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Full Scale Thermo-hydraulic Simulation of a Helium-Helium Printed Circuit Heat Exchanger

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1. Introduction

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

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

In this paper, the thermo-hydraulic full scale simulation is performed to study the temperature distributions, thermal stress, pressure drop and outlet temperature in a Helium-Helium printed circuit heat exchanger (PCHE) in a VHTR simulate helium loop. The entire PCHE is composed of 40 stacks of rectangular shaped micro-channels for helium gas [type A] (inlet temperature, 400℃) and 40 stacks of semi-ellipse shaped micro-channels for helium [type B] (inlet temperature, 300 ℃). The experimental result is compared to that of computer simulation, COMSOL multi-physics software [1]. The Helium-Helium PCHE is considered a prototype of the newly developed PCHE by Korea Atomic Energy Research Institute (KAERI).

2. Structure of Model

The core dimension of the PCHE represented in Fig. 1 is 216 mm (W) x 340 mm (L) x 160 mm (H) [2]. The channel length of the effective heated region of the cold side is 0.4m and the hot side 0.34 m, respectively. The chemically etching treated [A type] metal sheet and [B type] metal sheet are stacked by a diffusion bonding as one set of metal sheets in [type A][type B] stacking sequence. The designed PCHE is composed of total 40 sets of metal sheets and the distance between each set has a thickness of 0.5 mm. The [A type] metal sheet passing hot helium in a 1.2 mm width of a micro-channel has 68 micro-channels and B type meta sheet flowing cold helium in a 1.2 mm has also 68 micro-channels. The material of the heat exchanger body is stainless steel 316 [STS 316].

3. Numerical Model

In this study, the finite element method (FEM) is used for discretization and the 3D unstructured meshes (tetr-

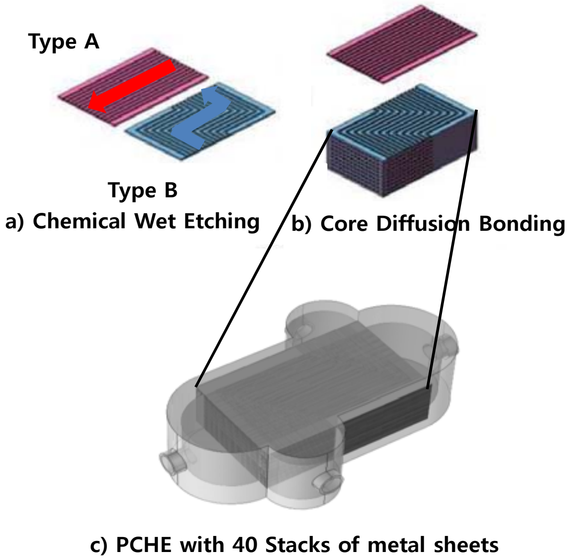

Fig. 1 Modeling of PCHE (COMSOL4.3b)

ahedral mesh) are used for the metal sheets and 1D meshes are used for all microchannels using COMSOL pipe flow module. The mass flow and temperature in the PCHE are governed by the following three equations, including the incompressible Navier-Stokes equation for laminar flow using pipe flow module in COMSOL (i.e. the continuity and the momentum equations):

$$\rho \frac{\partial \vec{u}}{\partial t} = -\nabla_t p \cdot e_t - \frac{1}{2} f_D \frac{\rho}{d_h} |\vec{u}| \vec{u} \quad (1)$$

$$\frac{\partial A \vec{u}}{\partial t} + \nabla_t \cdot (A \rho \vec{u} e_t) = 0 \quad (2)$$

where, e_t is the tangential unit vector along the edge, ρ and f_D are the density of the fluid and the Darcy friction factor, respectively. $\vec{u}$ is the velocity of the fluid, d_h is hydraulic diameter of the micro-channels and A is the cross section area of the micro-channels.
The energy equation is as following;

$$\rho C_p (\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T) = \nabla \cdot (k \nabla T) \quad (3)$$

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 for the flow velocity ($\vec{u}$), the three equations are simultaneously simulated until the velocity ($\vec{u}$) and temperature (T) are converged. The PARDISO as a direct method is used because the three equations are weekly coupled. The relative tolerances are 10^{-5} for both the velocity ($\vec{u}$) and temperature (T).

4. Results and Discussion

Figure 2 shows the generated meshes for COMSOL multiphysics simulation [3]. Total numbers of meshes are 226640. The flow regime is a laminar flow due to the small diameter of the microchannel. As boundary conditions, the uniform mass flow rate and constant temperature are applied to for inlets. The Nusselt number and the Darcy friction factor are obtained from the 3D simulation results of the single micro-channels in [Type A] and [Type B]

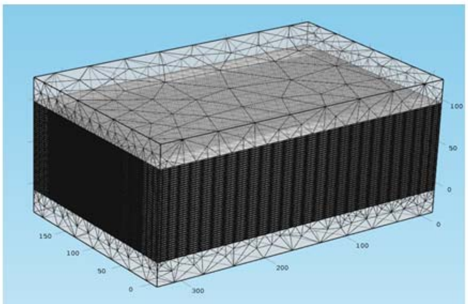

Fig. 2 Generated meshes for computer simulation

The shape of the pipe for the primary system is square [type A] and that of the pipe for the secondary system is a semi-ellipse [type B]. Table 1 summarizes the comparison with the experiment and the COMSOL 4.3b simulation results.

Table 1. Summary of the comparison with the experiment and simulation results.

	Experiment	COMSOL
Inlet temperature [type A]	400℃	400℃
Inlet temperature [type B]	300℃	300℃
Outlet temperature [type A]	323.39℃	325.1℃
Outlet temperature [type B]	379.56℃	380.8℃
Δ P [type A]	2.96kPa	2.96kPa
Δ P [type B]	31.2kPa	31.2kPa
Mass flow rate [type A]	0.0986 kg/s	0.0986 kg/s
Mass flow rate [type B]	0.0890 kg/s	0.0890 kg/s
Maximum thermal Stress	-	37.5MPa

The shaded portions of Table 1 are the initial boundary conditions and the others are the numerical simulation results. The outlet temperature of the primary system is 323.39℃ and 379.56℃ for [Type A] and [Type B] in experiment, but the numerical simulation shows that the temperature is 325.1℃ and 380.8℃, respectively. The maximum temperature difference is less than 1.7℃. For pressure drop, the simulation results are the same with experiment. As a result, the Helium-Helium PCHE simulation is in a good agreement with experiment.

Figure 3 shows temperature distribution and thermal stress distribution. We can see the temperature distributions are quite similar in both experiment and simulation. The maximum stress is obtained only 37.5MPa in this simulation condition. The Helium-Helium PCHE estimated having enough margins for thermal stress (thermally safe) because the yield strength of STS 316 is 300MPa at 400℃.

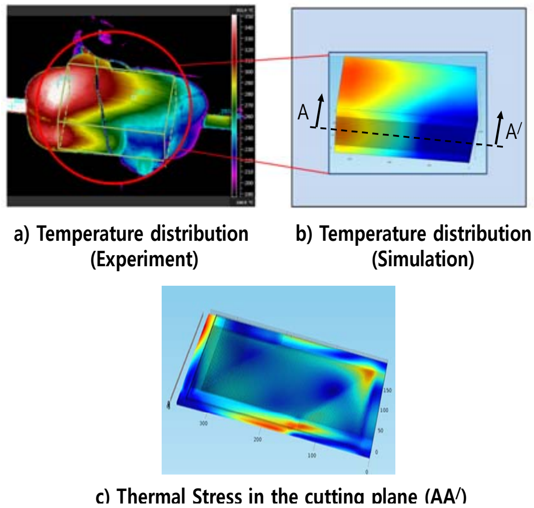

Fig. 3 Comparison of experiment and simulation

The simulations are performed on the following computer (Intel(R) Xeon (R) CPU, 2.4 GHz (2 Processors), and 160 GB RAM (64 bit)). This computer consumes approximately 2 weeks to obtain a simulation result.

5. Conclusion

The full scale thermo-hydraulic simulation was successfully performed to obtain temperature distribution, pressure drop and thermal stress in 40 sets of flow channel stacks in a helium-helium printed circuit heat exchanger in a VHTR simulate helium loop. We obtained a quite similar temperature distribution with the 3D measured infrared temperature distribution. To our knowledge, this is the first full scale numerical study on the PCHE, which considers all microchannels, that the convection effect on the outside surfaces of the PCHE is applied .

ACKNOWLEDGEMENT

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