Evaluation of Sodium Leak Detection Time in SFR

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1. Introduction

In SFR (Sodium-cooled Fast Reaction), a leakage of sodium coolant from the reactor vessel is one of postulated events. Generally, to detect the sodium leakage, two types of detectors can be applied. Leaked liquid sodium can be detected by a conductive type probe attached on the guard/containment vessel and sodium aerosol can be detected by an aerosol ionization detector equipped in inert gas circulation system. To be detected by the aerosol detector, concentration of sodium aerosol needs to be higher than a specified concentration level given by the aerosol detector.

In order to detect the sodium aerosol generated by sodium leakage from the reactor vessel, nitrogen circulation system for the annulus space between the reactor vessel and the containment (or guard) vessel is generally provided. Detection time is highly dependent on the leak rate, the leak location, and the nitrogen injection rate.

In this study, for evaluation of a nitrogen circulation system aerosol detection time at a given leakage rate is calculated using an aerosol solver, 'aerosolEulerFoam' which was developed on the OpenFOAM framework[1]. The 'aerosolEulerFoam' solves GDE (general dynamics equation) for aerosol motion and Navier-Stokes equations for fluid flow.

2. Methods and Results

'aerosolEulerFoam' is an Eulerian aerosol solver[2] which can simulate nucleation, aerosol coalescence, condensation/evaporation, diffusion, Brownian motion, and drift motion. Aerosol deposition is caused by sedimentation, Brownian diffusion, drift near a solid surface. In this section, governing equations and the models of Brownian diffusion and drift are described.

2.1 Governing equations

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[2].

Continuity equation

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

where, $\boldsymbol{u}, \rho, \boldsymbol{f}, \gamma$ are velocity vector, mixture density, total flux of liquid concentration drifting away from the mixture motion, and ratio between local vapor density and local particle density, respectively.

Momentum equations

$$\partial_t(\rho \boldsymbol{u}) + \nabla \cdot (\rho \boldsymbol{u}\boldsymbol{u}) = -\nabla p - \nabla \cdot \boldsymbol{\tau}, \quad (2)$$

where, p is static pressure and $\boldsymbol{\tau}$ is defined as $\boldsymbol{\tau} = -\mu[\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T] + \frac{2}{3}\mu(\nabla \cdot \boldsymbol{u})\boldsymbol{I}$. μ is viscosity.

Energy equation

$$c_p[\partial_t(\rho T) + \nabla \cdot (\rho \boldsymbol{u} T)] = \nabla \cdot (k \nabla T) - (\boldsymbol{\tau} : \nabla \boldsymbol{u}) + D_t p, \quad (3)$$

where, k, c_p are thermal conductivity and specific heat, respectively.

Number density equation

$$\partial_t(\rho M_i) + \nabla \cdot (\rho \boldsymbol{u} M_i) + \nabla \cdot \left(\rho \boldsymbol{u}_i^p M_i\right) = \nabla \cdot \left(D_i^p \nabla \rho M_i\right) + J_{M_i}, \quad (4)$$

where, $M_i, \boldsymbol{u}_i^p, D_i^p, J_{M_i}$ are aerosol number density divided by density, particle velocity, particle diffusion coefficient, source term related with nucleation and condensation, respectively. The subscript i is used to denote a section index for an aerosol size group.

Mass fraction equations

$$\partial_t\left(\rho Y_j\right) + \nabla \cdot \left(\rho \boldsymbol{u} Y_j\right) - \nabla \cdot \left(Y^{-1} \boldsymbol{h} Y_j\right) = R_j, \quad (5)$$
$$\partial_t\left(\rho Z_j\right) + \nabla \cdot \left(\rho \boldsymbol{u} Z_j\right) - \nabla \cdot \left(Z^{-1} \boldsymbol{f} Z_j\right) = S_j, \quad (6)$$

where, $Y_j, Z_j, \boldsymbol{h}, R_j, S_j$ are vapor mass fraction, particle mass fraction, vapor mass concentration drift flux($\boldsymbol{h} = \gamma \boldsymbol{f}$), vapor and particle mass concentration source terms, respectively.

2.2 Brownian diffusion model

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

$$D^l(s) = \frac{k_B T C_c}{3\pi \mu d}, \quad (7)$$

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.

2.3 Drift model

Large-sized particle is deposited on a surface by inertial force. Schiller-Naumann model to calculate drift velocity of a particle is written as

$$\partial_t \boldsymbol{v}(\mathrm{s}) + [\boldsymbol{v}(\mathrm{s}) \cdot \nabla] = -\frac{1+0.15Re_d^{0.687}}{\tau}[\boldsymbol{v}(\mathrm{s}) - \boldsymbol{u}] + (1-\gamma)\mathbf{g}, \quad (8)$$

where, $\boldsymbol{v}, \tau, \mathbf{g}$ 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 $\boldsymbol{v}$.

2.4 Geometry of FFTF aerosol leak case

Aerosol transport in case of FFTF sodium leak was analyzed using 'aerosolEulerFoam' solver. Schematic of the FFTF reactor is displayed in Fig. 1[3]. Guard vessel and cold leg are insulated. Surface temperature of the reactor vessel varies according to elevation. Sodium is assumed to be leaked from the upper region of the cold leg. Sampling pipe is attached under the hot leg.

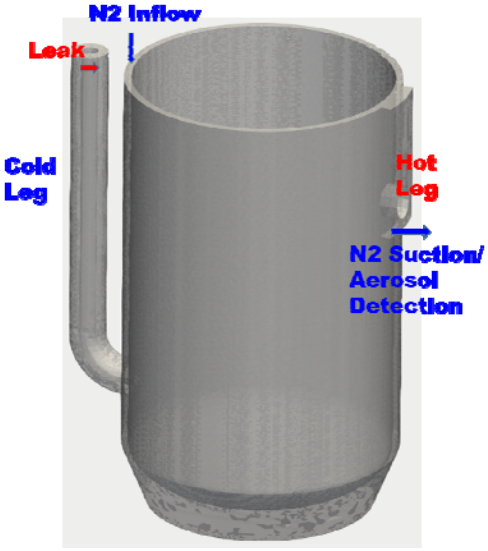

Fig. 1. Schematic of FFTF[3]

2.5 Simulation of aerosol transport

From fixed boundary conditions of temperatures given by the insulation outer surface and the reactor vessel outer surface, temperatures were obtained by CHT (conjugate heat transfer) simulation for the domain including the insulation material and the annulus space between two vessels. Fig. 2 shows calculated temperature field. The solution results were utilized for the aerosol simulation in which the fluid regions were only solved.

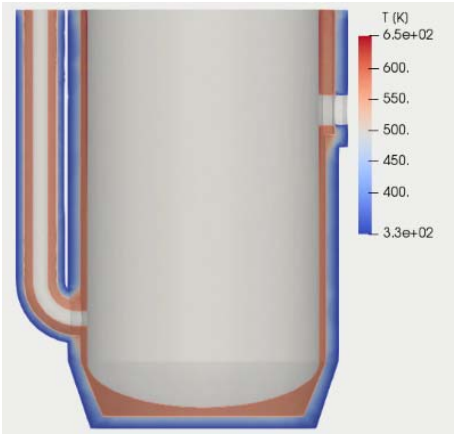

Fig. 2. Temperature distribution by CHT

2.5 Simulation of aerosol transport

Number of cells of generated grid system for the computational domain is about 2 million as shown in Fig. 3. At a given leak rate, detectable particle mass flow rate at the entrance of the sampling line was 6E-11 kg/s.

Fig. 3. Grid system

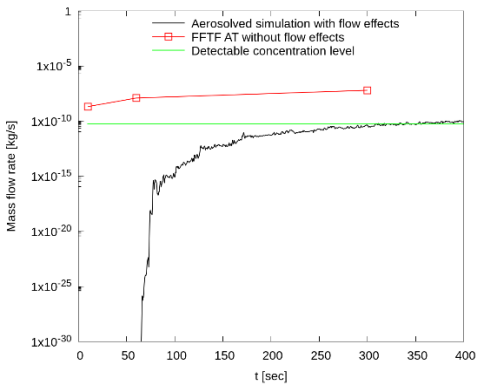

Fig. 4. Aerosol detection time calculation

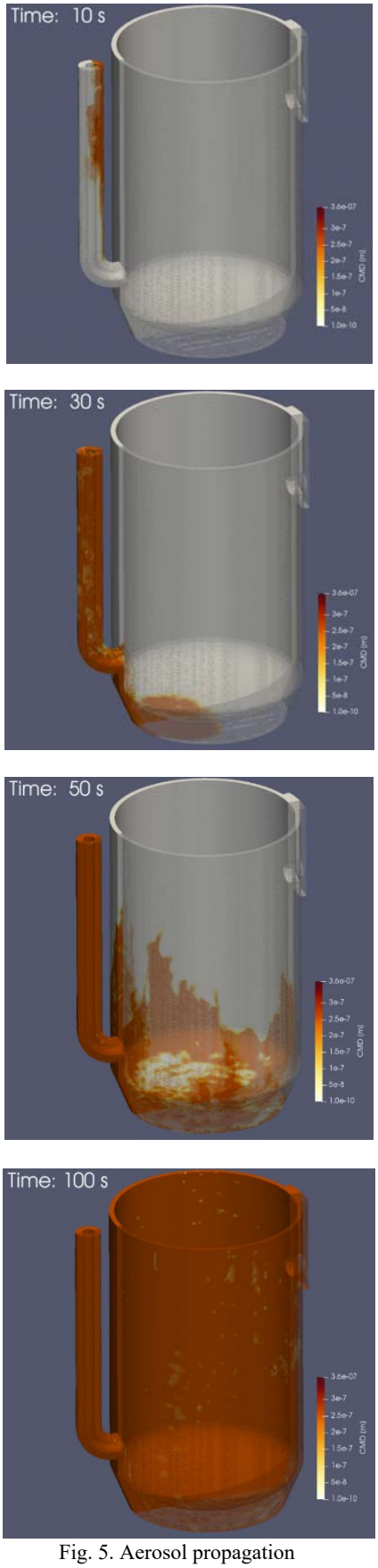

Fig. 5. Aerosol propagation

Fig. 4 shows transient particle mass flow rate at the entrance of the sampling line. Time to detect the aerosol was evaluated to be between 6 ~ 7 minutes. For the analysis in [3], aerosol dynamics was not coupled with the fluid flow and the detectable time was roughly estimated between few minutes and several hours. Fig. 5 shows aerosol propagation characteristics from the cold leg upper part to the sampling line. Around 100 seconds after the sodium leak, sodium aerosol arrives at the sampling line but the concentration level is not enough to be detectable. The detection time may vary by nitrogen injection rate, leak location, and leak rate. These parameters need to be evaluated for decision of optimal nitrogen injection rate and design of nitrogen circulation system.

3. Conclusions

Sodium leak detection time was calculated by an Eulerian aerosol solver. For FFTF sodium leak case, detection time was more clearly evaluated. This feasible analysis tool can be applied to decision of operational condition and design of containment nitrogen circulation system for SFR.

ACKNOWLEDGEMENT

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