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Validation of a Bulk Condensation Model for a Steam Jet Simulation

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Introduction

- Key facility to mitigate consequences from severe accident is spray injection system. Spray can decrease peak pressure inside the containment with mechanism of bulk and wall condensation but condensation also may cause increase hydrogen concentration due to decreased steam volume.
- Condensation phenomena should be understood thoroughly to devise an optimal strategy for spray injection.
- Bulk condensation includes nucleation from vapor and condensational growth from the nucleated seed or a droplet. In this study, a bulk condensation model is reviewed and validated by utilizing simple steam injection experimental data. For the analysis of water aerosols from condensed steam, 'aerosolEulerFoam' solver developed on the OpenFOAM framework was utilized.

Governing Equations & Models

- 'aerosolEulerFoam' is an Eulerian aerosol solver which can simulate nucleation, aerosol coalescence, condensation/evaporation and deposition.
- Generally, continuity, momentum and energy equations need to be solved for fluid flow. For aerosol transport simulation, equations for aerosol number density, mass fraction of vapor and particle are additionally solved

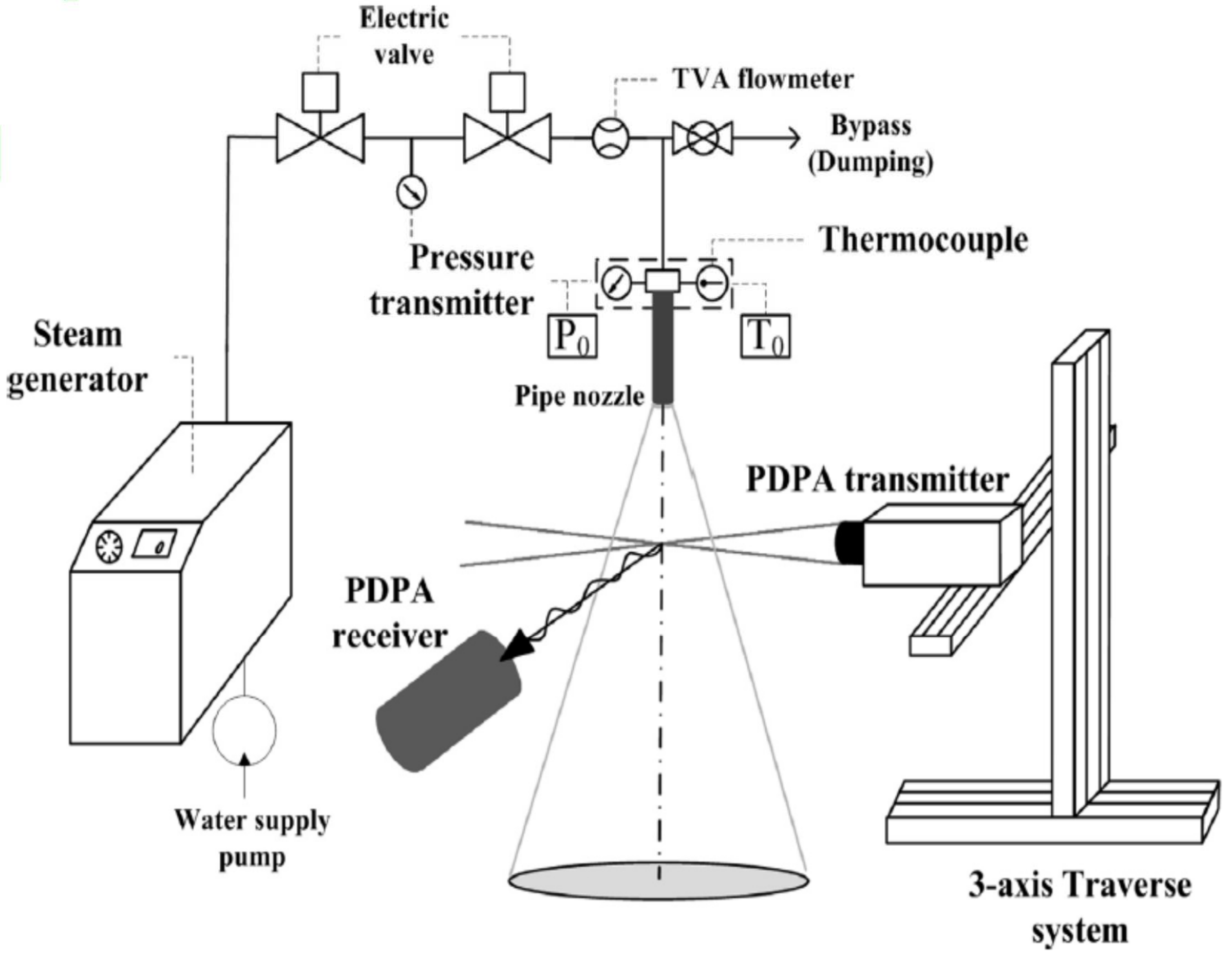
$$\partial_t\rho + \nabla\cdot(\rho\boldsymbol{u}) + \nabla\cdot[\boldsymbol{f}(1-\gamma)] = 0$$
$$\partial_t(\rho\boldsymbol{u}) + \nabla\cdot(\rho\boldsymbol{uu}) = -\nabla p - \nabla\cdot\boldsymbol{\tau}$$
$$c_p[\partial_t(\rho T) + \nabla\cdot(\rho\boldsymbol{u}T)] = \nabla\cdot(k\nabla T) - (\boldsymbol{\tau}:\nabla\boldsymbol{u}) + D_t p$$
$$\partial_t(\rho M_i) + \nabla\cdot(\rho\boldsymbol{u}M_i) + \nabla\cdot\left(\rho\boldsymbol{u}_i^p M_i\right) = \nabla\cdot\left(\boldsymbol{D}_i^p\nabla\rho M_i\right) + J_{M_i}$$
$$\partial_t\left(\rho Y_j\right) + \nabla\cdot\left(\rho\boldsymbol{u}Y_j\right) - \nabla\cdot\left(Y^{-1}\boldsymbol{h}Y_j\right) = R_j$$
$$\partial_t\left(\rho Z_j\right) + \nabla\cdot\left(\rho\boldsymbol{u}Z_j\right) - \nabla\cdot\left(Z^{-1}\boldsymbol{f}Z_j\right) = S_j$$

- A generalization of classical multi-component theory for homogeneous nucleation was used. Nucleation mass flow S_j^{nuc} is obtained using nucleation rate, J_N, number of molecules of component j in a critical cluster, N_j, molecular mass of species j, m_j. A mass of the freshly nucleated droplet is equal to twice that of the critical cluster, expressing that these virgin droplets are likely to grow after nucleation, while the critical clusters have equal probability to grow or shrink after nucleation
- Condensation and evaporation are reverse processes of one mechanism. Condensed mass is added to the particle mass and at the same time same mass is subtracted from the vapor mass, and vice versa for evaporated mass.

$$S_j^{nuc} = 2J_N N_j m_j,\ S_j^{evap/cond} = 2\pi D_j \bar{d}\rho Y_j^s f\left(\bar{d},\lambda\right)\left(E_j - \frac{S_j}{W_j}\right)N,$$

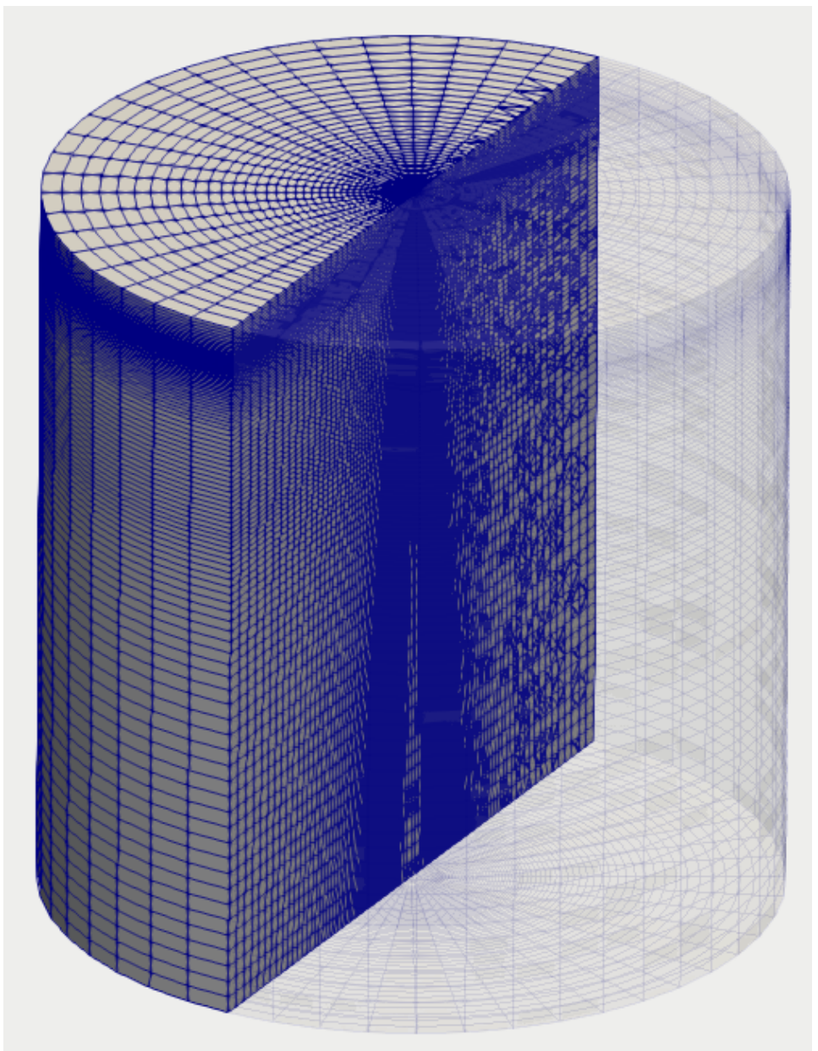
- where, $\bar{d}, Y_j^s, f, E_j, S_j, W_j, N$ are count mean diameter, saturation mass fraction of component j, Fuchs factor, equilibrium saturation of component j, saturation of species j, mole fraction in the droplet's phase, number concentration of particle(=ρM), respectively.

Computation & Results

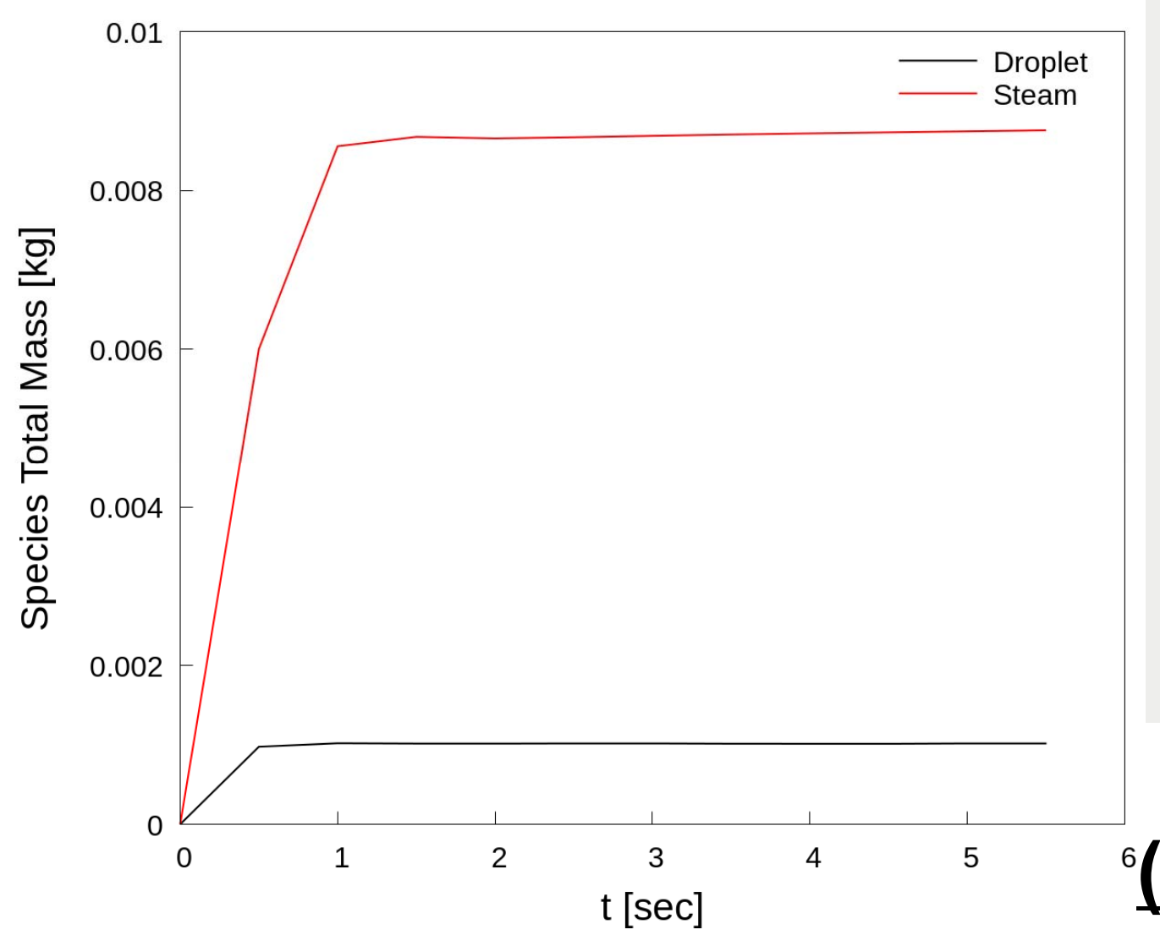


Layout of a steam jet

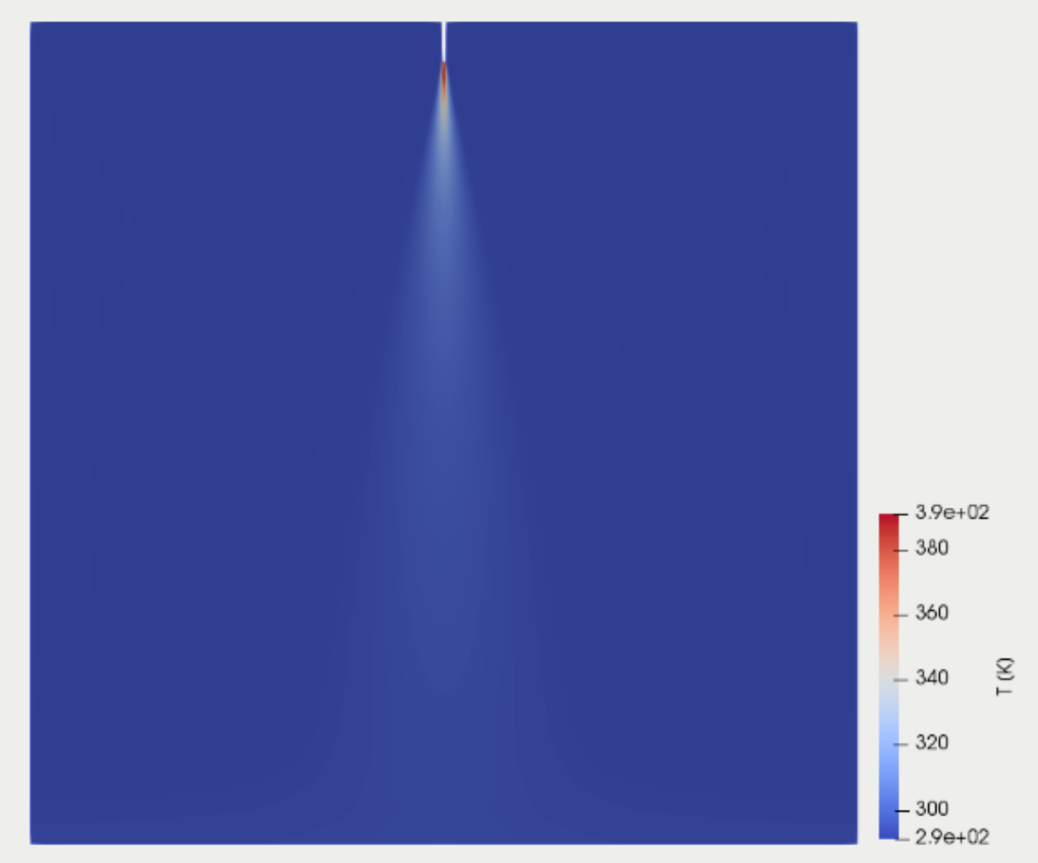
- Geometry: 10mm pipe nozzle
- Steam jet condition: 105℃, 50kg/h
- Reynolds no.: 140,700
- Ambient air: 19 ℃
- Mesh: 298,080 hexahedra
- Turbulence model: k-w SST
- 15 sections for aerosol representative mass range: 5E-24 to 5E-10kg



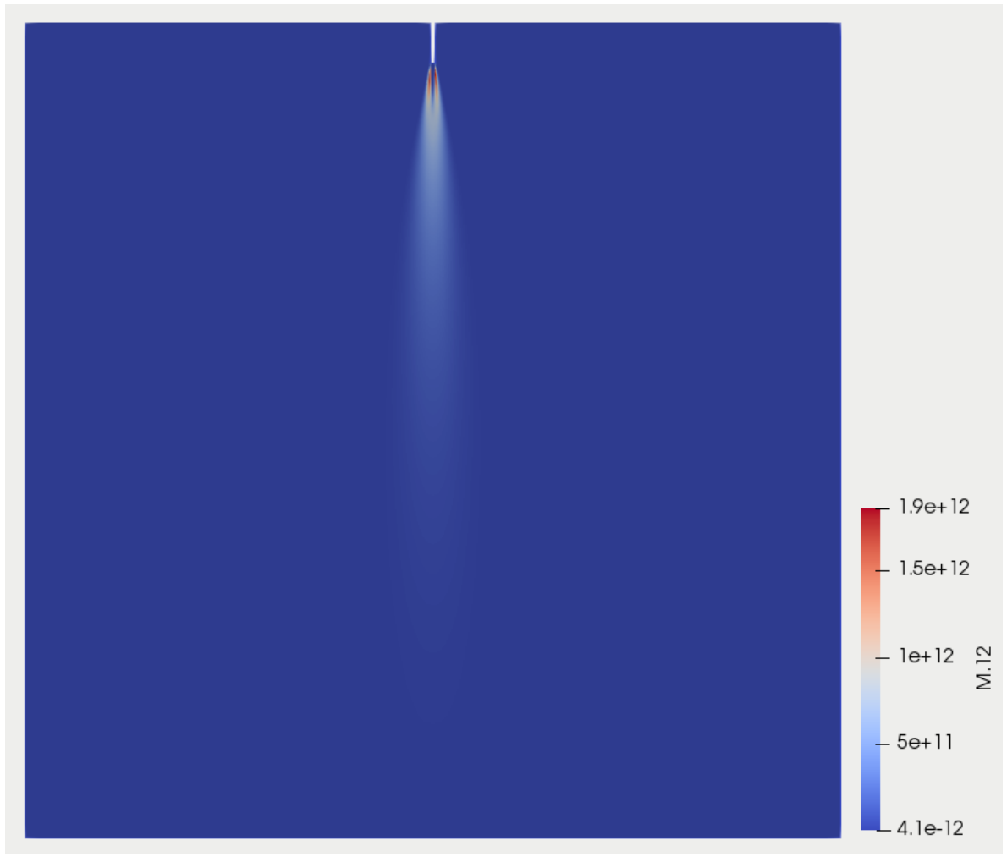
Grid system



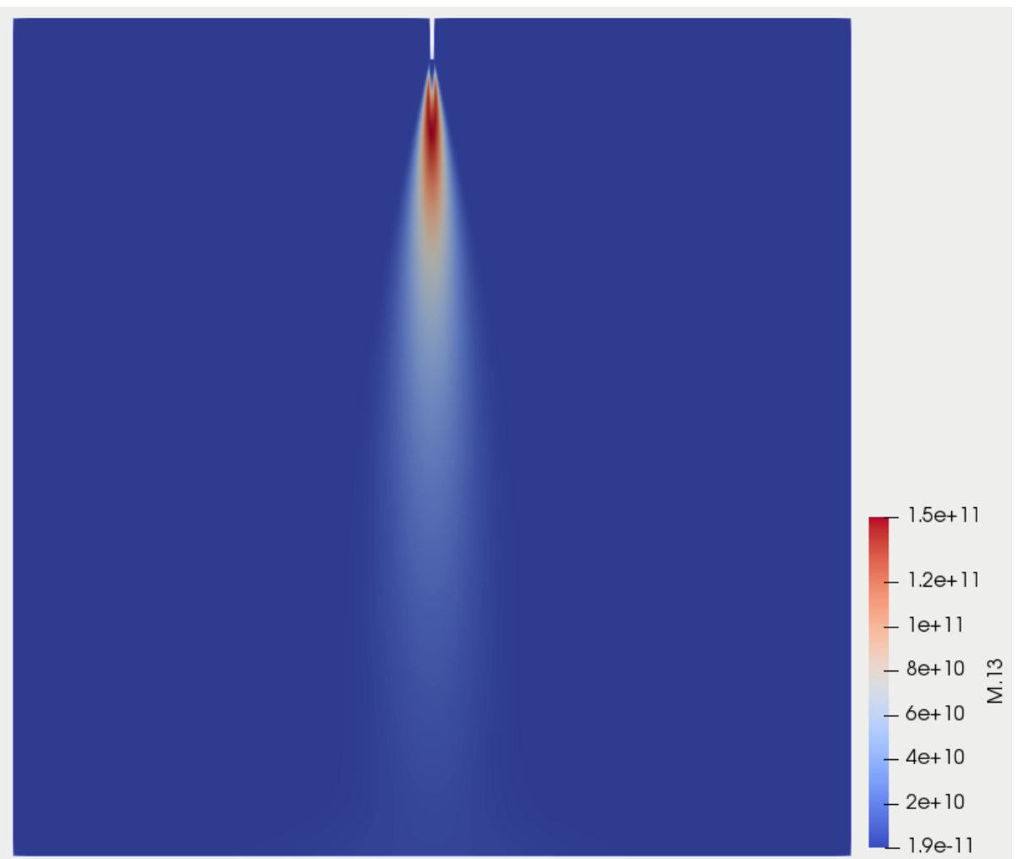
Species total mass



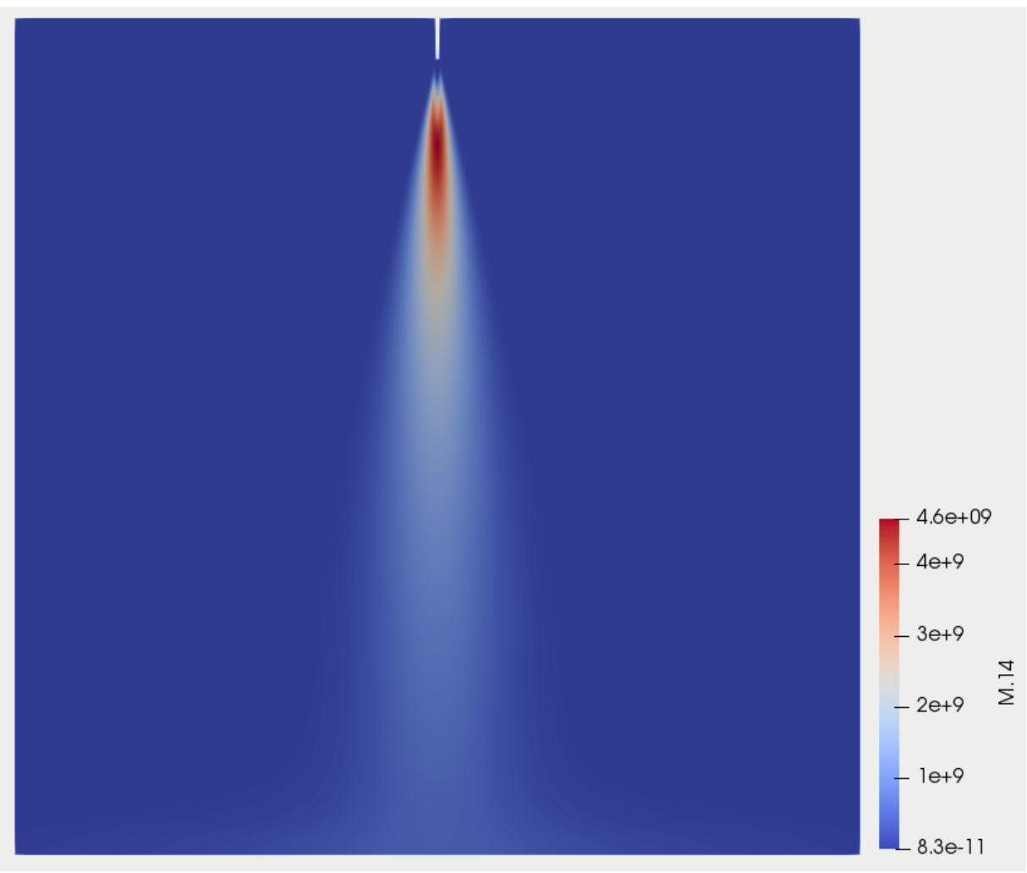
Temperature



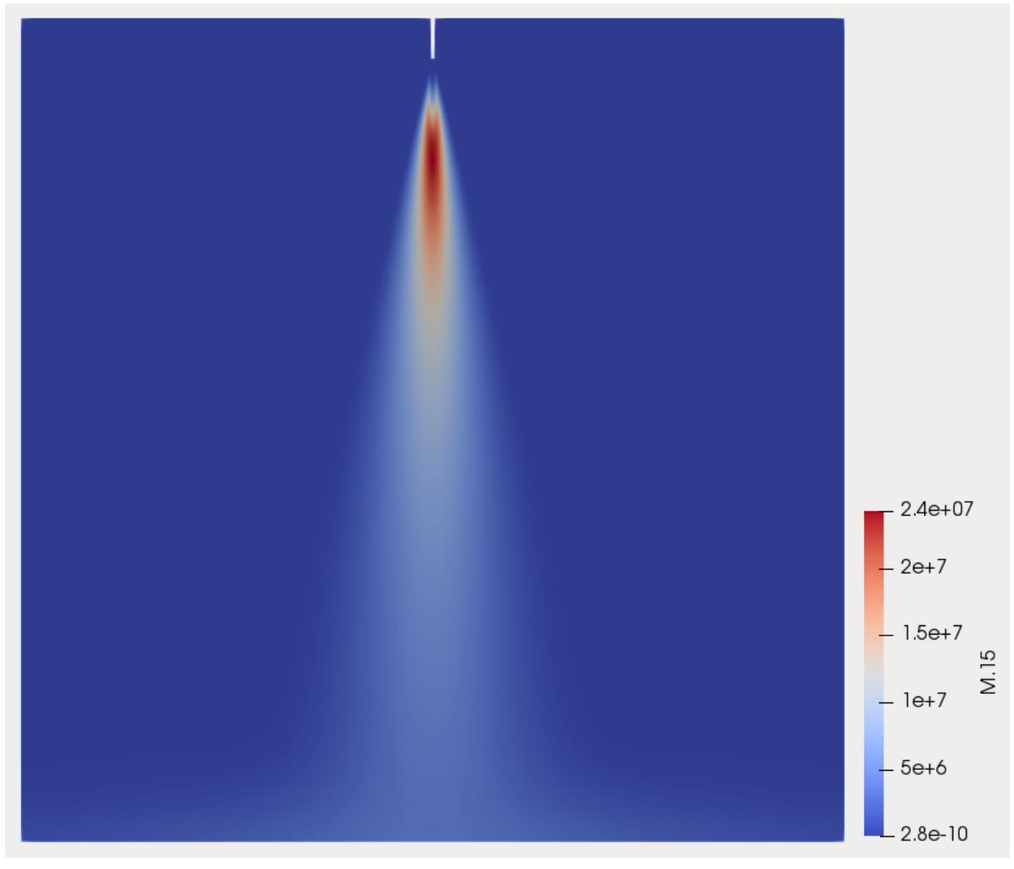
Particle concentration (#/kg, section of 5E-13kg)



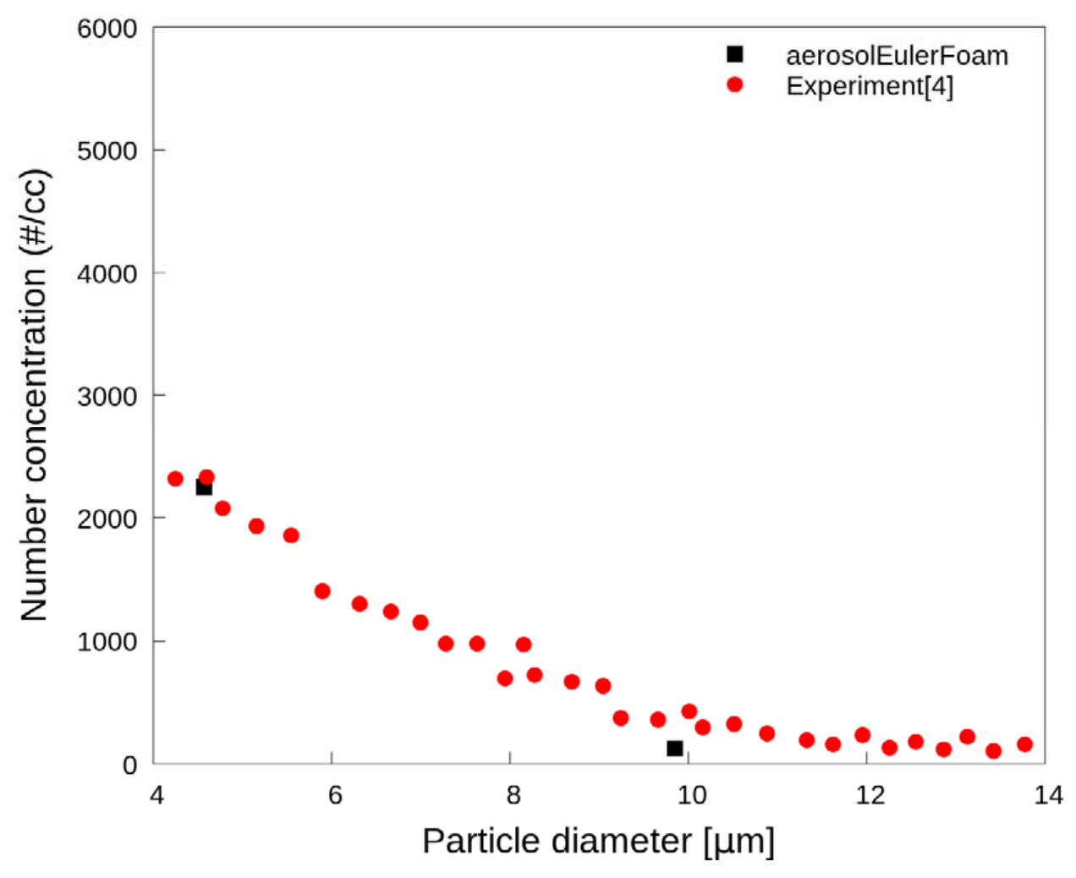
Particle concentration (#/kg, section of 5E-12kg)



Particle concentration (#/kg, section of 5E-11kg)



Particle concentration (#/kg, section of 5E-10kg)



Number concentration ($z/d=10$, $r/r_{T0.5}=1.043$)

Conclusion

- Nucleation and condensational models implemented in the 'aerosolEulerFoam' solver has been validated by comparing with a steam jet experimental data. Droplet formation was well simulated and number concentration was compared with experiment.
- Number concentration data using 'aerosolEulerFoam' solver are in good agreement with experimental data. This means that nucleation and condensational growth models are adequate for this steam jet case. Other flow characteristics such as temperature decay rate, normalized temperature radial temperature profiles and temperature half width, etc. will be investigated by additional work.
- It was found out that the inlet boundary condition of the steam jet test may strongly affect the numerical simulation results. Additional study will be carried out to evaluate solution dependency on the inlet boundary conditions, especially, injection of larger aerosols formed on the injection pipe wall which is caused by low temperature of the pipe wall of the experimental facility.
- This research work will contribute to integration of the models for bulk condensation and aerosol behaviors and containmentFoam which is a solver for hydrogen safety evaluation in a NPP containment.