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Methodology Development for 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]. The figure. 1 shows physical models grouped by modules required to simulate hydrogen safety in a NPP containment. Implementation of all the models for each phenomena in a single code makes it complicated to run for long-term accident scenarios. Modularization of an analysis code is a commonly used technology to keep the code manageable. 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. Another important thing is a development of tools helping an analysis procedure to make a final conclusion of a hydrogen safety in a specific NPP. So, 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.

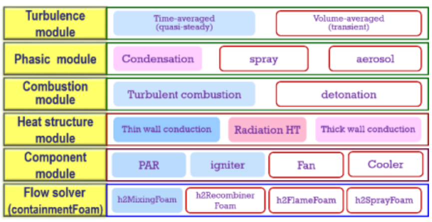

Fig. 1. Modularized code system for hydrogen safety analysis.

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. There are two difference approach which are an Euler-Lagrange two-fluid approach and an Euler-Euler two-fluid approach. Both approaches have advantages and disadvantages, but the Euler-Euler approach has more advantageous to apply the severe accident analysis. So, the module for the simulation of spray cooling is under development based on the Euler-Euler approach using OpenFOAM. To verify the spray cooling module, a comparison of spray tests which is TOSQAN [3] will be conducted.

2. Development of numerical methods

2.1 Spray modeling

The gas and the 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. reactingTwoPhaseEulerFoam in OpenFOAM, 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 phase system is run time selectable and can optionally represent different types of momentum, heat and mass transfer. There are also several models for the interaction terms. We select reactingTwoPhaseEulerFoam to evaluate the applicability to analysis of water spray system. 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.

2.2 Benchmark problem: TOSQAN experiment

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] Test No. 101 is the reference test with air-steam mixture (A-S), whereas test 102 is the reference test with air-steam-helium mixture (A-S-H). The other tests are performed by changing the spray injection mass-flow rate, the spray injection temperature, the superheating, the initial gas temperature, the difference between saturation temperature and injection temperature, etc.

The TOSQAN facility shown in Fig. 2 consists of a closed cylindrical vessel (7m^3 volume, 4.8 m the total height, 1.5m internal diameter) 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. The TOSQAN vessel has thermostatically controlled by heated oil circulation to control the gas and wall temperature.

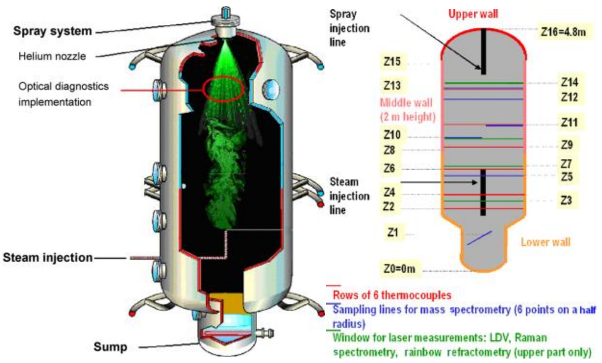

Fig. 2. Overview of the TOSQAN facility [7]

2.3 Preliminary analysis

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

We first selected test No.101 as a benchmark problem. The initial conditions of experiment and preliminary analysis are summarized in table.1. The gas temperature is 120 ºC, the pressure is 2.5 bar, the steam volume fraction is 0.6. The wall temperature is 120 ºC during the tests. The water injection conditions are 30 g/s of mass flow rate, 25 ºC of the temperature. The spray temperature was varied during the test from 22 to 27 ºC. So, we assume that the spray temperature is 25 ºC.

A 2-D axisymmetric computational model was developed as shown in Fig 3. The mesh was generated using blockMesh in OpenFOAM. In this Preliminary analysis, the number of cells are 2699. The discretized equations are applied for each cell. In the experiment, the initial droplet velocity is 20 m/s. In order to make the droplet velocity ~~as~~ same as the experiment, it is needed to decrease the mesh size using refined mesh as shown in Fig. 4. A computational cost is dependent on number of cells and time steps. The number of time steps is determined by a simulation time period and cell size. If a smaller cell size is used, a smaller dt must be used. It is necessary to optimize the size of a computational mesh and distribution of cell size in the mesh with an implemented numerical scheme to get numerical results on an available computing time. Preliminary analysis was carried out based on the only mass flow rate.

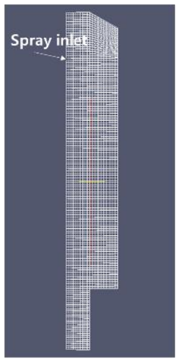

Fig. 3 Internal wire mesh

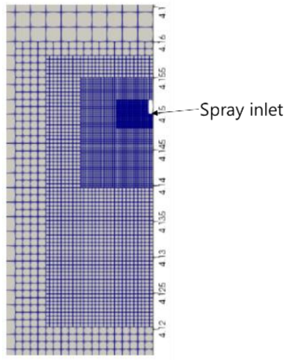

Fig. 4 very refined mesh around injector

Table 1: Initial information

	Initial gas mixture characteristics				Spray characteristics		
	Mixture	Tg (ºC)	P (bar)	Xs	Qinj (g/s)	Tinj (ºC)	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

The thermo-dynamical global behavior concerns the pressure variation in the TOSQAN vessel. Results for the total pressure at the final equilibrium are presented on the fig. 5 and table 2. In this table, results are given for the different modellings made by the code users [8]. The tendency of the pressure of OpenFOAM results can be seen to follow the experimental results.

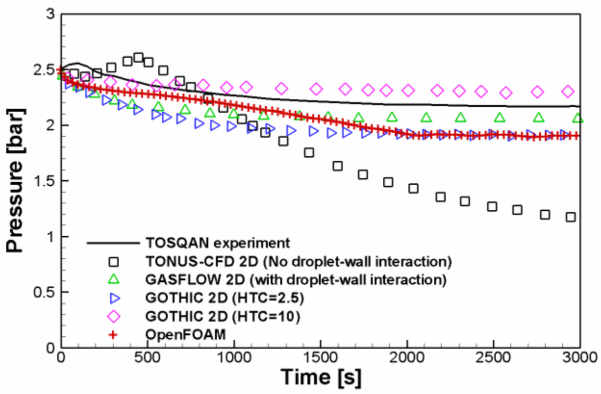

Fig. 5 Time evolution of the total pressure

Table 2. Final Pressure

CODE	Pressure (bar)	CODE	Pressure (bar)
TOSQAN	2.152	GOTHIC 2D(HTC =2.5)	1.89
TONUS-CFD 2D	1.36	GOTHIC 2D(HTC =2.5)	2.29
GASFLOW 2D	2.05	OpenFOAM	1.90

2.4 Future works

As mention before, the initial droplet velocity is 20 m/s in the experiment. In order to make high droplet velocity and spray angle without major changes in cell size, the spray injection model will be developed. To get better results, both the interaction model for the gas and the droplet and the wall condensation model will be modified.

3. Conclusions

A 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 is observed that the analysis results follows the pressure variation in the TOSQAN vessel well. In the future, the spray injection model will be developed to simulate spray characteristics. Also, the interaction model for the gas and the droplet and the wall condensation model in OpenFOAM will be modified.

ACKNOWLEDGEMENT

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