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Preliminary Simulation of Aerosol Dynamics in the Cover Gas Region of the PGSFR

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Introduction

- The cover gas region of PGSFR is filled with argon gas. From the sodium pools, sodium vapor is generated by molecular diffusion and mixed into the cover gas. Sodium aerosol is produced by nucleation and grown into various sizes of aerosols by condensation and agglomeration. The sodium aerosols float inside the cover gas region by natural convection and deposit on the structures or settle down on the sodium free surfaces.
- The sodium aerosol deposition on the surfaces of components might affect the heat transfer characteristics to the structures and hinder the operation of the instruments installed in the cover gas region. Thus, it is necessary to figure out the aerosol dynamics inside the cover gas region.
- In this work, aerosol behavior inside the cover gas region of the PGSFR is simulated preliminarily using an OpenFOAM solver, 'aerosolEulerFoam'. The solver is validated for a natural convection case and applied for a simulation of aerosol motion in the cover gas region.

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

$$\partial_t \rho + \nabla \cdot (\rho \boldsymbol{u}) + \nabla \cdot [\boldsymbol{f}(1-\gamma)] = 0$$

$$\partial_t (\rho \boldsymbol{u}) + \nabla \cdot (\rho \boldsymbol{u}\boldsymbol{u}) = -\nabla p - \nabla \cdot \boldsymbol{\tau}$$

$$c_p[\partial_t(\rho T) + \nabla \cdot (\rho \boldsymbol{u} T)] = \nabla \cdot (k \nabla T) - (\boldsymbol{\tau}:\nabla \boldsymbol{u}) + D_t p$$

$$\partial_t(\rho M_i) + \nabla \cdot (\rho \boldsymbol{u} M_i) + \nabla \cdot \left(\rho \boldsymbol{u}_i^p M_i\right) = \nabla \cdot \left(\boldsymbol{D}_i^p \nabla \rho M_i\right) + J_{M_i}$$

$$\partial_t(\rho Y_j) + \nabla \cdot (\rho \boldsymbol{u} Y_j) - \nabla \cdot \left(Y^{-1} \boldsymbol{h} Y_j\right) = R_j$$

$$\partial_t(\rho Z_j) + \nabla \cdot (\rho \boldsymbol{u} Z_j) - \nabla \cdot \left(Z^{-1} \boldsymbol{f} Z_j\right) = S_j$$

- Small-sized particle is deposited on a surface by diffusion. Diffusion flux $\boldsymbol{f}^{\text{diff}}$ mainly depends on D_i^p. Stokes-Einstein equation, a model for the Brownian diffusivity for a sphere body is given by

$$D^l(s) = \frac{k_B T C_c}{3\pi\mu d}$$

- where, k_B, C_c, d are the Boltzmann constant, Cunningham correction factor, and aerosol diameter, respectively. Cunningham correction factor accounts for surface slip of small particles.
- Large-sized particle is deposited on a surface by inertial force. Schiller-Naumann model to calculate drift velocity of a particle is written as

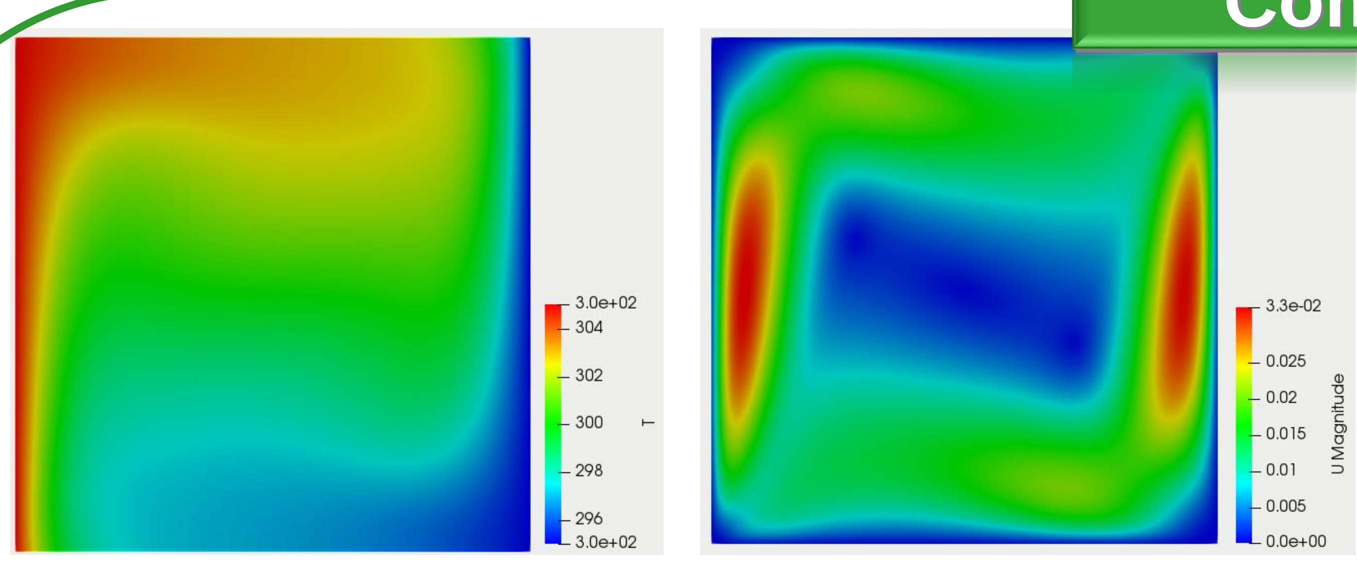
$$\partial_t \boldsymbol{v}(s) + [\boldsymbol{v}(s) \cdot \nabla]\boldsymbol{v}(s) = -\frac{1+0.15 Re_d^{0.687}}{\tau}[\boldsymbol{v}(s) - \boldsymbol{u}] + (1-\gamma)\mathbf{g},$$

- where, $\boldsymbol{v}, \tau, \mathrm{g}$ are particle velocity, particle relaxation time, gravitational acceleration, respectively. τ is defined as $\tau = \rho^p d^2/(18\mu)$ and Re_d is a function of $\boldsymbol{v}$.
- In a flow region with a temperature gradient, thermophoretic force is acting on particles. The thermophoretic force is expressed as

$$F_T = -\frac{6\pi\mu\nu d_p C_s}{1+3C_m Kn} \frac{\frac{k_g}{k_p} + C_t Kn}{1 + 2\frac{k_g}{k_p} + 2C_t Kn} \frac{\nabla T}{T},$$

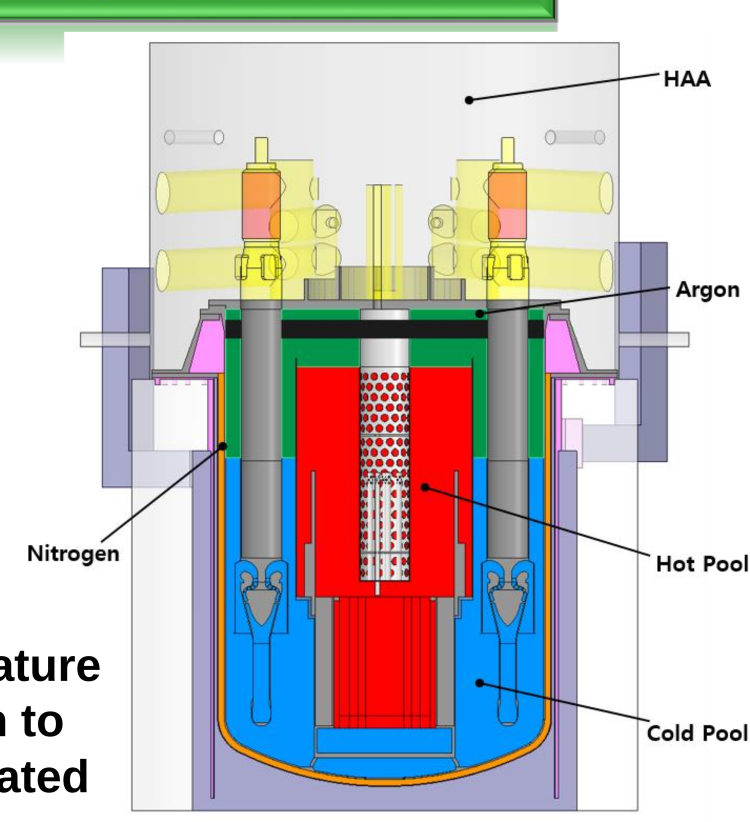
- where, $C_s, C_m, C_t, Kn, k_g, k_p$ denote thermal slip coefficient, velocity slip coefficient, thermal jump coefficient, Knudsen number, thermal conductivity of gas, and thermal conductivity of particle, respectively.

Computation & Results

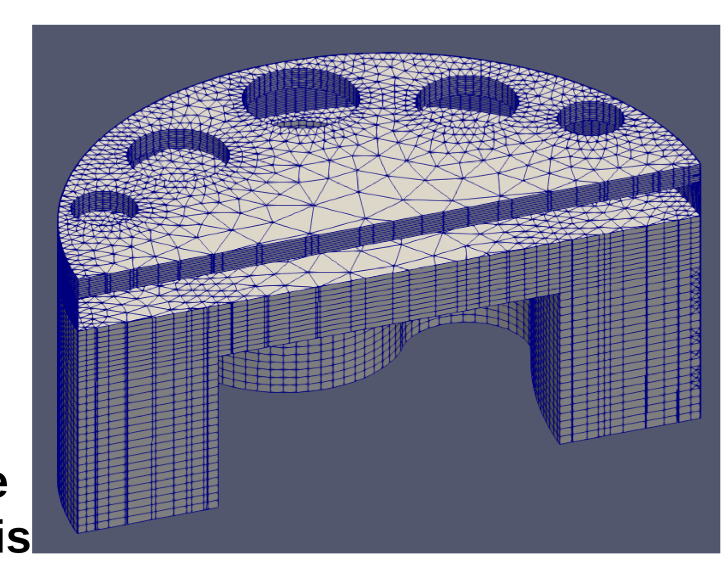


Temperature (left) and velocity (right) contours of a natural convection case

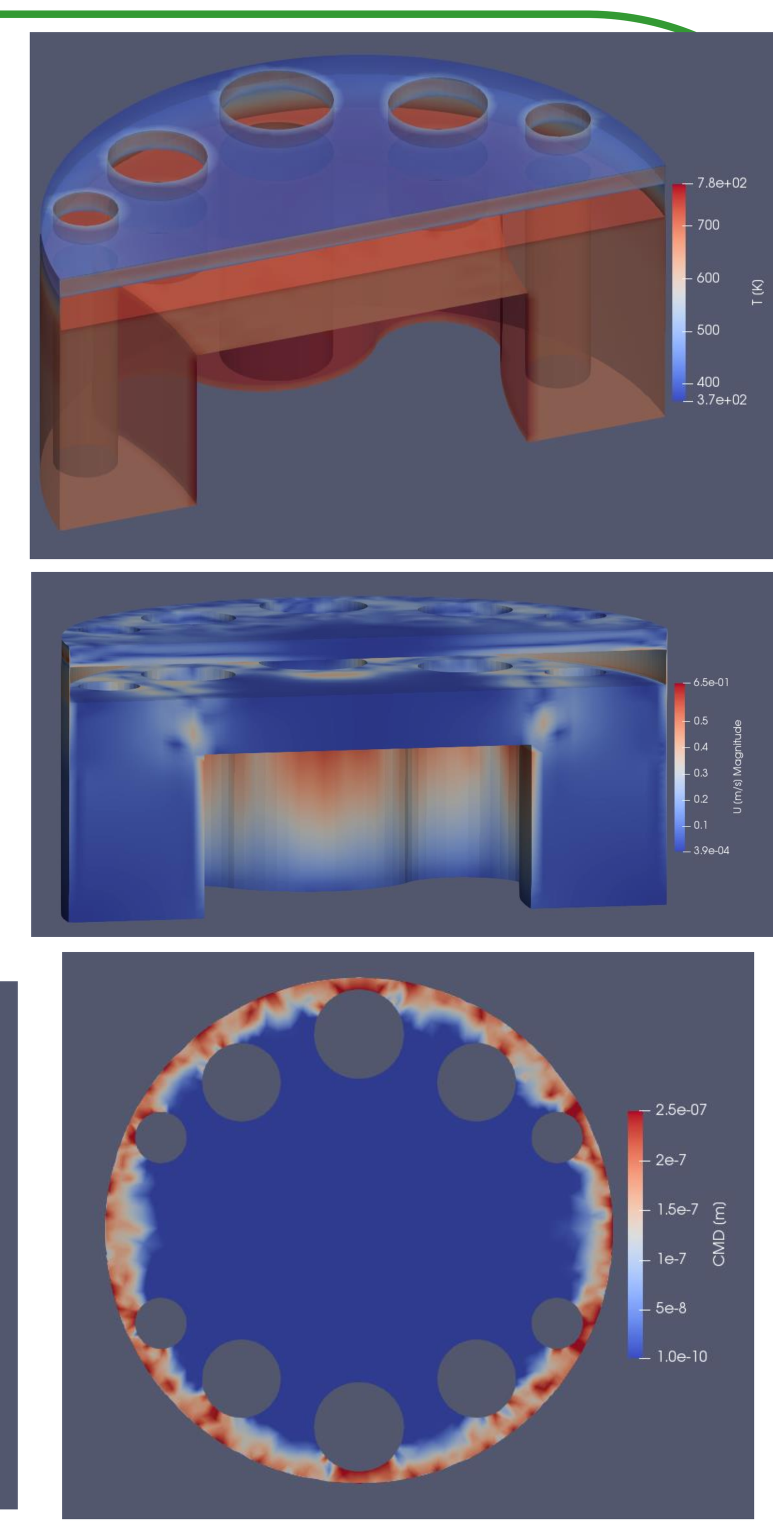
- The OpenFOAM solver was validated for a natural convection case. Temperature difference between two walls was set to 10K and other parameters are given to set Ra number to be 10^5. Average Nusselt number at the left wall was calculated as 4.5261 which is very similar to the value of 4.5231 of a reference.
- Temperatures at the reactor vessel, the reactor head, the pumps, the heat exchangers, the upper shield structure, and the redan were obtained from a previous simulation data for a cover gas region simulation
- Temperatures of the structures range between 540℃ of the hot pool and about 150℃ of the reactor head. The hot sodium vapor is transported to the upper region passing through the narrow gap between the upper shield structure and the reactor vessel.
- At the lower temperature region around the narrow gap, aerosol size is bigger than the other space which show possibility of aerosol growth near the reactor vessel in the upper cover gas region. If the aerosols grow and agglomerate more and more in the region, there is a possibility of small blockage in the gap which is about 13 mm. By the way, an inert gas purification system is mounted on the reactor head and the inflow and outflow of the system can affect the aerosol behavior.



PGSFR cover gas region



Grid system for an aerosol simulation



Temperature (top), velocity (middle), CMD (bottom)

Conclusion

- Sodium aerosol in the cover gas region was simulated and the aerosol growth was shown near the narrow gap.
- The aerosol growth and deposition can affect flow characteristics of the upper cover gas region and the heat transfer to the structures and the operation of the instruments in the cover gas region.
- If the aerosols grow and agglomerate more and more in the gap region, there is a possibility of small blockage in the gap which is about 13 mm.
- Therefore, more specific simulation is required to investigate the aerosol transport features reflecting on an inert gas purification system installed in the cover gas region.