

Thermal Analysis of High-Power Steady-State Fully Radiation-Cooled MPD Thrusters with Permanent Magnets for In-Space Propulsion

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Abstract: The Magneto-Plasma-Dynamic (MPD) thruster that we developed doesn't have water-cooled solenoidal coils but permanent magnets. As a permanent magnet to apply a magnetic field in this study, Samarium Cobalt (SmCo) magnet was selected because it has high values of a maximum energy product and good thermal characteristics. A fully radiation-cooled (FRC) MPD thruster with SmCo magnet will be developed as a practical MPD thruster. Therefore, thermal analysis of the FRC-MPD thruster was carried out. As the result of a previous FRC-MPD thruster, the maximum temperature of permanent magnets was 1,033 K. It was much higher than irreversible demagnetization temperature of SmCo (620 K). The FRC-MPD thruster needs structural change and material change. The new structure (structure 2-7) were designed and analyzed. As a result, the maximum temperature of permanent magnets of structure 4 was lower than previous FRC-MPD thruster by 110 K. And the maximum temperature of permanent magnets was dropped 19 K by changing material from Macor (commercially available ceramics) to Mo. In order to make temperature drop more, the structure of parts of FRC-MPD thruster was coated by black and white paint. It was proved that using black and white paint was effective for decrease of the temperature.

I. Introduction

AT Osaka institute of technology, high power steady-state Magneto-Plasma-Dynamic (MPD) thruster have investigated for manned Mars exploration. There are many problems for practical use. The heat of in operation and lifetime of electrode are obstruct development practical use MPD thruster on a large scale. Even among them, we focused heat in operation.

A quasi-steady MPD thruster doesn't fit for practical use in space, because of its weight and complicated system. And, conventional MPD thrusters were equipped with water-cooled coils which apply the magnetic field. So, the thruster systems is complicated, because of increasing external systems, such as circulating pump and heater. A practical MPD thruster system is required with light and simple structure. The MPD thruster that we developed doesn't have water-cooled coils but permanent magnets. However, the problem about focusing on heat remains unsolved. The heat are conducted from thruster to permanent magnets. Therefore, temperature of permanent magnets are higher than irreversible demagnetization temperature. Then, applied magnetic field are decreased by to cause irreversible demagnetization. Thus, permanent magnets must be protected from generated heat. And, MPD thruster of experiment

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model is made water-cooled. However, a practical MPD thruster can't use water-cooling as the cooling method. Therefore, the cooling method was changed from water-cooling to radiation-cooling. By using these, a fully radiation-cooled (FRC) MPD thruster was designed for the purpose of practical use.

As aims of this research, temperature of permanent magnet is made lower than irreversible demagnetization temperature. And, structure suitable for complete radiation-cooled MPD thruster is made decide from analysis result.

II. Selection of magnet

Permanent magnet suitable for MPD thruster was selected by compare 4 permanent magnets. 4 permanent magnets were Samarium Cobalt (SmCo) magnet, Neodymium (Nd) magnet, Ferrite magnet and Alnico (Al-Ni-Co) magnet. And, the selection of suitable permanent magnet was carried out following 4 values.

A. Residual Magnetic Flux Density

Figure 1 shows graph of Residual Magnetic Flux Density. In this graph, high values were showed except Ferrite magnet.

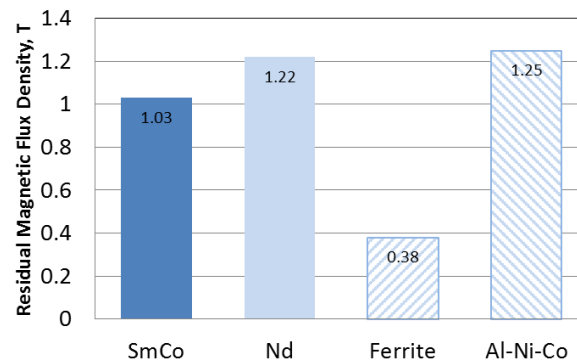


Figure 1. Residual Magnetic Flux Density.

B. bH_c Coercivity

Figure 2 shows graph of bH_c coercivity. In this graph, SmCo magnet and Nd magnet were showed high value.

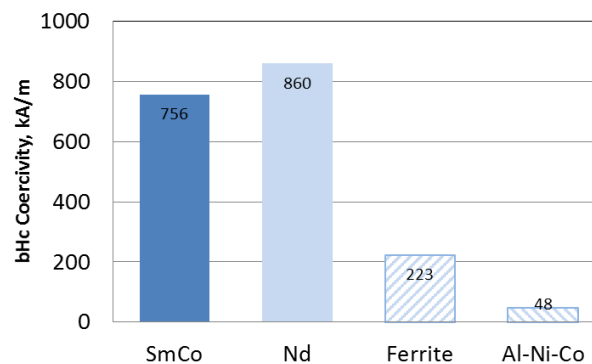


Figure 2. bH_c coercivity.

C. Maximum energy product

Permanent magnet suitable for MPD thruster was regarded magnetic force as important. Therefore, maximum energy product was used. Figure 3 shows graph of maximum energy product. In this graph, SmCo magnet and Nd magnet were showed high value. So, these magnets can apply magnetic field higher than the other magnets.

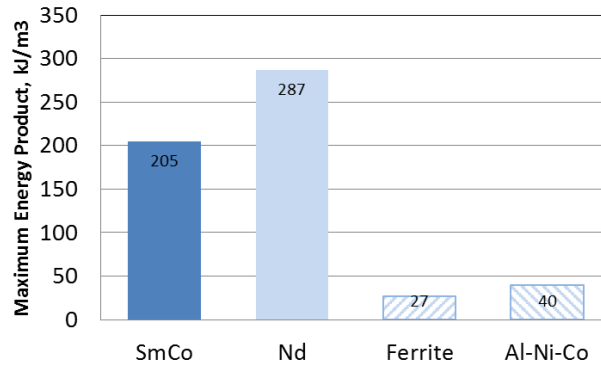


Figure 3. Maximum energy product.

D. Thermal coefficient

A FRC-MPD thruster is anticipated that permanent magnets will be exposed high temperature by heat to conduct from thruster. Permanent magnet is have decreased magnetic force whenever temperature of permanent magnet rises. Therefore, permanent magnet is selected in small value of a thermal coefficient. Figure 4 shows graph of a thermal coefficient. In this graph, SmCo magnet and Al-Ni-Co magnet were showed small value.

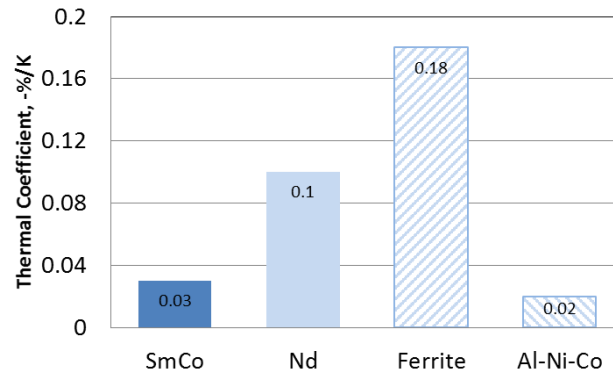


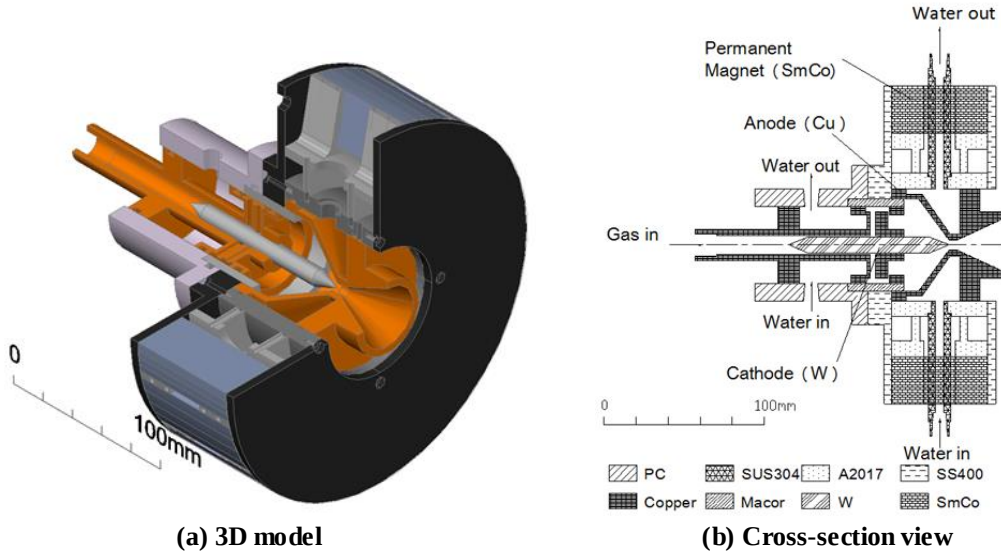
Figure 4. Thermal coefficient.

From these, permanent magnet suitable MPD thruster was selected SmCo magnet and Nd magnet about value of a maximum energy product. And, in value of thermal coefficient, SmCo magnet could be confirmed 1/3 of Nd magnet. So, SmCo magnet was selected permanent magnet suitable for MPD thruster in this research.

III.MPD thruster

A. Water-cooled MPD thruster

Figure 5 show the 3D model and the cross-section of the water-cooled MPD thruster, respectively. This thruster has a magnet circuit which consists of yokes, SS400 plates, sandwiching permanent magnets around the anode in order to apply of an axial magnetic field. Figure 6 shows the shapes of the permanent magnet. The strength of applied magnetic flux density can be freely changed by increasing and decreasing the number of permanent magnets. And, anode and cathode holder were water-cooled.



B. Fully radiation-cooled MPD thruster

A FRC-MPD thruster was designed so that magnetic circuit of water-cooled MPD thruster can be reused. Figure 7 shows 3D model and the cross-section of the previous structure of FRC-MPD thruster (structure 1). Parts of FRC-MPD thruster are anticipated increasing temperature, because of without water-cooled. Therefore, most thruster parts were constitute refractory material, (pure tungsten, TZM). Characteristics of structure 1 is seen in Fig. 8. First, heat to conduct to radial direction is controlled with insulator. Second, metal parts which was located inside of insulator make to conduct heat to axial direction. And, heat is conducted to the backward of thruster. Finally, heat is discharged in space through radiation plate.

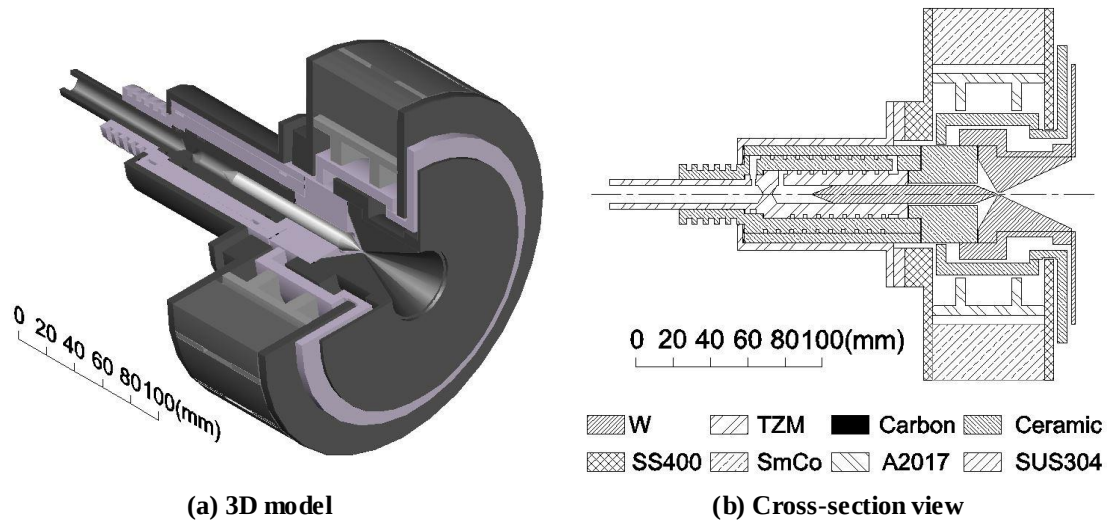


Figure 7. FRC-MPD thruster.

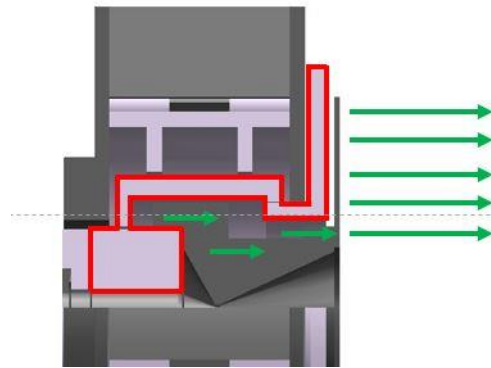


Figure 8. Characteristics of structure 1.

IV. Thermal analysis of fully radiation-cooled MPD thruster

In this research, thermal analysis was carried out with Thermal Desktop (C&R Technologies, Inc.). Structure of FRC-MPD thruster was examined that could be decreasing steady-state temperature distribution of SmCo magnet. Permanent magnet was have irreversible demagnetization temperature, it were mentioned above. Therefore, optimum structure of FRC-MPD thruster was defined a structure as temperature of permanent magnet lower than irreversible demagnetization temperature of SmCo (620 K).

A. Thermal analysis condition of changing structure

FRC-MPD thrusters changing structure were developed based on a previous structure of FRC-MPD thruster (structure 1). They were developed 3 type. And, they were called structures 2, 3, 4, respectively. Figure 9 shows analysis models of structures 1 - 4. Structure 1 was a previous structure of FRC-MPD thruster.

Characteristics of structure 2 was located an insulator with the thickness instead of metal parts of structure 1. Therefore, heat to conduct to radial direction was going to restrain than structure 1.

Characteristics of structure 3 was divided an insulator into three parts. So, not only structure 3 but also a multi-layer insulator FRC-MPD thruster were called. The concept was to restrain to conduct to heat by thermal conduction, and to promote to conduct to heat by heat transfer.

Characteristics of structure 4 was changed the material of the center of the three parts to tungsten from ceramic. Therefore, heat to conduct to radial direction was going to restrain by insulation effect with materials, and was promoted heat to conduct to axial direction.

4 types of FRC-MPD thruster were analyzed with analysis conditions (see table 1). Analysis conditions were calculated from experimental results at 8.0 kW. The analysis time was installed steady-state. Applied heat to the cathode and the anode were 300 W and 4,770 W, respectively. The most suitable structure of the electric discharge room circumference was postulated that lowest structure of steady-state temperature of permanent magnet. In this analysis, the temperature change of permanent magnet was compared by changing structure of the electric discharge room circumference.

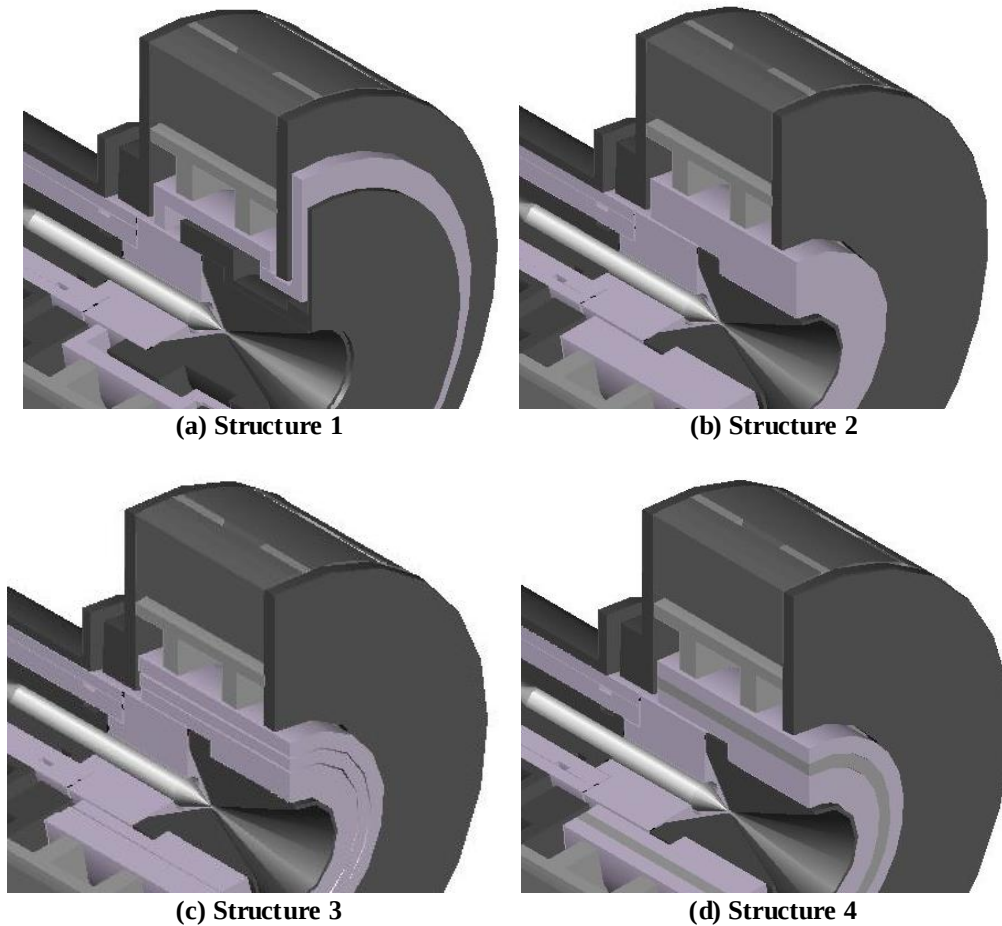


Figure 9. Analysis models.

Table 1. Analysis conditions.

Analytic Model	Structure 1-4
Analysis Time	Steady-State
Input Power, W	8,000
Applied Heat to the Cathode, W	300
Applied Heat to the Anode, W	4,770
Software	Thermal Desktop

B. Thermal analysis result of changing structure

Table 2 shows maximum temperature and minimum temperature of permanent magnet of structures 1 - 4, respectively. And, steady state temperature distribution of permanent magnet of structures 1 - 4 are seen in Fig. 10. As the results, structure 1 was highest temperature of permanent magnet. And, structure 4 was lowest temperature of permanent magnet. The difference of temperature of structures 1 and 4 were 110 K. From these results, characteristics of previous structure was not suitable structure of FRC-MPD thruster. As a cause of temperature rise, it is thought that heat to conduct to radial direction was not able to prevent by lack of thickness of insulator. Thickness of insulator of structure 1 was half of other structure. So, insulation effectiveness was appeared conspicuously by thickness of insulator that compare structure 1 and structure 2. Therefore, it is thought that mounting of insulator with thickness is effective. And, the difference of temperature of structures 1 and 2 were 26 K.

As shown in Fig. 10 (b) and (c), temperature distribution of structure 3 was lower than structure 2. Also, the difference of temperature of structures 2 and 3 were 80 K. This result was appeared insulation effectiveness by increasing insulator parts. In other words, this insulation effectiveness is thought that mechanism of conduct to heat is difference between heat transfer and thermal conduction. So, the heat transfer conduction (heat transfer) with parts more plural can restrain the heat of the diameter direction than the conduction heat transfer (thermal conduction) with one part.

Temperature distribution of structure 4 was lower than structure 3, see in Fig. 10 (c) and (d). Also, the difference of temperature of structures 3 and 4 were 4 K. This insulation effectiveness was the influence of changing the material of the center of the three parts to pure tungsten (W) from ceramic. That is, difference of characteristics of materials produced insulation effectiveness. However, temperature change was low. Also, it is thought the analysis error by mesh shapes.

Finally, structure 4 can be assumed the most suitable structure of FRC-MPD thruster by changing structure.

Table 2. Temperature of permanent magnet.

Structure Number	Minimum Temperature, K	Maximum Temperature, K
1	908.1	1,033
2	877.4	1,007
3	834.8	927.1
4	831.1	923.1

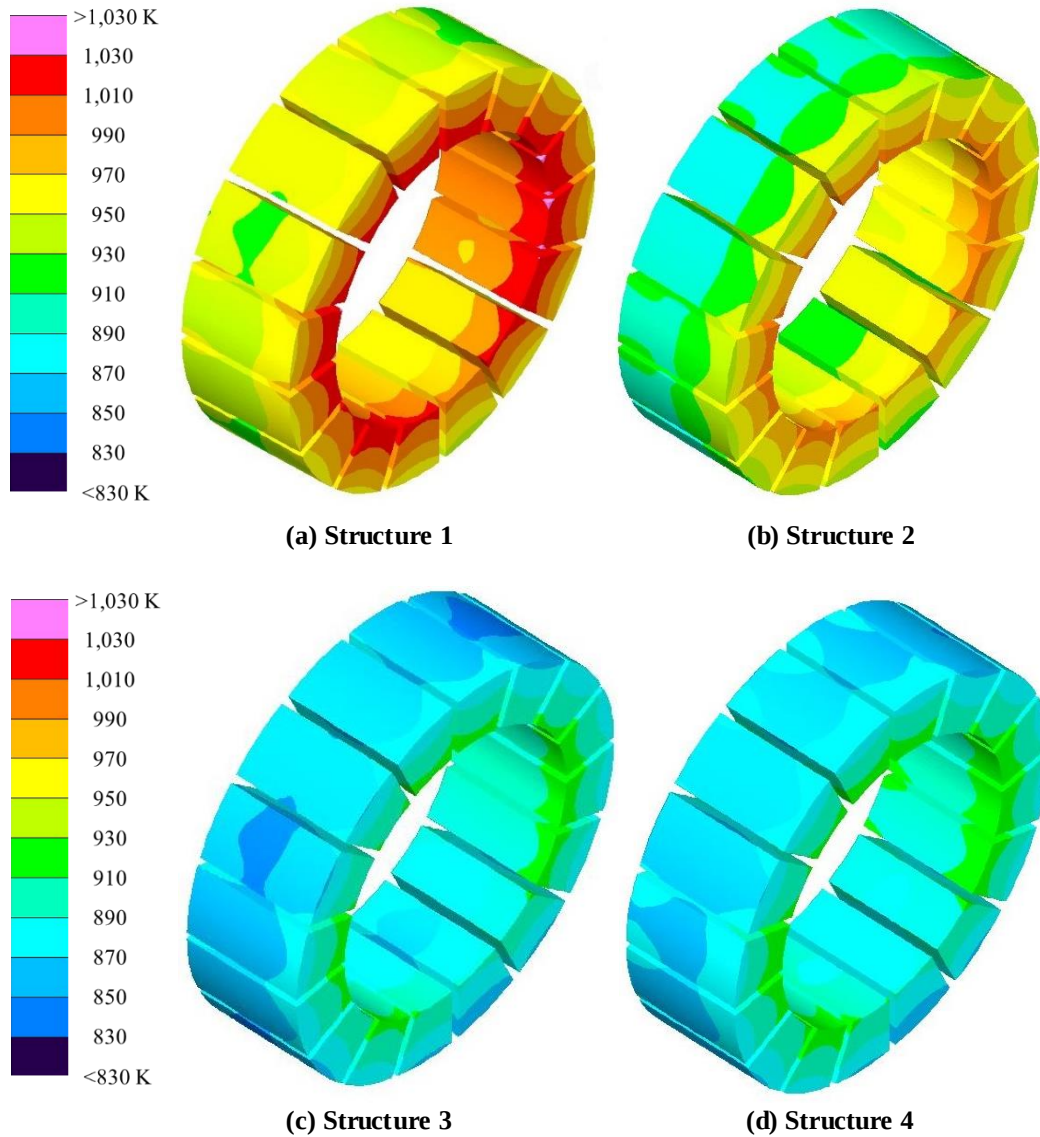


Figure 10. Steady state temperature distribution of permanent magnet.

C. Thermal analysis condition of changing material

Changing material to pure tungsten (W) from ceramic was showed the insulation effectiveness by before section. However, it was thought the analysis error by mesh shapes. Therefore, changing material that except pure tungsten (W) were verified the insulation effectiveness, and were compared to temperature distribution.

In these analysis, structures of changing materials were developed based on a multi-layer insulator FRC-MPD thruster (structure 3). They were developed 3 type. They were called structures 5, 6, 7, and the material of the center of the three parts were BN, C, Mo, respectively. In analysis of structure 4, the temperature range were 1,770 – 2,000 K. Therefore, the high melting point materials having melting points more than 2,000K were required. So, the materials which was had used before were used. The analysis condition was the same of before.

D. Thermal analysis result of changing material

Figure 11 shows steady state temperature distribution of permanent magnet of structures 4 – 7. And, Maximum temperature and minimum temperature of permanent magnet of structures 4 – 7 were shown in table 3, respectively. As shown in Fig. 11, temperature distribution of structure 7 was lower than the other structure. Also, the difference of

temperature of structures 4 and 7 were 15 K. From these results, analysis error by the mesh shape may be said low probability.

The temperature changes were not seen in compared structure 4 and 5. Also, the difference of temperature of structures 4 and 5 were 10 K. So that, the contribution degree to the temperature drop of the permanent magnet by the materials change were thought be small. However, temperature changes by material change was seen a little in this result. Therefore, thermal conductivity was focused on. Thermal conductivity at the ordinary temperature were W of 169-176 W/(m·K), BN of 30-50 W/(m·K), C of 23.9 W/(m·K), Mo of 138 W/(m·K). But, temperature changes by only the difference of thermal conductivity could not be explained. Moreover, thermal emissivity was focused on as well. The standard thermal emissivity were W of 0.43, C of 0.8 - 0.9, Mo of 0.37. Therefore, analysis results could be explained the influence of thermal conductivity and thermal emissivity. Also, it was thought that most of temperature change was influenced to thermal emissivity.

Finally, structure 7 can be assumed the most suitable structure of FRC-MPD thruster by changing material.

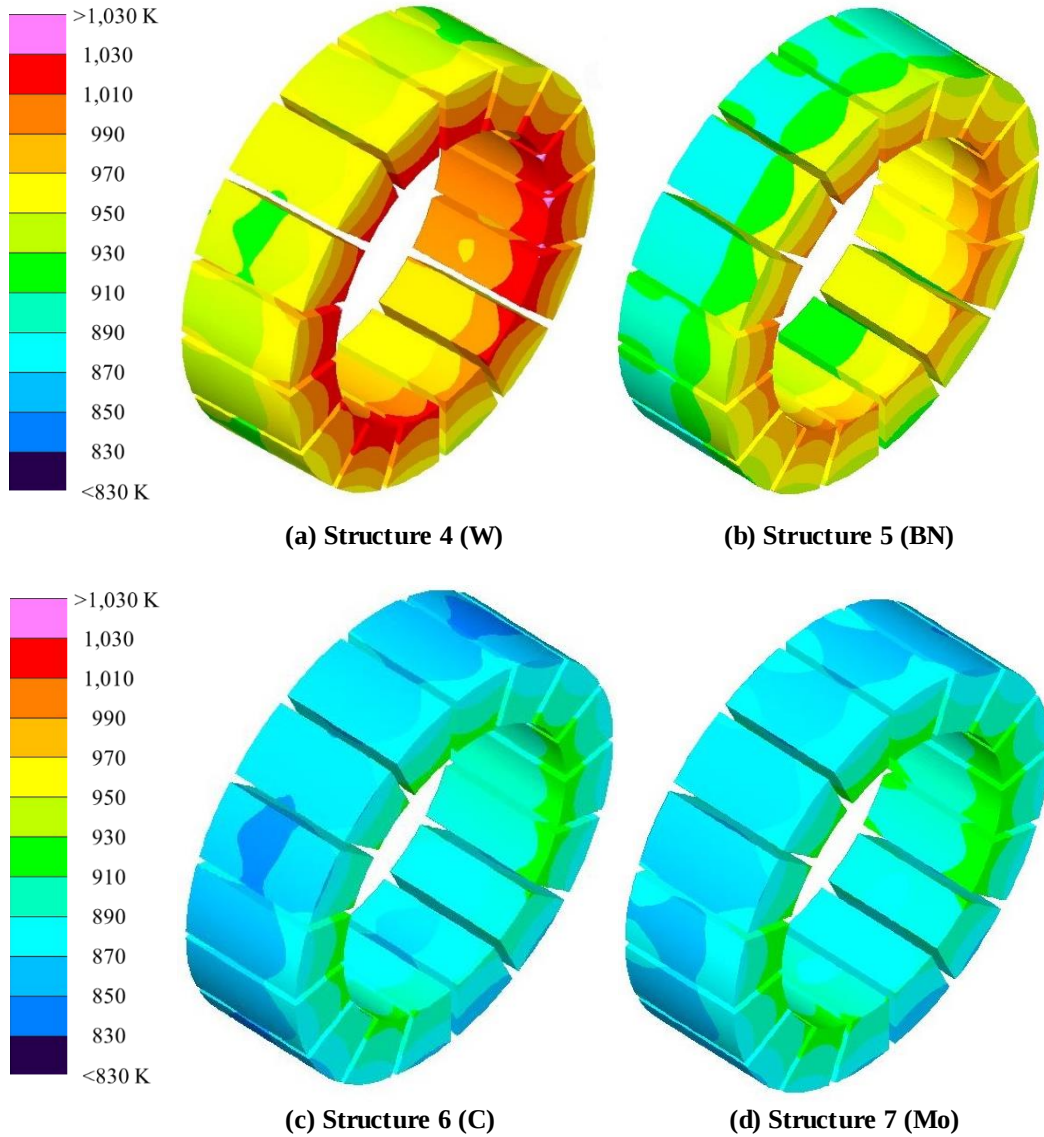


Figure 11. Steady state temperature distribution of permanent magnet.

Table 3. Temperature of permanent magnet.

Structure Number	Minimum Temperature, K	Maximum Temperature, K
4	831.1	923.1
5	827.5	916.0
6	824.3	913.1
7	822.5	911.9

E. Thermal analysis condition of changing emissivity

As shown in before section, the analysis results by material change were likely to the difference of thermal conductivity and thermal emissivity in materials. Also, thermal emissivity was gave large influence in temperature change. Therefore, temperature of permanent magnet may be dropped by changing thermal emissivity and thermal absorptivity. The thermal emissivity and thermal absorptivity were changed painting black and white paints in magnetic circuit. As the analysis of changing thermal emissivity, structure 1 of the most high temperature distribution and structure 7 of the most low temperature distribution were used and. There were called structures 8 and 9, respectively. And, painting black and white paint was defined by changing thermal emissivity of surface part. Figure 12 shows thermal emissivity changing point of 3D model and cross-section. As shown in Fig. 12, black surfaces and black lines were showed black paint, and white surfaces and white lines were showed white paint. Also, green surface of 3D models and point without black and white lines of cross-section were showed it was not changing thermal emissivity. The parts which is near the center axis of thruster were painted white paint, because heat to conduct to radial direction from heat source was going to restrain. And, inside of permanent magnet were painted white paint due to restrain heat to conduct to permanent magnets. Next, black paint were painted outside of the thruster. Because, it was thought heat in inside of the thruster was discharged to the space by raising thermal absorptivity of outside of thruster. The analysis condition were same of before.

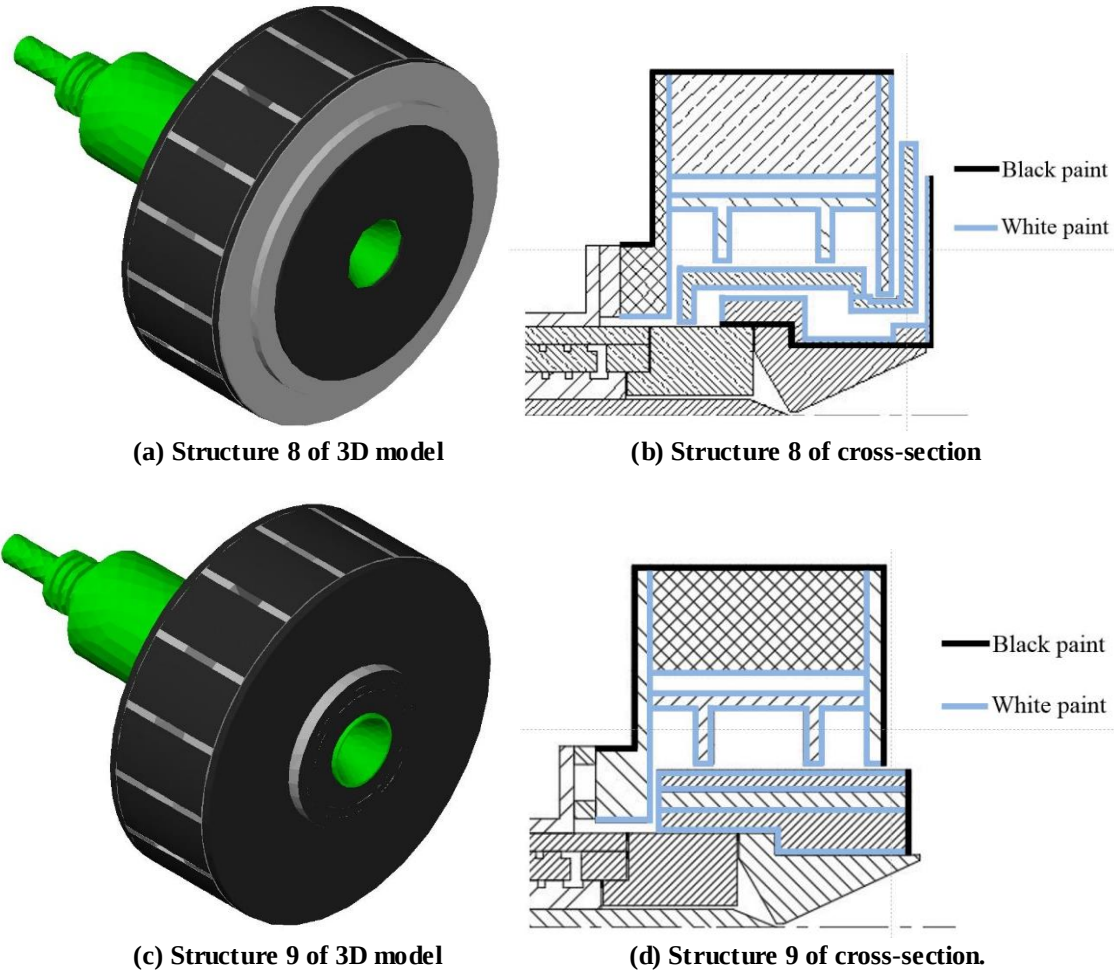


Figure 12. Analysis models.

F. Thermal analysis result of changing emissivity

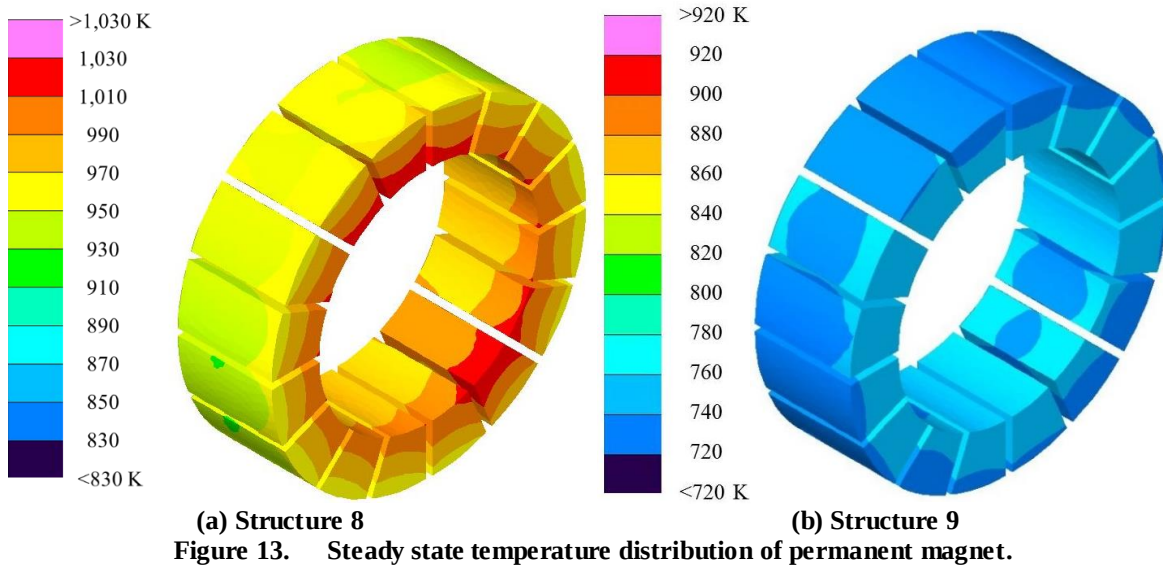
Maximum temperature and minimum temperature of permanent magnet of structures 1, 7, 8 and 9 were shown in table 4, respectively. And, Figure 13 shows steady state temperature distribution of permanent magnet of structures 8 and 9. In structures 1 and 8, a maximum temperature of were decreased 4 K, but a minimum temperature was increased 20 K. Also, temperature distribution was seen to be decreasing temperature of permanent magnet in overall. As the reason to increased minimum temperature, to discharge heat of inside of the thruster was promoted by painting black paint in outside of the thruster.

In structures 7 and 9, maximum temperature of were decreased 150 K, and minimum temperature was decreased 101 K. The temperature change of permanent magnet was successful than changing structure of analysis condition.

So, it is said that painting black and white paint was much effected to decrease temperature of permanent magnet. However, these analysis results were higher than the irreversible demagnetization temperature of SmCo magnet (620 K). On the other hand, it is thought that feasibility of FRC-MPD thruster was showed.

Table 4. Temperature of permanent magnet.

Structure Number	Minimum Temperature, K	Maximum Temperature, K
1	908.1	1,033
7	822.5	911.9
8	927.8	1,029
9	721.2	759.7



V.Conclusion

The following results were obtained.

- FRC-MPD thrusters were designed and were carried out thermal analysis. In structure 1, temperature of permanent magnet was not decreased by thickness lack of the insulator. Therefore, to increase thickness of the insulator and to divide an insulator into a number of parts were executed in changing structure. Then, maximum temperature of permanent magnet could be decreased 110 K.
- Maximum temperature of permanent magnet was decreased 15 K by used high melting point materials. However, it was understood the contribution degree to the temperature drop of the permanent magnet by the materials change were thought be small.
- In structure 8, maximum temperature of permanent magnet was decreased 4 K by painting black and white paint. However, minimum temperature was increased 20 K. In structure 9, maximum temperature of were decreased 150 K, and minimum temperature was decreased 101 K. It is said that painting black and white paint was much effected to decrease temperature of permanent magnet by these results. And, it is thought that feasibility of FRC-MPD thruster was showed.

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