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Effects of Natural Convection & Radiation inside Hot-Gas-Duct on Temperature Distribution on the Surface

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1. Introduction

A very high temperature gas-cooled reactor (VHTR) is a fourth-generation nuclear power reactor that uses the ceramic coated fuel, TRISO, in which the fission product gas does not leak even at temperatures higher than 1600 ℃.

The VHTR necessarily requires an intermediate loop composed of a hot gas duct(HGD), an intermediate heat exchanger (IHX) and a process heat exchanger.[1] The IHX is one of the important components of VHTR system because the IHX transfers the 950℃ high temperature massive heat to a hydrogen production plant or power conversion unit at high system pressure.[2]

Hot gas duct (HGD) is a unique component of a gas cooled reactor (GCR). It links the outlet of a GCR vessel to the inlet or outlet of an intermediate heat exchanger as shown in Figure 1. The internal of a HGD is insulated using a ceramic fiber insulator (Kaowool) to prevent a mechanical failure itself from high-temperature and high pressure operating conditions. The coolant temperature at the internal of a HGD can go up to 950℃.

The temperature distribution on a surface of horizontal HGD is important subject in designing the HGD because it can give the maximum allowable temperature of the HGD surface. The surface temperature distribution will be affected by both free convection and radiation on the HGD outer surface. Free convection is formed by a volume expansion (buoyance or body force) of air heated by the hot surface of HGD.

The experimental and simulation investigation for heat transfer of the free convection from the cylinders is reported with empirical correlations [3, 4]. However, there is no experimental and simulation work done for the geometry of an internally insulated cylinder (or a porous media cylinder) such as HGD form. A series of HGD tests are carried out at the small scale nitrogen gas loop at Korea Atomic Energy Research Institute. [5]

For this reason, in the present investigation, the thermo-hydraulic simulation for a horizontal HGD is performed to investigate the temperature distributions and fluid flow.

2. Numerical Model

In this study, the flow and temperature at the air are governed by the following three equations, including

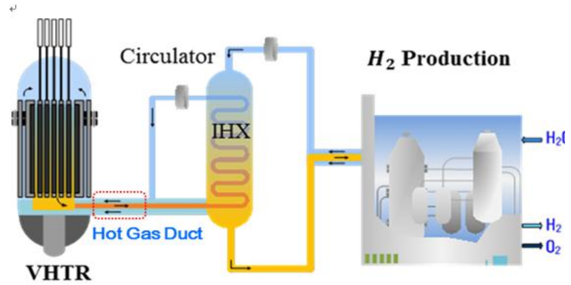


Fig. 1 Conceptual Layout of a Very High Temperature gas- cooled Reactor. (VHTR)

the 2D incompressible Navier-Stokes equation for laminar flow using CFD module in COMSOL[6] (i.e. the continuity and the momentum equations):

$$-\nabla_t p \cdot e_t - \frac{1}{2} f_D \frac{\rho}{d_h} |u| u + F \cdot e_t = 0 \tag{1}$$

$$-\nabla_t \cdot (A\rho u e_t) = 0 \tag{2}$$

and the energy equation are as following;

$$\rho C_p \vec{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q \tag{3}$$

Where, e_t is the tangential unit vector along the edge, ρ and f_D are the density and viscosity of the fluid, respectively and u is the velocity of the fluid for the momentum equation. In addition, C_p, k and T are the specific heat capacity at constant pressure, thermal conduction coefficient and temperature, respectively for the energy equation.

Since the equations (1) - (3) are coupled with the flow velocity (u), the three equations are simultaneously simulated until both velocity (u) and temperature (T) are converged. The PARDISO as a direct method is used because the three equations are weakly coupled. The relative tolerances are 10^{-3} for both the velocity (u) and temperature (T).

The flow and temperature in the Kaowool insulator are governed by the following Brinkman equation (3) for laminar flow using porous module in COMSOL. The equation (5) and (6) are heat transfer equations at the porous module in COMSOL.

$$0 = \nabla \cdot \left[-pI + \frac{\mu}{\varepsilon_p} (\nabla u + (\nabla u)^T) - \frac{2\mu}{3\varepsilon_p} (\nabla \cdot u) I \right] - \left(\mu k^{-1} + \beta_F |u| + \frac{Q_{br}}{\varepsilon_p^2} \right) u + F \tag{4}$$

$$\rho C_p u \cdot \nabla T = \nabla \cdot (k_{eff} \nabla T) + Q + Q_{vd} + Q_p \tag{5}$$

$$k_{eff} = \theta_p k_p + (1 - \theta_p) k \tag{6}$$

Where ε_p is the porosity, θ_p and k_p are the solid volume fraction and solid thermal conductivity of the porous module.

3. Structure of Model and Boundary condition

The HGD is provided with an internal thermal insulator to protect the pressure pipe from the high-temperature gas. The internal insulation composed of a Stainless steel liner tube, ceramic fibrous insulator (Kaowool) as shown in Figure 2.

- Pipe outer diameter 101.6 mm
- Thickness of Pipe 5.7 mm
- Diameter of flow channel 21.4 mm
- Thickness of insulator 32.4 mm

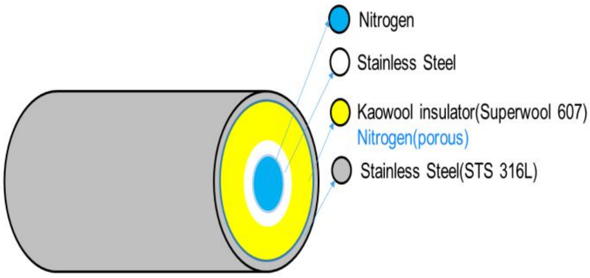


Fig. 2 Structure of HGD Model

The flow regime is a laminar flow. Figure 2 shows the geometrical model and boundary conditions for a HGD in COMSOL. As for boundary conditions, the constant heat flux, symmetric boundary, open boundary with room temperature and volume force are applied in COMSOL.

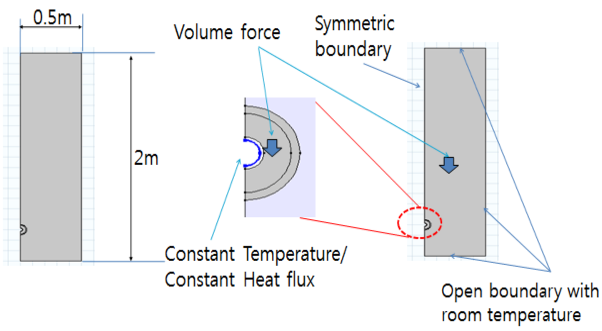


Fig. 3 Boundary conditions and geometrical model of a HGD in COMSOL 5.

In this model, the finite element method (FEM) is used for discretization and the 2-Dimensional unstructured meshes (triangular elements, quadrilateral elements, edge elements, vertex elements) are used for mesh generation. Figure 4 shows the generated meshes for COMSOL 5.

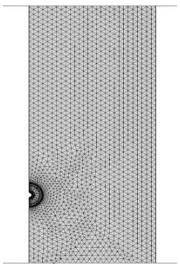
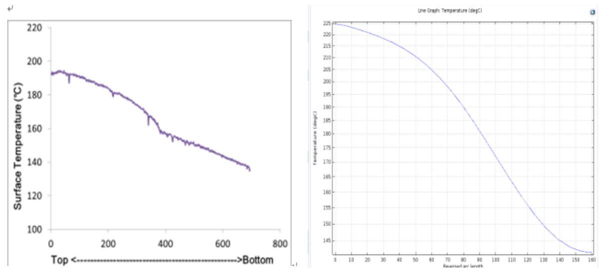


Fig. 4 Generated meshes for computer simulation.

4. Results and Discussion

Figure 5 shows the experimental results and the simulation results of COMSOL 5 analysis. From the figure it is observed that the temperature distributions at the surface of HGD are similar.

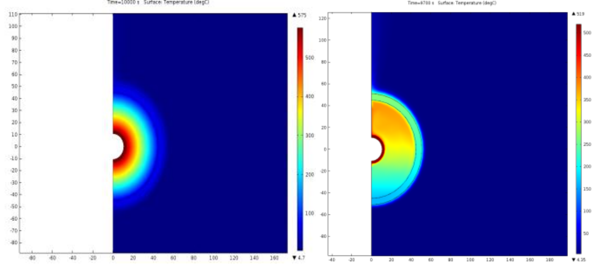


(a) (b)

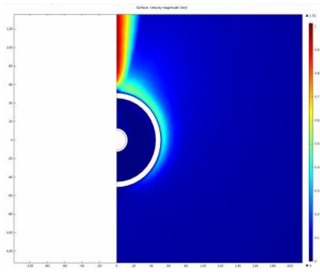
Fig. 5 Comparison of experiment and simulation results of surface temperature profiles at horizontal HGD.
(a) Experiment (135℃ ~194℃) (b) Simulation (141℃ ~224℃)

Figure 6 shows the temperature and velocity distributions of the HGD. Figure 6(a) shows the temperature distribution when the porous model is not applied at insulator. The temperature difference is 4.5℃ between the top and bottom when the porous is not applied. But experiment result is 135℃ ~194℃. The temperature difference is similar (141℃ ~224℃) when the porous model is applied at kaowool insulator.

From the Figure 6(b) and (c), we can see the temperature distributions and natural convection in the HGD. It is also found that buoyant force and temperature difference cause a natural convection.



(a) (b)



(c)

Fig. 5 Result of simulation
(a)Temperature distribution (b) Temperature distribution (porous apply) (c) Velocity distribution

The simulations are performed on the computer with the following configurations: (Intel(R) Xeon (R) CPU, 2.4 GHz (2 Processors), and 160 GB RAM (64 bit)). The total run time takes approximately 1hour to solve this model.

5. Conclusion

Thermo-hydraulic simulation using the COMSOL commercial solver is successfully performed at a uniform heat flux condition in a horizontal HGD. We obtained nonlinear temperature distribution from the COMSOL simulation with the assumption of the insulator in a HGD governed with conduction and convection heat transfer in porous medium. However, the temperature distribution at the surface of a HGD is overestimated very large compared with experimental results because initial heat flux and radiation were not exactly considered. For future work, we will consider the radiation heat transfer in porous media.

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