Performance Tests on the Electromagnet of Secondary CRA Gripper System of the PGSFR

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1. Introduction

The Prototype Gen-IV SFR (PGSFR) adopts a passive shutdown design concept, which is combined with a group of secondary control rod drive mechanisms (SCRDM). The system automatically releases the control rod assembly (CRA) around the set temperature in an emergency condition of the reactor, and then drops the CRA by gravity without any external control signals and any actuating power[1,2].

This paper describes the design of a passive shutdown system consisted of a thermal expansion device and an electromagnet. The electromagnet design concept for gripping and releasing the secondary control rod assembly is also suggested, and the several functional tests of the electromagnet are performed in the high temperature environment condition, and the test results are presented.

2. Design concept of passive shutdown system

The passive shutdown system of SCRDM consists of a thermal expansion device, an electromagnet to hold or trigger off the CRA, and an armature attached on CRA extension rod head. The passive shutdown system located at bottom end of the SCRDM driveline uses the thermal expansion function and electromagnetic force. The driver motor, stroke seal bellows, bushing and head support concepts of the SCRDM, as represented in Figure 1, are same as those of the primary control rod drive mechanism. The main differences between them are the CRA gripper type and the electromagnet location.

2.1 Design Requirements and Materials

The design conditions of the mechanical parts of the passive shutdown system are listed in Table 1.

When the core exit temperature of the primary sodium goes up around the set point, the thermal expansion device expands and pushes the CRA head down, the magnet flux gap between the electromagnet stator bottom and the armature of the CRA head top is then enlarged and the electromagnetic force holding a CRA is weakened, and the CRA drops into the reactor core by its deadweight.

The materials of the SCRDM components are represented in Table 2. The drive shaft in the region of the thermal expansion device is made of an Inconel 718.

2.2 Thermal Expansion Device

The length of the thermal expansion device is about 2.86 m, which will be fixed based on the coolant temperature transients of the reactor operation bases. The diameter is limited by a control assembly duct inner space of 100 mm in diameter. The outer diameter of the thermal expansion device is determined by 90 mm taking into account a clearance of 5 mm. The design concept is represented in Figure 2.

The inner diameter at the lower region is 86 mm. The length is about 1.181 m. The inner and outer diameters of its upper region are 64 mm and 70 mm, respectively. The region extends to below the bushing device, and the whole length is 2.86 m long.

Thermal expansion coefficients of the thermal expansion device are represented in Table 3. The total expansion difference between SS316 and Inconel 718 is expected to be about 1.7 mm ~ 2.6 mm when the environment sodium temperature rises up about 100^{o}C ~ 150^{o}C more than the normal operation temperature. The calculation results are as follows;

$$1.7 \text{ mm} = \sim (6.0 \times 10^{-6} /^oC) \times (100^oC) \times (2.86 \text{ m}).$$
$$2.6 \text{ mm} = \sim (6.0 \times 10^{-6} /^oC) \times (150^oC) \times (2.86 \text{ m})$$

The basic behaviors of the passive shutdown system depending to the environment temperature are represented in Figure 3. An additional design parameter study to trigger off the CRA is going on.

2.3 Electromagnets

The electromagnet is located in a limited space and submerged in high temperature sodium environment. The installation space for the electromagnets is allowed by 80 mm in diameter, and about 300 mm in length. The design concept is shown in Figure 2. The electromagnet cores enclose the coil and protect the sodium ingress into the coil. The inside diameter of the outer core is 66 mm. The outer diameter of the inner core is 49 mm. The electromagnet coil is a circular type wire with a mineral insulated stainless sheath [3,4].

A power of DC ~ 15V and 7.5A is supplied on the coil. A total of 264 coil turns is available inside the electromagnet core, and the cross section of each coil is 1.54 mm^2. The ampere turns of 1,980 AT are calculated. The availability of the tentative sizing was checked [3].

The electromagnets are fabricated for the two kinds of core materials, in which the relative permeability values of the core materials are given. The test mockup is represented in Figure 4.

2.4 Secondary CRA Head

A magnetic circular plate is attached to the CRA extension rod top. The extension rod plays a role of the armature of the electromagnetic system.

The armature size is 60 mm in diameter, and the thickness is about 20 mm. The diameter at the redan of the extension rod is 74 mm, which is compatible with the bottom shape of the thermal expansion device, as shown in Figure 2.

3. Performance Tests of Electromagnets

The electromagnetic forces on the CRA head with a 1 mm air gap are in the range of ~ 30 kg_f. Thus, the thermal expansion difference of the thermal expansion device to trigger off the CRA shall be controlled within 1 mm at the setting temperature. Design feasibility tests using the several test mockups of the electromagnets are being performed[4].

The electromagnetic forces on the CRA head are tested by changing the design parameters such as the coil supply currents, the gap size between the electromagnet static core and the moving armature of the CRA head.

The electromagnetic force test results for the several cases in Table 4 are represented in Table 5 and Figure 5. The electromagnetic forces are existed in the range of 5 kg_f to 260 kg_f depending on the gap sizes and core materials [4].

The electromagnet trigger-off time was tested for the several cases in Table 4 using the same method [5]. The average response time is 0.184 seconds in the case of using SS410 material as an armature, while the 2.25Cr-1Mo material as an armature has a response time of 0.16 seconds as shown in Figure 6.

The final acceptability of the electromagnetic response time data obtained by these tests will be evaluated with CRA drop test results because the control rod drop time should be within 1 ~ 2 seconds including the electromagnetic response time.

4. Summary

The application feasibility of the electromagnet of a passive shutdown system was verified based on several test results in point of view of the electromagnetic force and the response time. In future, the thermal expansion device system integrated with this electromagnet will be verified.

ACKNOWLEDGEMENT

This study was supported by the MSIP through its National Nuclear Technology Program.

REFERENCES

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[4] Lee, Jae-Han, “The first performance tests of a high temperature electromagnet of the PGSFR secondary CRDM, SFR-190-DM-458-004, 2015.07.
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Table 1 Design conditions of passive shutdown device

Parameters	Requirements
Installation space limit	< 100 mm in diameter
Gripper off mechanism	Bimetal thermal expansion difference : ~ 1.0 mm (operating temperature:600°C~650°C)
CRA mass	~ 50 kg
Gripper type	Electromagnet with solenoid coil

Table 2 Materials of CRDM passive shutdown device

No.	Components	Materials
1	Electromagnet coil	Cu
2	Electromagnets & armature	SS410 /2.25Cr-1Mo
3	Drive shaft corresponding to the thermal expansion region	Inconel 718 (or Mod9Cr-1Mo)
4	Thermal expansion device	SS316
5	Drive line guide tube	SS316

Table 3 Thermal expansion coefficients of thermal expansion device materials

	SS316		Mod.9Cr-1Mo (Inconel718)	
Temp [°C]	Thermal Expansion [E-6 mm/mm/°C]	Thermal Conductivity [W/(m°C)]	Thermal Expansion [E-6 mm/mm/°C]	Thermal Conductivity [W/(m°C)]
425	19.6	20.1	13.4(14.13)	27.9(17.7)
450	19.8	20.5	13.6	27.9
475	20	20.8	13.7	27.9
500	20.2	21.2	13.8	27.9
525	20.4	21.5	14.0(14.4)	27.9(19.4)
550	20.6	21.9	14.2	27.8
575	20.9	22.2	14.4	27.7
600	21.1	22.6	14.6	27.6
625	21.4	22.9	14.9(14.9)	27.5(21.2)

Table 4 Test cases of electromagnets according to the design parameter variations

Test type	Test No	Index	Material	Test temp. [°C]	Current [A]	Gap [mm]
1	4	SS410-20-7.5	**core** : SS410 **armature**: SS410	20	7.5	0
2	5	SS410-600-15		600	15	0
3	7	SS410-600-7.5		600	7.5	0
4	6	2.25Cr-1Mo-20-7.5	**core** : SS410 **armature** : 2.25Cr-1Mo	20	7.5	0
5	5	2.25Cr-1Mo-20-15		20	15	0
6	8	2.25Cr-1Mo-600-7.5		600	7.5	0
7	6	2.25Cr-1Mo-20-7.5		20	7.5	0.3
8	5	2.25Cr-1Mo-600-7.5		600	7.5	0.3

Table 5 Electromagnetic forces according to design parameter variations

	Gap of fixed core and armature (mm)	Temperature(°C) / Coil current					
		20 (7.5A)	20 (15A)	200 (7.5A)	200 (15A)	600 (7.5A)	600 (15A)
A	0	> 220	> 260	225 ~240	> 260	210~220	215~240
B	0.3	95 ~115	130 ~145	95 ~120	145 ~155	97 ~108	142~156
C	0.6	43 ~ 55	80 ~ 95	48 ~ 52	87 ~ 91	48 ~ 51	83 ~ 89
D	1.0	22 ~ 24	40 ~ 45	20 ~ 22	42 ~ 44	19 ~ 21	42 ~ 44
	Test type #1,2,3, **Armature(SS410)**, Coil turns (256T), Electromagnetic force (Kg_f)						

	Gap of fixed core and armature (mm)	Temperature(°C) / Coil current					
		20 (7.5A)	20 (15A)	200 (7.5A)	200 (15A)	600 (7.5A)	600 (15A)
A	0	> 230	> 260	> 230	> 260	230~243	> 260
B	0.3	93 ~111	161~165	-	-	106~114	146 ~152
C	0.6	49 ~ 54	89 ~ 95	56 ~ 61	93 ~ 97	49 ~ 56	87 ~ 94
D	1.0	23 ~ 24	45 ~ 48	22 ~ 24	46 ~ 47	20 ~ 21	44 ~ 46
	Test type #4,5,6, **Armature(2.25Cr-1Mo)**, Coil turns (256T), Electromagnetic force (Kg_f)						

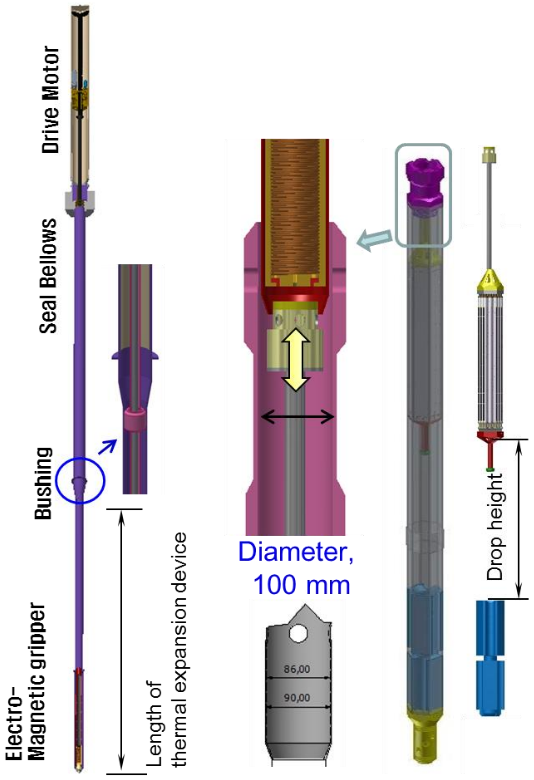

Fig.1 Design concepts of the passive shutdown system and secondary control rod drive system

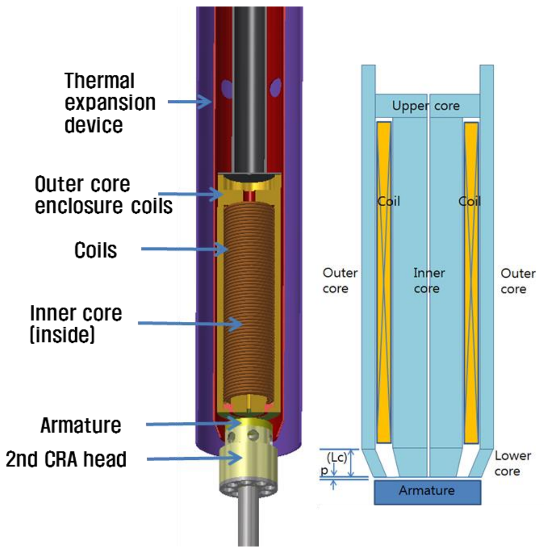

Fig.2 Design concept of electromagnet and thermal expansion device

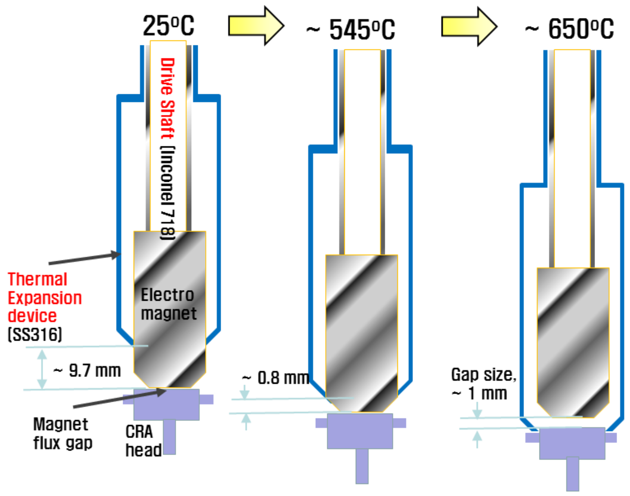

Fig.3 Basic behaviors of thermal expansion device depending on the environment temperature

Fig.4 Test mockup of electromagnet

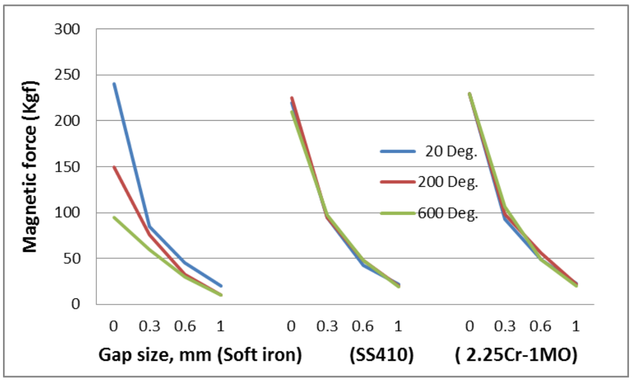

Fig.5 Electromagnetic forces on CRA head of a passive shutdown system

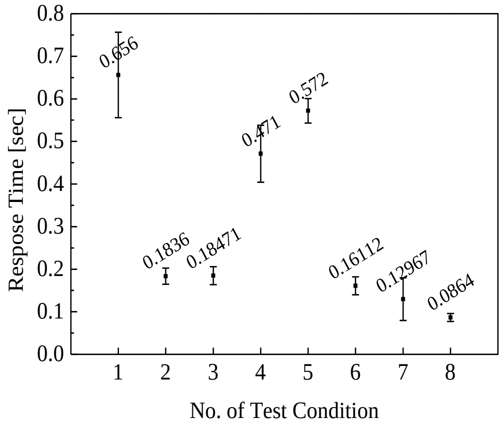

Fig.6 Trigger-off response time of the electromagnet of the secondary control rod drive system