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Analysis of LSGMF test using OpenFOAM

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1. Introduction

One of the phenomena in the behavior of hydrogen within containment buildings is stratification, which can occur during the release and diffusion phases of hydrogen. It is influenced by phenomena such as jet release, buoyancy, steam condensation, and hydrogen diffusion. Predicting the distribution of hydrogen concentration due to hydrogen diffusion could play a crucial role in the assessment of hydrogen risk within containment structures before evaluating hydrogen control measures such as dilution and removal.

Furthermore, gas mixing phenomena are dependent on the size of the enclosure. Therefore, a thorough understanding of the phenomenon and validation of evaluation techniques should be achieved through large-scale experiments that simulate real containment buildings. The Large-Scale Gas Mixing Facility (LSGMF) test [1,2], conducted at the Whiteshell Laboratories of the ACEL, is a large-scale gas mixing experiment that provides data suitable for code validation. It operates at a scale similar to nuclear power plant containment structures and compartments.

In this study, we aim to validate the LSGMF test for hydrogen risk analysis by using OpenFOAM [3].

2. Modeling

2.1 Test facility

The LSGMF is a concrete structure measuring approximately 10.3 m x 8.2 m x 11.0 m, with a wall thickness of 0.45 m and an internal volume of about 1000 m^3. An overview of the experimental setup is depicted in Fig. 1. Helium was injected instead of hydrogen, and steam was not introduced. Helium injection occurred at the BT (Blow-Through) tube location shown in Fig. 1, with two tube diameters of 0.05 m and 0.30 m used for the experiments. The BT elevation is situated 0.6 m above the bottom floor and positioned within the central area of the containment building, at distances of 4.1 m and 5.1 m from the sidewalls along the x and y axes, respectively. The helium injection lasted a total of 600 seconds, with a pressure maintained at 100 kPa throughout the experiment. The initial temperatures were 18 °C for the air and wall temperature within the building, and 16 °C for the helium injection temperature. Details of the test variables related to helium injection flow rate can be found in Table I. And Table II shows the location of the sensors measuring He concentration. Along the x-axis of Figure 1, sensors P1 to P5 are located at a distance of 4.1 m, directly above the He injection tube. And sensors P6 to P10 are positioned at 6.15 m approximately 2 m away from the helium injection tube.

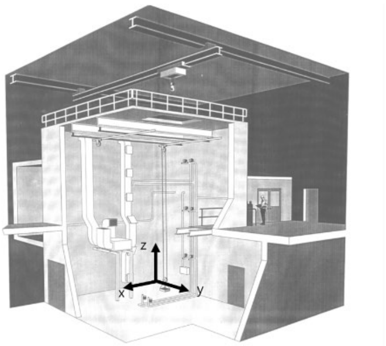


Fig. 1. Schematics of the LSGMF test facility

Table 1. Test variables

Test variables		Jet diameter	
		0.0508 m	0.305 m
Jet velocity		8.6 m/s	0.24 m/s
He injection flow rate	Volume flow rate	0.0175 m^3/s	
	Mass flow rate	2.97 g/s	

Table 2. Locations of the sensors

Sensor ID	Height (m)
P1, P6	1.21
P2, P7	3.57
P3, P8	5.93
P4, P9	8.29
P5, P10	10.6

2.2 Governing equations

In compressible fluid dynamics, the governing equations mass continuity, momentum conservation, and energy conservation can be formulated as follows:

$$\frac{\partial \rho_k}{\partial t} + \nabla \cdot (\rho_k \boldsymbol{v}) + \nabla \cdot \boldsymbol{J}_k = m_k \omega_k \tag{1}$$

$$\frac{\partial (\rho \boldsymbol{v})}{\partial t} + \nabla \cdot (\rho_k \boldsymbol{v} \otimes \boldsymbol{v}) = -\nabla \mathrm{p} + \nabla \cdot \tau + S_M \tag{2}$$

$$\frac{\partial (\rho h)}{\partial t} - \frac{\partial p}{\partial t} + \nabla \cdot (\rho \boldsymbol{v} h) = \nabla (k \nabla \mathrm{T}) + \nabla \cdot (\boldsymbol{v} \cdot \tau) + \boldsymbol{v} \cdot S_M + S_E \tag{3}$$

where ρ is the density, k denotes the species, $\boldsymbol{v}$ is mass average flow velocity, $\boldsymbol{J}_k$ is diffusion flux of the kth species, m is the molar mass, ω is the molar production rate, p is the pressure, τ is the stress tensor; h is the total enthalpy; S_M is the external power source; k is the thermal conduction coefficient; T is the temperature; S_E is the energy source.

2.3 Numerical modeling

A mapped mesh based on the Salome platform was employed to create the grid model for the LSGMF geometry as shown in Fig. 2. The total mesh count amounted to approximately 117,000, with the minimum mesh size being around 0.018 m. The analysis utilized the newly developed contain3d solver [4], specifically designed for an analysis of severe accident phenomena in a containment building. This solver is developed based on the fireForm solver of OpenFOAM, and has additional features of steam condensation, and hydrogen mitigation using Passive Autocatalytic Recombiner (PAR).

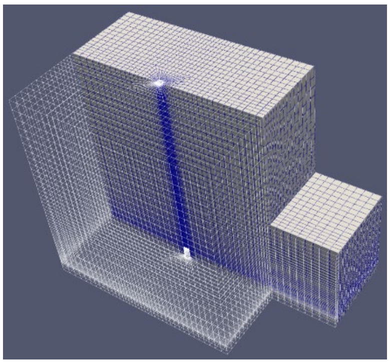
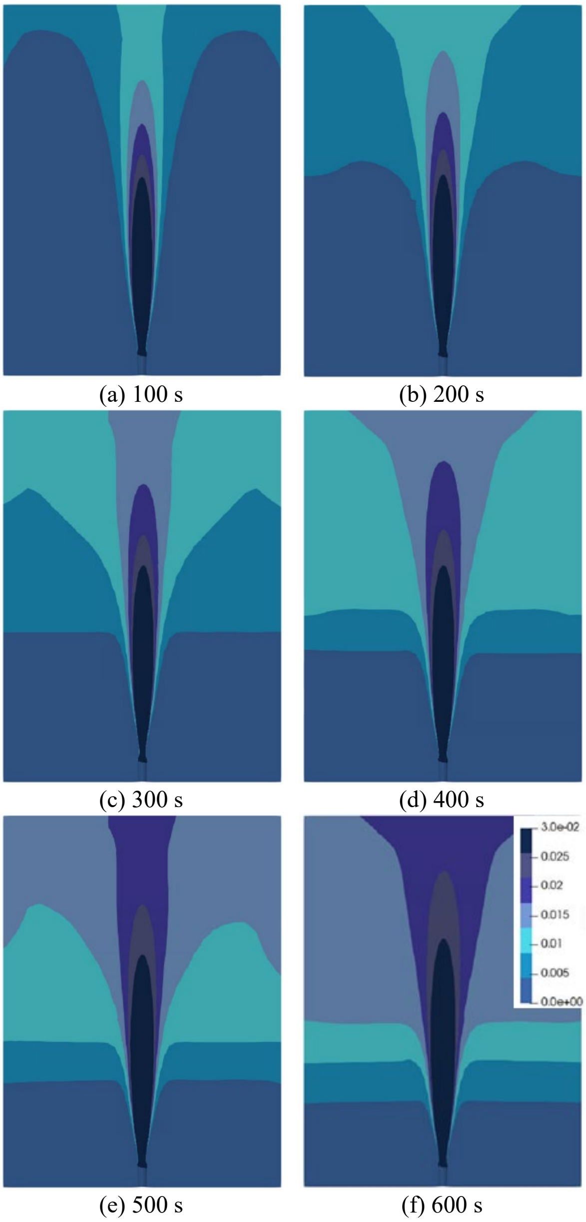


Fig. 2. Grids of LSGMF

3. Results

In this study, analysis was carried out for the case involving a 30.5 cm diameter pipe as indicated in Table I. The main focus of the LSGMF experiment was to investigate the occurrence of stratification during helium injection as an alternative for hydrogen. Consequently, comparisons were made for helium concentrations at the upper part of the building (sensors P4, P5, P9, and P10) using various turbulence models.

In Fig. 3, contour of the concentration of helium over time is presented. The analysis results indicate that, for all turbulence models, the test results of maintaining helium concentration below 3% until the end of the test duration (600 s) is reasonably well simulated. Furthermore, in terms of the prediction of upper building concentration, the accuracy of the standard k-ε model appears to be the highest among the considered turbulence models as shown in Fig. 4.

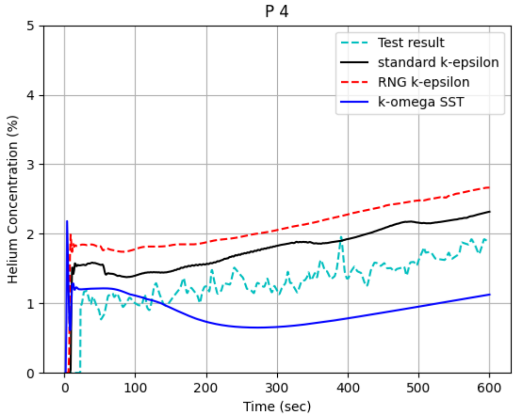


(a) 100 s (b) 200 s

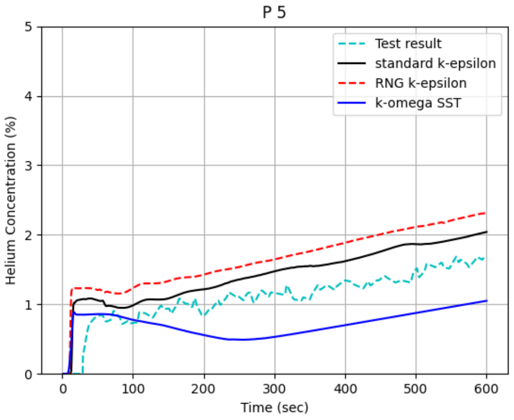
(c) 300 s (d) 400 s

(e) 500 s (f) 600 s

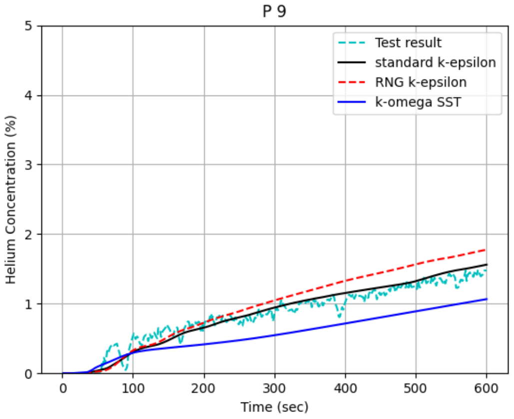
Fig. 3 Helium mole fraction (standard k-ε model)



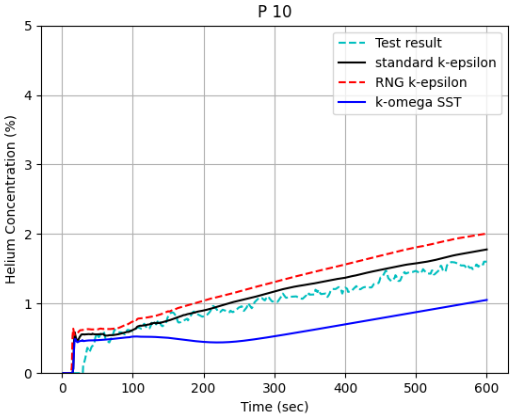
(a) P4



(b) P5



(c) P9



(d) P10

Fig. 4 Helium mole fraction at the upper part of the building (P4, 5, 9 and 10)

3. Conclusions

In this study, the validation of a new OpenFOAM solver, contain3d, designed specifically for analyzing severe accident phenomena within containment buildings, was performed using the LSGMF test. The analysis results demonstrate that the helium concentration in the upper part of the building is accurately simulated. And Further validation of the new solver will involve additional experiments that incorporate steam condensation and the utilization of PAR for hydrogen mitigation.

Acknowledgments

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REFERENCES

[1] Jones, S.C., and Chan, C.K., “Buoyancy Induced Gas Mixing in a Large Enclosure Data Report: Experiments Performed in the Large Scale Gas Mixing Facility, Series GMSR01”, AECL Technical Note, CAB-TN-085, 1997.
[2] Cheng Peng, Lili Tong, Xuewu Cao, Numerical analysis on hydrogen stratification and post-inerting of hydrogen risk, Annals of Nuclear Energy, Vol. 94, p. 451, 2016.
[3] https://www.openfoam.com/
[4] Jongtae Kim, Establishment of a base system for 3D analysis of hydrogen distribution in a containment building (Step 2), KINS/HR-1911, 2022.