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Computational Modelling of Spray System Deployment to a NPP Scale-Down Model for Severe Accident Mitigation

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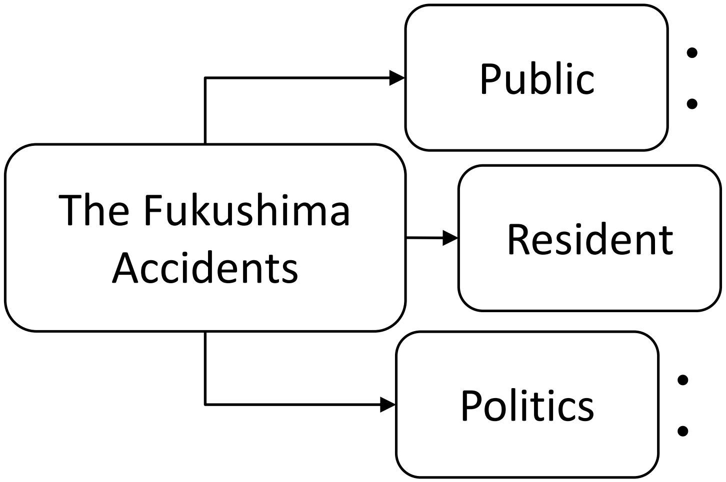
1. Introduction

Background

Purposes & approaches

Background

- **After the Fukushima accident,**



Public:
- Release of radioactive material from NPPs
- Concernment of food which has radionuclide

Resident:
- Low confidence in nuclear safety
- Fear of exposure to radioactivity from a severe accident
- Anxiety of losing residence from a severe accident

Politics:
- Tightened regulations regarding nuclear energy
- Increase in antinuclear activities

- **For the safety of Nuclear Power Plants (NPPs),**
  - ✓ Containment Filtered Vented System (CFVS) planned to be installed
  - ✓ Other post-Fukushima safety equipment has been installed
  - ✓ But, no mitigation measures are available once radioactive materials are released into the environment.

Purpose & approaches

- Purpose
  - To investigate engineering applications of spray technology for mitigating severe accident consequences
  - To develop a numerical method for spray technology
  - To analyze dependency of the spray efficiency on the freestream(wind) velocity and distances of spray nozzle
- Approaches
  - ANSYS CFX was used to develop a numerical model for the use of spray technology outside NPPs.
  - Mathematical equations, modeled for spray scrubbers, were used.
  - Numerical simulations were performed at 1/50th scale of a typical containment building. These results will be used to validate the results from experimental investigation.

2. Mathematical modeling

Capture of solid particles

Capture of solid particles in the air

- The number of solid particles removed by a single droplet

$$N_c = \eta_s \frac{\pi d_p^2}{4} |\boldsymbol{U_S} - \boldsymbol{U_P}| \frac{N_s}{dV}$$

N_c: The number of solid particles removed by a single droplet
d_p: The diameter of a droplet
N_s: The number of solid particles in an element volume
dV: An element volume
$|U_S - U_P|$: relative velocity between solid particles and a droplet

- Inertial impaction parameter

$$\psi = \frac{\rho_P d_S^2 |\boldsymbol{U_F} - \boldsymbol{U_P}|}{9\mu d_P}$$

d_s: The diameter of a solid particle
μ : The viscosity of fluid around a droplet
ρ_P: The density of fluid around a droplet
$|U_F - U_P|$: relative velocity between a droplet and fluid around a droplet

- Total removal efficiency of solid particles in the system

$$\eta_{total} = 1 - \frac{\dot{m}_{out,solid}}{\dot{m}_{in,solid}}$$

- Removal efficiency of solid particles by a single droplet

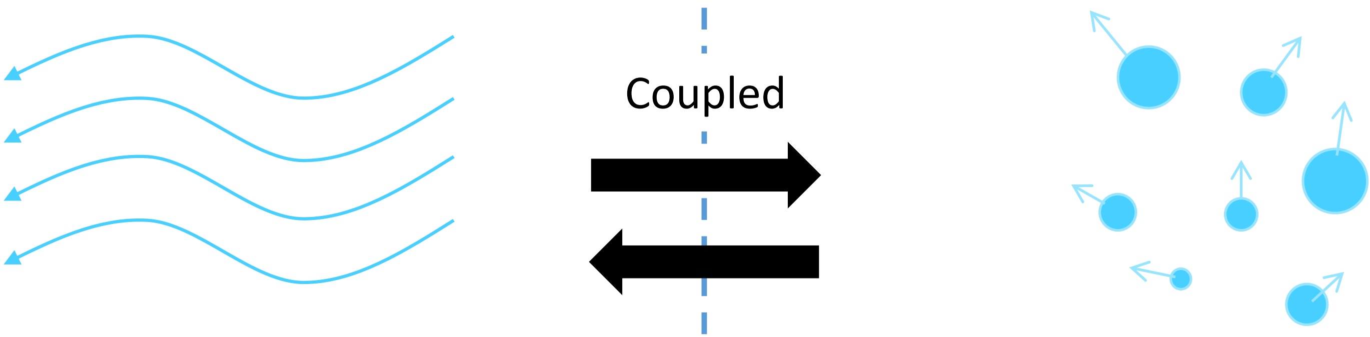
$$\eta_s = \left(\frac{\psi}{\psi + 0.7}\right)^2$$

3. Numerical simulation

Flow state
Geometry
Mesh
Spray injection & dust release
Boundary conditions

Flow state

Eulerian | **Lagrangian**



Eulerian

- **Objective**: Air & TiO_2 dust
- **Density**: Incompressible flow
- **Time**: Steady state
- **Turbulence**: The k-ε model
- **Etc**: 10 μm of TiO_2 dust diameter

Lagrangian

- **Objective**: Sprayed water droplets
- **Shape**: Sphere
- **External forces**: Gravity and drag
- **Drag**: Schiller Naumann model
- **Breakup**: TAB model
- **Etc**: Particle mass source term

Geometry & mesh

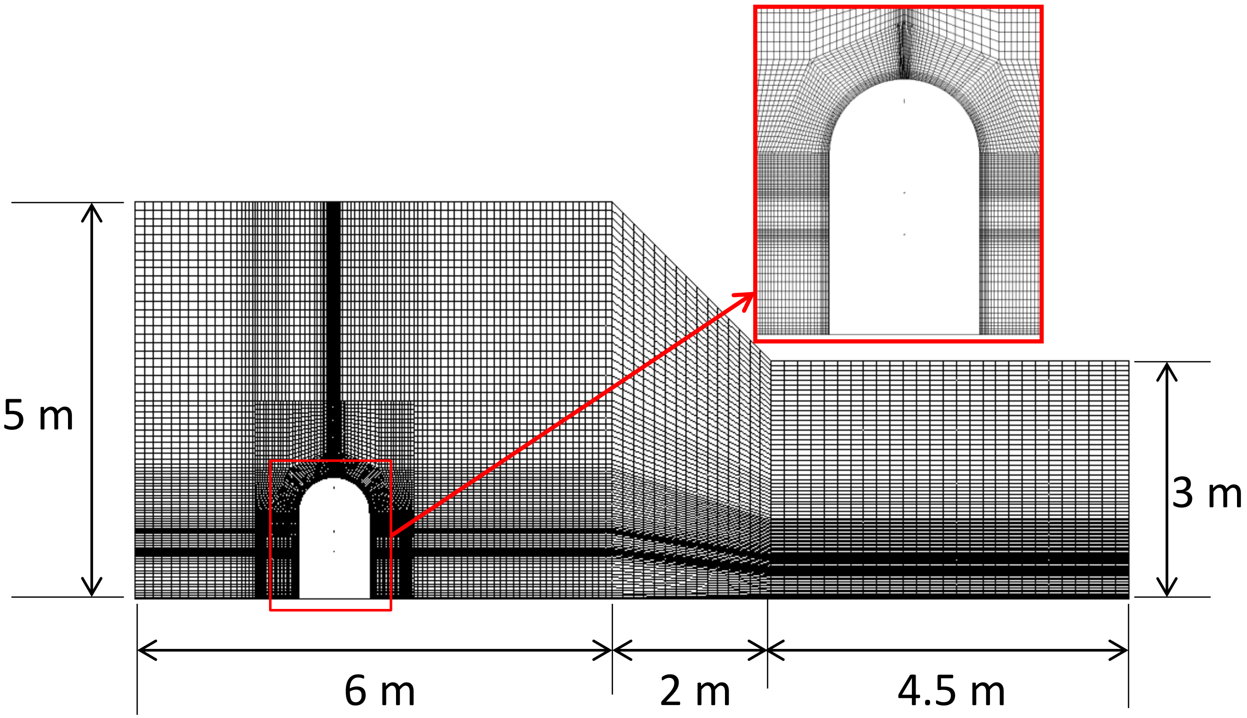


Fig 1. Geometry & mesh

- **Software for mesh**
  - ICEM-CFD
- **The number of elements**
  - About 1.7 million
- **The shape of elements**
  - Hexahedron
- **Size of this setup**
  - 1/50th of a NPP
- **Containment geometry**
  - Height: 1.53 m
  - Radius: 0.45 m

Boundary conditions

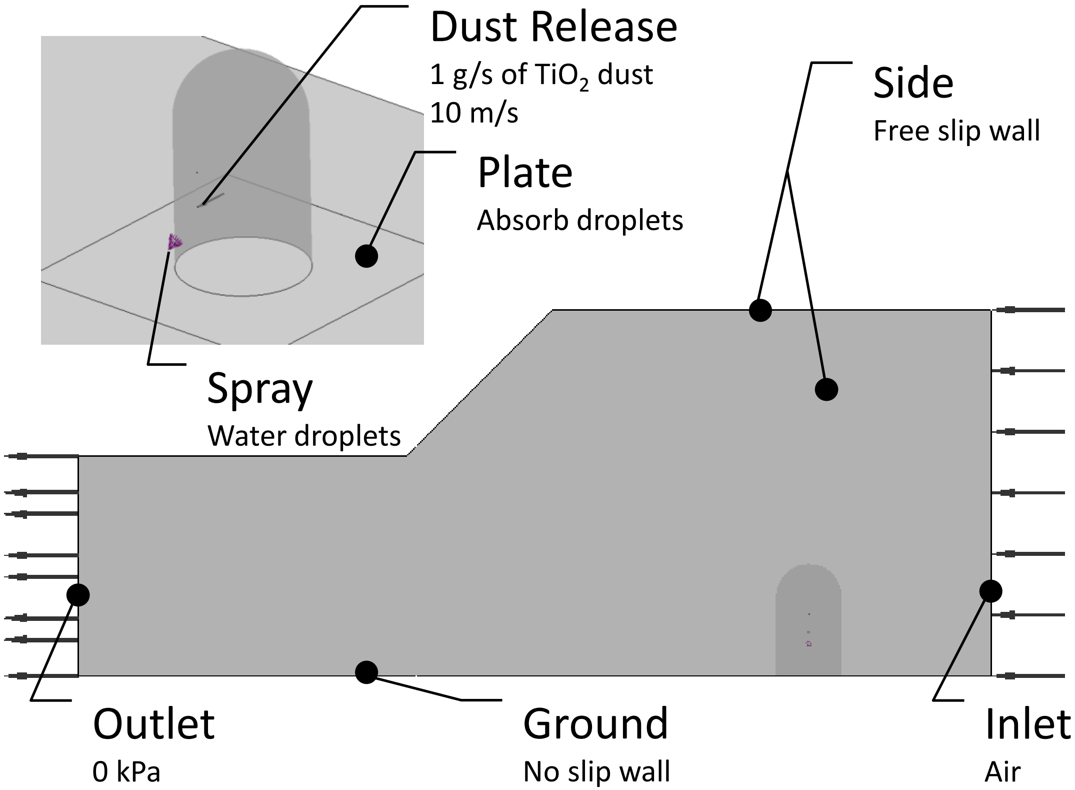


Fig 2. Boundary conditions

Table 1. Cases following the nozzle distance

	Inlet velocity (m/s)	Nozzle distance (cm)
Case 1	0.5 1.0 1.5 2.0	60
Case 2	0.5 1.0 1.5 2.0	30

Spray injection & dust release

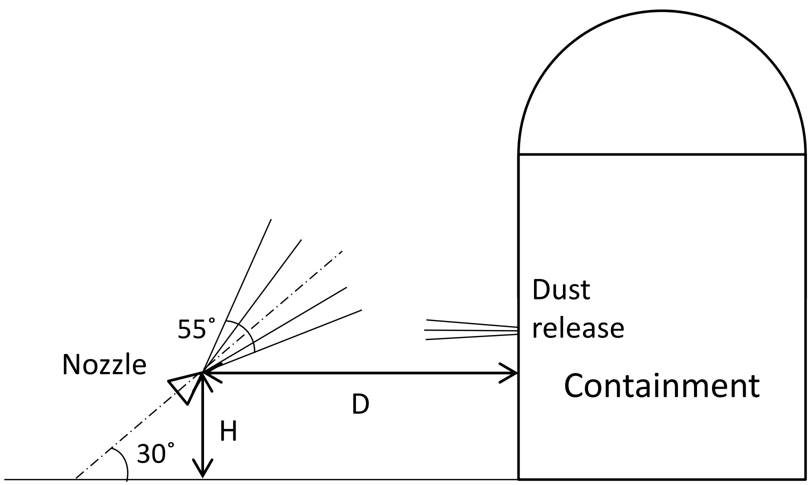


Fig 3. Spray nozzle & dust release position

- **Nozzle position**
  - D: 30 & 60 cm
  - H: 40 cm (Maximum of Firetruck)
- **Nozzle properties**
  - Flow rate: 6 liter/min
  - Spray angle: 55˚
  - Spray shape: Cone
- **Dust release**
  - Diameter: 6 mm
  - Height: 60 cm
  - Mass flow rate(TiO_2): 1 g/s
  - Velocity: 10 m/s

4. Results & discussions

Removal efficiencies of TiO_2 dust

Collection efficiency of droplets

Mesh dependency test

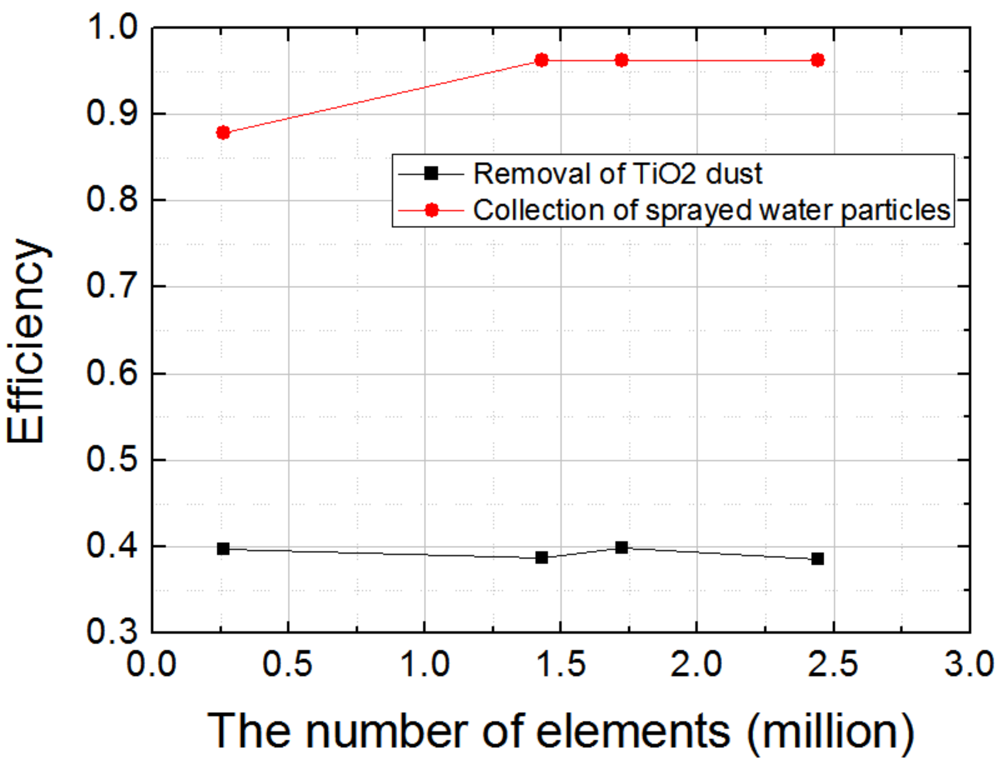


Fig 4. The results of mesh dependency test

- Removal efficiency of TiO_2 dust was almost independent on the number of mesh elements.
- Collection efficiency of sprayed water droplets was converged after about 1.4 million elements.
- If the number of elements exceeds 1.4 million, the error from mesh becomes small.
- In this study, the number of elements was about 1.7 million. Therefore, the results are reasonable.

The results of Case 1 (1/2)

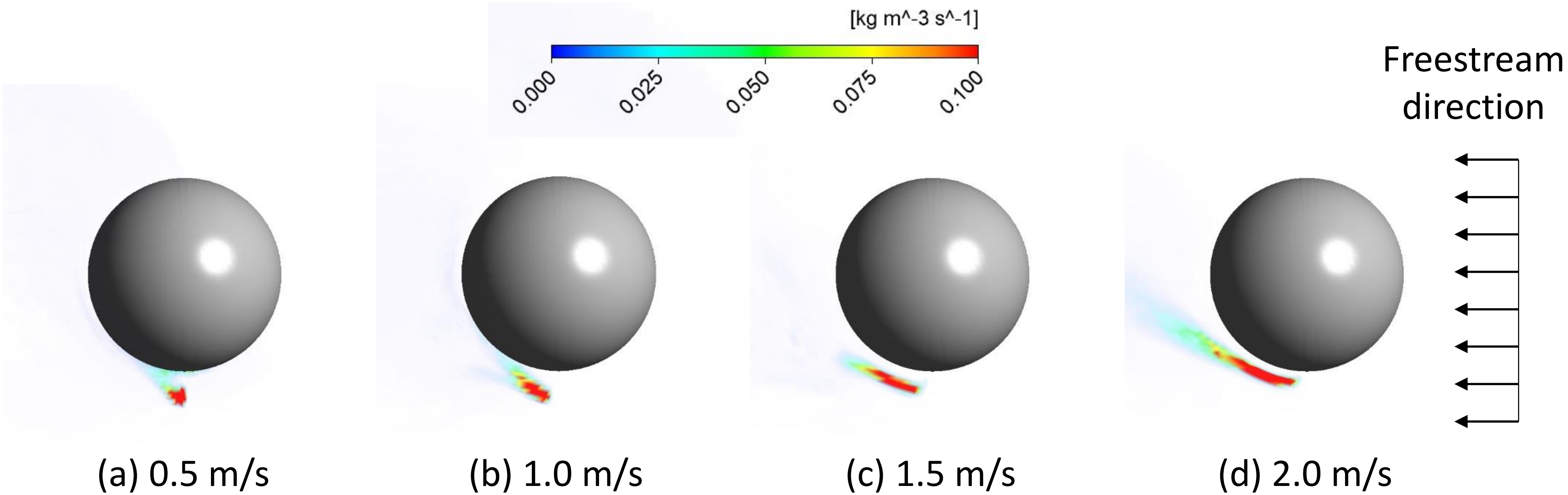


Fig 5. Removal distribution of TiO_2 dust in Case 1

- An increase in the freestream velocity, lengthens removal region toward back side
- Water droplets, which successfully capture TiO_2 on back side, may not be collected on the plate boundary and fly away following the air flow

The results of Case 1 (2/2)

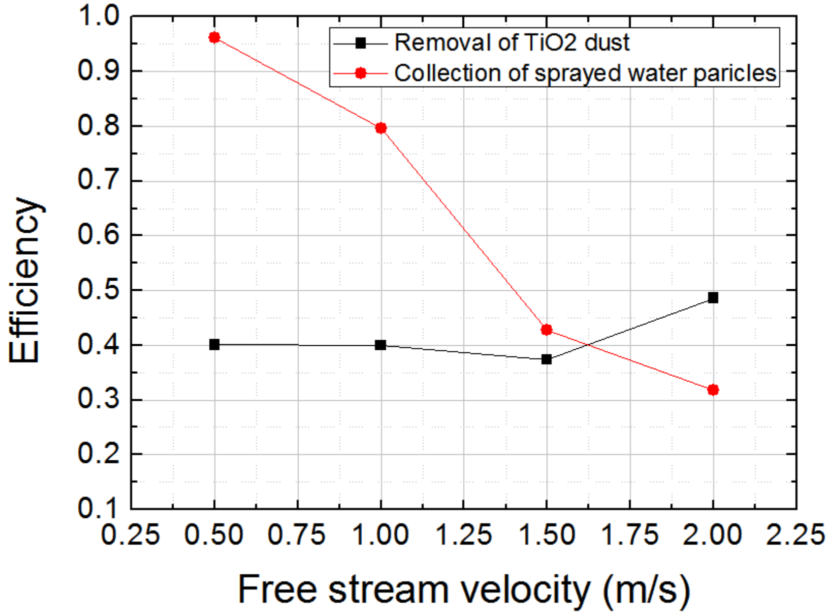


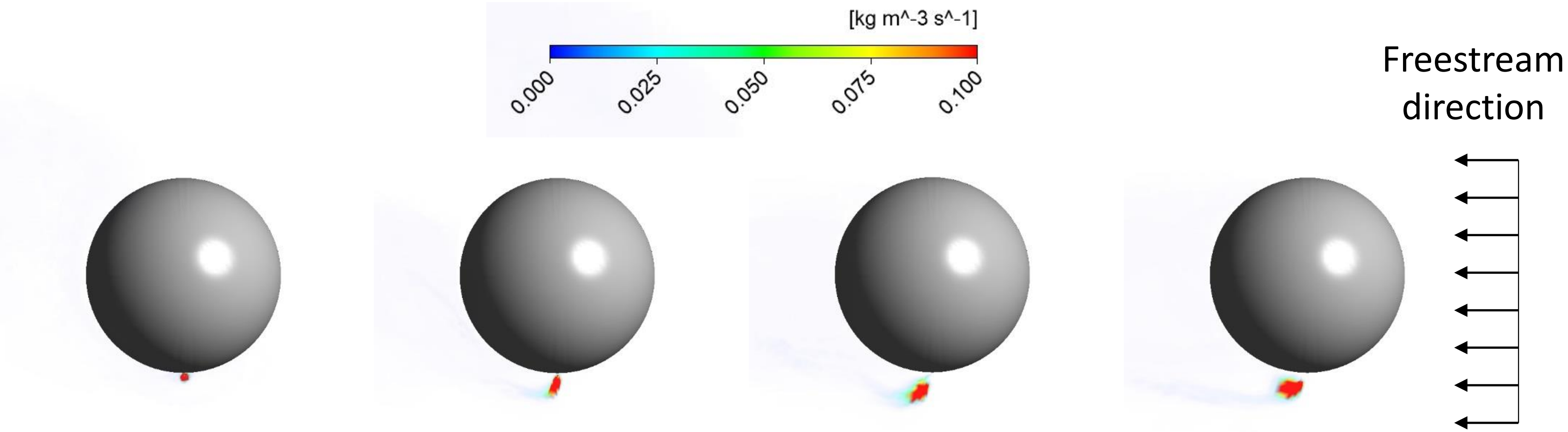
Fig 6. The results of Case 1

- Removal of TiO_2 dust
  - ✓ the removal efficiency is ~40% at 0.5 m/s.
  - ✓ the removal efficiency decreases until 1.5 m/s following an increase in velocity of freestream.
  - ✓ the removal efficiency rises about 10 % compared with the result of 0.5 m/s with a 2 m/s.

- Collection of water droplet
  - ✓ Collection efficiency decreases sharply following an increase in the freestream velocity.
  - ✓ Collection efficiency is ~96% at a 0.5 m/s.
  - ✓ Collection efficiency is ~33% at a 2.0 m/s.
  - ✓ This value is too low to prevent dispersion of radioactive materials.

➢ If the freestream velocity is larger than 1.0 m/s in 1/50th scale, the collection efficiency of the water particles is very low.

The results of Case 2 (1/2)



(a) 0.5 m/s (b) 1.0 m/s (c) 1.5 m/s (d) 2.0 m/s

Fig 7. Removal distribution of TiO_2 dust in Case 2

- Following an increase in the freestream velocity, removal region increased
- In Case 2, an increase in freestream velocity was helpful to remove TiO_2 dust in the air

The results of Case 2 (2/2)

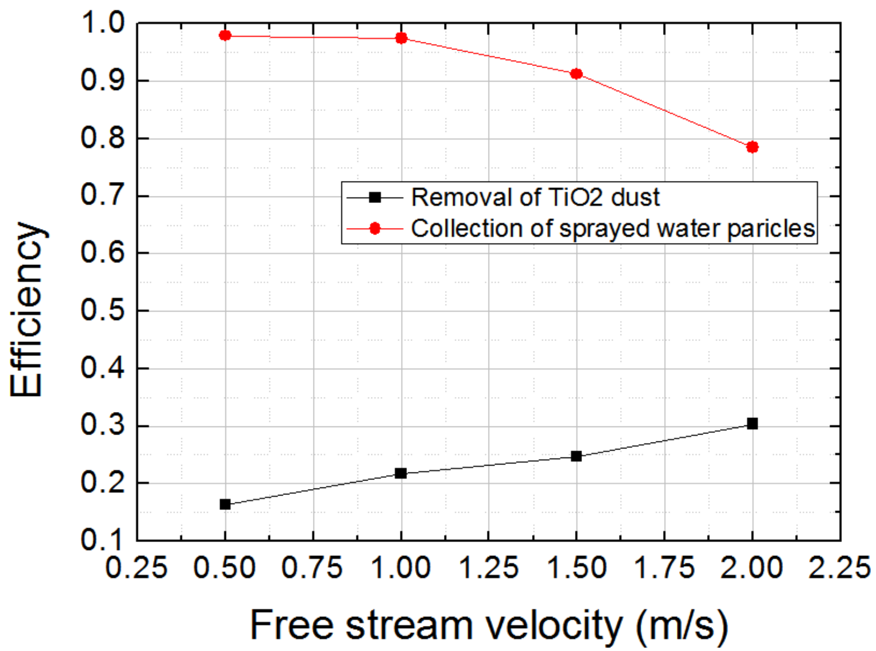


Fig 8. The results of Case 2

- Removal of TiO_2 dust
  - ✓ Removal efficiency was ~16% at 0.5 m/s.
  - ✓ Removal efficiency was ~30% at 2 m/s.
  - ✓ Removal efficiency increased almost linearly following an increase in velocity.
  - ✓ Overall removal efficiencies of TiO_2 dust were lower than the results for Case 1.
- Collection of water droplet
  - ✓ Collection efficiency decreased following an increase in velocity.
  - ✓ Collection efficiency was ~98% at a 0.5 m/s.
  - ✓ Collection efficiency was ~78 % at 2 m/s.
  - ✓ Overall collection efficiency of water particles was higher than Case 1.
  - ✓ The effect of freestream was smaller in Case 2 due to shorter distance of the spray nozzle to containment.

➢ If the freestream velocity is fast, it is better to use spray nozzle closely from the containment building

5. Summary

Summary

Further work

Summary

1. Mesh dependency test
   - The results of mesh dependency test shown that if 1.4 million elements, with having shape of hexahedron, exceed, the error from mesh is small enough to be negligible.

2. At 60 cm from the containment surface,
   - If the freestream velocity is lower than 1.0 m/s in 1/50th scale, the spray nozzle can be helpful to prevent dispersion of radioactive aerosols into the atmosphere.
   - However, the freestream velocity over 1.0 m/s, spray is not effective in preventing the dispersion.

3. At 30 cm from the containment surface,
   - If the freestream velocity is over 1.5 m/s, results show improvement over the case at 60 cm.

Further work

- Improvement of numerical modeling considering other capture mechanisms such as diffusion and interception
- Consideration of the wall film effect on containment surface
- Experimental study with a NPP model scaled down 1/50th
- Validation of the numerical modeling with experimental data
- Investigation of spray technology for real scale applications based on the numerical model and the dimensionless analysis.
- Application of spray system around NPPs based on the use of fire truck or fixed spray structures.

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Thank you for your attention.