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Thermal Analysis using CFD for Control Rod Position Indicator

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1. Introduction

Control Element Drive Mechanism(CEDM)s of the integrated reactors developed in the future need precise Position Indicator(PI)s of control rods to control their cores because they use fission reaction heat for heating the coolant during start-up and controls the core without boric acid. Also, the 1E-Class PI applied to commercial nuclear power plants is not suitable for integrated reactors due to its low resolution and accuracy. Therefore, we are considering to apply a high-performance MagnetoStrictive Position Transmitter (MSPT)[1] to indicate a position of control rod. This requires environmental verification of MSPT, which includes thermal acceleration aging. For the aging, maximum temperature of MSPT should be predicted to calculate a period of aging using Arrhenius's equation.

This paper describes the process and results of calculating the maximum temperature of MSPT through CFD analysis by simulating the conditions around the MSPT during normal operation of the integrated reactor.

2. Modeling and Analysis Results

This chapter describes the CFD modeling and analysis results. The analysis was performed using the commercial ANSYS Fluent tool and the model of MSPT applied to the analysis is BTL7[2] from BALLUFF.

2.1 Geometry and materials

As shown in Figure 1, the pressure vessel of the CEDM with MSPT was simplified to a quarter geometry model. The model consists of pressure vessel, MSPT, air inside/outside of MSPT, primary coolant, moving parts and upper/lower holder.

The pressure vessel is cylinder-shaped and is about 1.3 meters long and about 1 cm thick. The MSPT is combined in the pressure vessel using an upper and lower holder. The minimum gap between the MSPT and the pressure vessel is 1 mm. The MSPT is about 80 cm long and inside of MSPT is empty(air).

In fact, the hot primary coolant enters the lower part of the pressure container of the CEDM and is filled inside the pressure vessel, including the driving part (magnetic and bearing, shaft, etc.) with complex structure. Due to its complex structure, it is difficult to CFD analysis reflecting the flow environment and also for conservatively calculating, the moving parts (red dotted line) including the part of the primary coolant was simplified into a cylindrical metal.

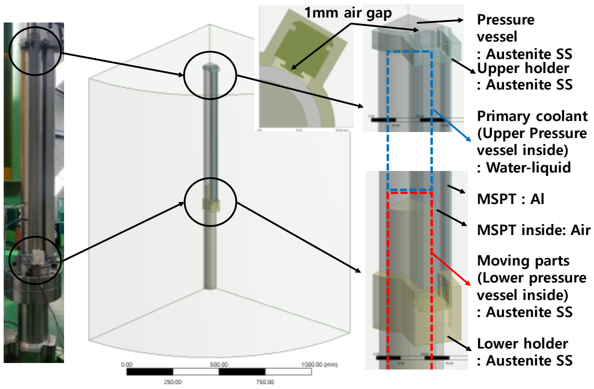

Fig. 1. Geometry and materials

The size of the entire space, including outside air of MSPT, is 1,000mm in radius and 1,636mm in height considering natural convection.

The metal parts except the MSPT is applied with austenite stainless steel, which is non-magnetic materials, because the MSPT detects the magnetic field of the magnet moving in the the coolant. The coolant and air use properties in the CFD tool. The input properties are shown in Table 1.

Table I: Input property of materials

Part	Input property
Pressure Vessel / Holder	Thermal conductivity: 16.6 w/m-k (@125℃)
MSPT	Thermal conductivity: 202.4 w/m-k
Primary coolant (@60℃)	Density: boussinesq 989.48, Specific heat: 4182 j/kg-k, Thermal conductivity: 0.6 w/m-k, Viscosity: 4.6957e-04, Thermal expansion coefficient: 5.1654e-04
Air	Density: incompressible ideal gas, Specific heat: 1006.43 j/kg-k, Thermal conductivity: 0.0242 w/m-k, Viscosity: 1.7894e-05

2.2 Mesh

The mesh of the model is shown in Figure 2. The elements /faces /nodes are 25,006,346 / 53,967,126 / 6,639,937. The elements are mostly hexahedron and wedge. The quality of the elements(Skewness) is 0.24 on average and 0.85 on maximum. The maximum and minimum volume of the element is 1.29e-12 m^3 and 1.39e-04 m^3.

2.3 Model & Solution methods

For the turbulence model setting, Realizable k-ε was used. To simulate the convection of air, the setting of air density is an incompressible-ideal-gas that is affected

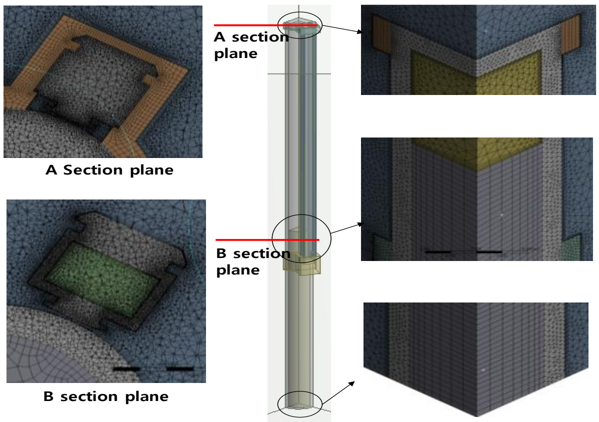

Fig. 2. Mesh

only by temperature and also under the gravitational conditions. The Radiation is adopted to the DO (Discrete Ordinates) model.

2.4 Boundary conditions

The boundary conditions of the model considering thermal conduction, convection and radiation are shown in Figure 3.

The conditions of the inlet pressure are entered on the radial side of the model so that the outflow of the air is determined by natural convection. Since it is a quarter model, symmetry conditions are set on the left and right sides. The temperature setting for radial side and upper surface is 50℃ which is the ambient temperature of outside air.

The lower surface of the pressure vessel and the moving parts is applied with the temperature of 120℃, which is the temperature of the coolant entering the CEDM, under the isothermal conditions. The cover surface of the reactor is applied with 70℃.

For the internal and external surfaces of the MSPT, the radiation emissivity was entered as 0.8 of Anodized Al and the emissivity of all other metal exterior surfaces was applied as 0.4 assuming a light oxide stainless steel.

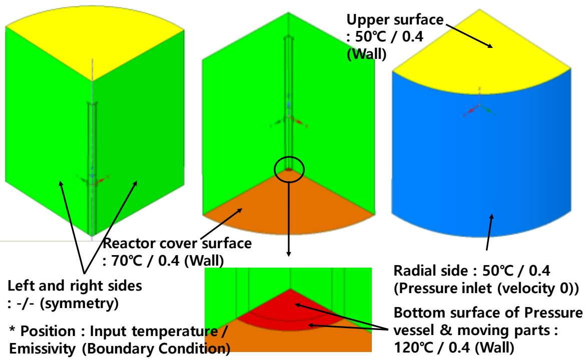

Fig. 3. Boundary conditions

2.5 Analysis results

The results of the streamline and temperature distribution for the CFD analysis of Figure 4(a) plane (a plane passing through the center of the MSPT) are shown in Figures 4(b) and 5(a). It was confirmed that the fluid was simulated as a natural convection in accordance with the form of streamlines for the fluid area in Figure 4(b).

The temperature distribution of the MSPT is shown in Figure 5(b), with a maximum temperature of 60℃ and the position is in contact with the lower holder at the bottom.

The total heat transfer rate for the entire model was calculated to confirm energy balance as 0.26 W.

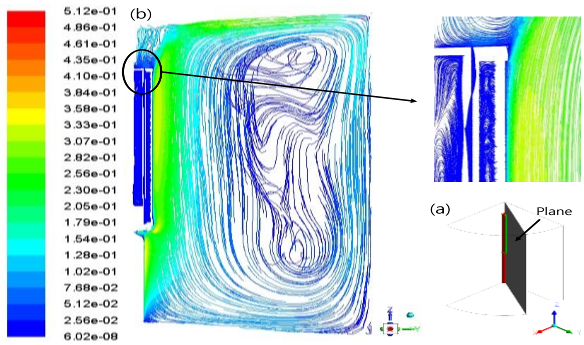

Fig. 4. (a) Plane (b) Stream line[m/s] of the plane

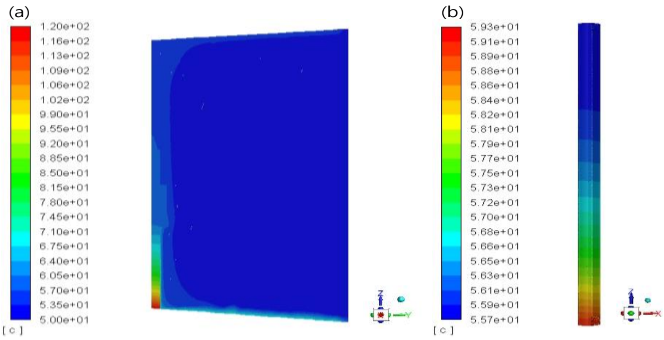

Fig. 5. Temperature[℃] distribution of the plane(a) and the MSPT(b)

3. Conclusions

The maximum temperature (60℃) of the MSPT can be used to estimate the accelerated thermal aging time of MSPT. The aging time shall be calculated using the value of the lowest (conservative) activation energy among the non-metallic parts of the MSPT, the aging temperature, operating temperature(60℃), the time of use in accordance with the Arrhenius equation.

Based on this, we plan to perform the accelerated thermal aging for the verification of the MSPT as 1E-Class equipment.

REFERENCES

[1] Tae-Won Na, Hyung Huh and Je-Yong Yu, Control rod position indicator with high performance for reactor precision control, Korea Nuclear Society(KNS), May 23-24, 2019
[2] "Datasheet MP727992(BTL7)" by BALLUFF