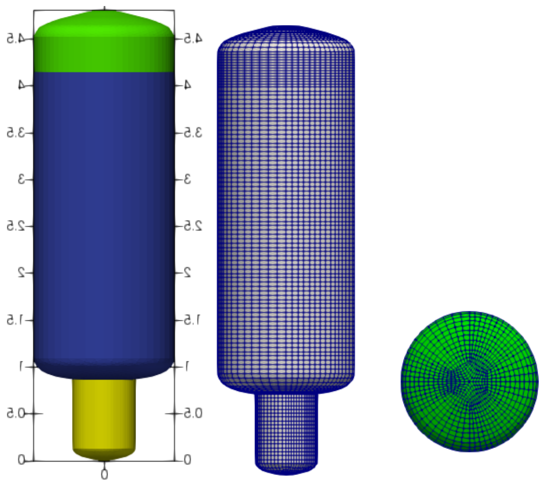

Fig. 2 Mesh system of TOSQAN test facility used for a preliminary analysis

We selected test No.101 as a benchmark problem. To simulate test No.101, the initial internal TOSQAN vessel condition, internal and wall temperature were the same as the experimental conditions. The initial conditions of experiment and preliminary analysis are summarized in table.1 [4]. The gas temperature is 120 °C, the pressure is 2.5 bar, the steam volume fraction is 0.6. The wall temperature is 120 °C during the tests. The water injection conditions are 30 g/s of mass flow rate, 25 °C of the temperature. The spray temperature was varied during the test from 22 to 27 °C. So, we assume that the spray temperature is 25 °C.

A 3D analysis computational model was developed. Based on the 3D CAD data of the TOSQAN, a 3D mesh was constructed using the SALOME as shown in Fig.2. In this Preliminary analysis, the number of cells are 58777 and the number of faces are 182257.

The preliminary analysis was performed to investigate the sensitivity of the major variables of the spray model and determine their values. The parameter conditions were summarized in table. 2. The droplet velocity is the spray droplet velocity at below 5 cm of the spray injection nozzle, Cdt table is a variable that controls the degree of spread of the sprays

Table 1. Initial information

	Initial gas mixture characteristics				Spray characteristics		
	Mixture	Tg (°C)	P (bar)	Xs	Qinj (g/s)	Tinj (°C)	D (μm)
Test 101	A-S	120	2.5	0.6	30	22~ 27	130
Input	A-s	120	2.5	0.6	30	25	150

Table 2. Parameter conditions

case	Droplet velocity	Cdt table	Spray angle
4	-5	1000	27.5
7	-0.5	100	27.5
8	-0.01	0	27.5
9	-0.01	100	27.5

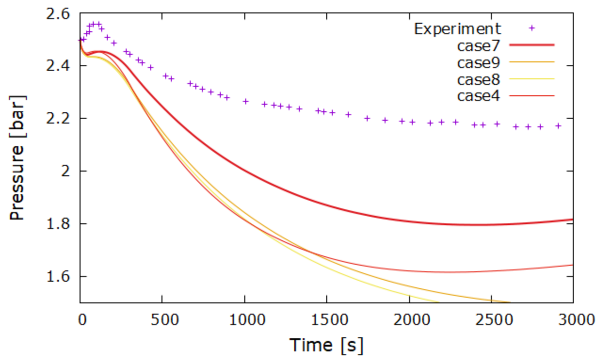

Fig. 3 Time evolution of the pressure

The thermo-dynamical global behavior concerns the pressure variation in the TOSQAN vessel. Fig. 3 shows the time evolution of the pressure in the TOSQAN vessel.

It is shown that as the increase in the droplet velocity and the spreadability of the spray, the pressure increases. The reason is that the contact between the droplet and the wall increases. The analysis results underestimate the experimental results. One of the reasons is the limitation of the water droplet wall evaporation model. It is shown in the Ref.5 that considering the droplet-wall interaction predicts the experimental results better, and depending on whether the droplet-wall interaction effect is considered or not, the pressure differed by 20 to 46% on the analysis pressure.

To take the droplet-wall interaction phenomena, a new grid near the wall will be constructed, and the wall heat transfer model will be improved.

3. Conclusions

It is underway to develop a methodology for 3D analysis of spray cooling in NPP containment. The methodology is going to be developed by using OPENFOAM library. The preliminary analysis was performed to evaluate the applicability of reactingTwoPhaseEulerFoam in OpenFOAM to the spray cooling module based on the TOSQAN test No. 101. It was found that the wall-droplet interaction is one of the major parameter affecting on the prediction of the pressure in the spray cooling. In ongoing research, the mesh system and the wall heat transfer model will be modified to better simulate the wall-droplet heat transfer.

ACKNOWLEDGEMENT

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