Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 29-30, 2015

Numerical Analysis for Heat transfer characteristic of Helium cooling system in Helium cooled ceramic reflector Test Module Blanket (HCCR-TBM)

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1. Introduction

Nuclear fusion energy has advantage in terms of safety, resource availability, cost and waste management. There is not enough experimental results about the fusion reactor due to the severe experiments restrictions like vacuum environment, plasma production and significant nuclear heating at the same time. Much research and time is required for the commercial fusion reactor. For technical verification against the commercialization of fusion reactor, 7 countries which are EU, USA, Japan, Russia, China, India, and South Korea are building an ITER in the south of France.

The main objectives of ITER project can be summarized into three types as follows [1]

- Plasma operation for a long time
- Large tokamak device technology
- Test blanket module (TBM) installation and verification

Helium cooled ceramic reflector (HCCR) test blanket module (TBM) is composed of four sub-modules and a common back manifold (BM). The HCCR TBM is cooled by a high-temperature helium coolant of 300 ºC. The breeder, a neutron multiplier and reflector are included in the HCCR TBM. TBM is essential device to verify the tritium production and the heat extraction. The continuous deuterium-tritium (D-T) reaction should occur in order to generate heat and neutrons. The generated neutrons will react with lithium which is breeder. As a result of this reaction, tritium and other neutron are generated. The newly created tritium will be transported and stored in the separated space. This tritium will be injected into the vacuum vessel and consumed by D-T reaction. He flowing inside TBM removes the heat from the structure directly facing the plasma and TBM itself. The extracted heat will be used to generate the power. The integrity of the TBM could be ensured by maintaining at the allowable temperature. The performance of the TBM determines the feasibility of the fusion reactor. The countries involved in the ITER project is independently developing TBM. The breeding material related to the tritium production could be divided into liquid and solid type. Beryllium is normally selected as a neutron multiplier. Additionally, lithium lead has been studied to perform two kinds of roles which are a breeder and a neutron multiplier at the same time in EU [2]. It is the helium cooled lithium lead (HCLL) TBM. Generally, He is used as the coolant for TBM. There are unique cases. Pressurized light water is used as the coolant for TBM in Japan [3]. Additionally, liquid lithium is used for breeder lithium TBM in Russia [4]. In South Korea, lithium, beryllium and helium are used as the breeder, the neutron multiplier and the coolant respectively in the pebble bed shaped compound. This type technology has high reliability because these materials has been studied in many countries and there are plenty of study results. An optimized arrangement for a breeder, a neutron multiplier could be determined by analyzing the neutron dynamics. However, if there is not proper cooling performance in TBM, the temperature for each components could be more than limit temperature. In conclusion TBM would be damaged and not be able to function properly.

In this work, the maximum temperature was confirmed and evaluated in the TBM by using the Computational fluid dynamics (CFD). New cooling channels were proposed to improve the cooling performance. Additionally, the sensitivity study about the He velocity was performed.

2. Numerical Analysis

CFD code, ANSYS-CFX 14.5 was used to evaluate the thermal performance of the HCCR TBM. Figure 1 shows the overview of TBM-set [5]. The He coolant is injected from the back of the TBM-shield. He flows the 3 first-wall (FW) regions, 2 side-wall (SW) regions and 3 breeding-zone (BZ) regions. The energy level of He coolant in the 2nd SW is the highest in terms of thermal dynamics. The estimated region with the highest temperature would be 3rd BZ. The breeding material generates the heat when the neutron reacts with the lithium. Although the power density of the 3rd BZ region is lower than other BZ regions, the temperature of the breeder material is the highest due to the heated He coolant. The required temperature for each material is shown in Table. 1 [6]. The coolant channel in the BZ regions are a simple hole. The diameter and the length of the channel is 7mm and 201mm. The total 68 channels are vertically arranged with two pairs of channels. Thermal-hydraulic analysis was performed only in a channel with surrounding material.

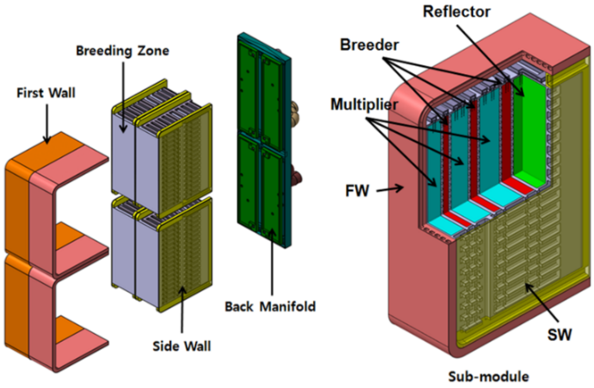


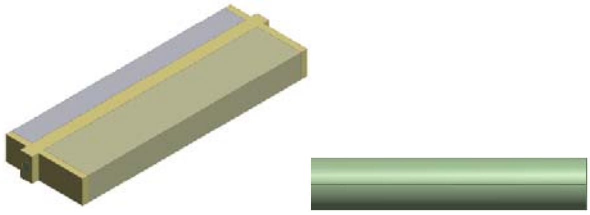
Fig. 1. Exploded and internal view of the HCCR-TBM

Table I: Selected materials for each TBM-set component and their requirements

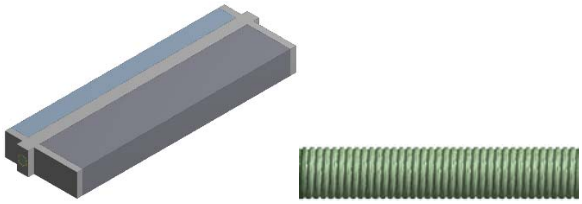
Components	Materials	Requirements
Structural material	KO-RAFM steel	300 °C ~ 550 °C
Breeder	Li$SiO4 pebble bed	<920 °C
Multiplier	Be pebble bed	<650 °C
Reflector	Graphite Pebbles bed	<1200 °C
Coolant	He (8 MPa, 300~500 °C)	

2.1 Geometry and mesh

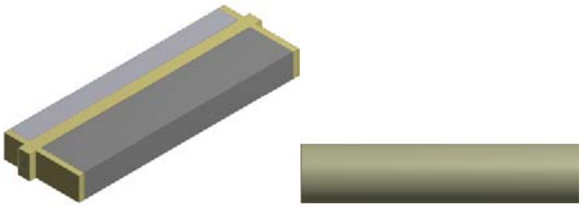
The 3 types of geometry were depicted in Fig. 2. Figure 2.(a) shows the present channel design. Half the entire shape of the breeder and a multiplier region was exactly displayed based on the volume of adjacent channel. Proposed new channel design is describe in Fig. 2. (b). Inner surface of the channel is manufactured with the screw shape [7, 8]. Inner diameter and the pitch of the channel is 6mm and 1mm, respectively. The thread overlap is 0.541 mm. This dimension follows ISO standard (Metric Thin Pitch). The equivalent diameter of the channel with screw shape is similar with that of the Fig. 2. (a). However, the heat transfer area between the He coolant and the structure is different. The heat transfer area of the Fig. 2. (b) is enlarged about 18%. The diameter of the channel in Fig. 2. (c) is 8.23mm. This channel is a simple geometry. This channel geometry was presented in order to verify the effects of radial expansion in the channel. The channel with a twisted tape was depicted in Fig. 2. (d). The swirl flow was studied as one of the enhancing the turbulent flow. The mesh quality of the Fig. (a), (b), (c) and (d) is min.: 0.209/avg.: 0.646, min.: 0.114/avg.: 0.830 and min.: 0.249/avg.: 0.644 and min.: 0.112/avg.: 0.840, respectively.



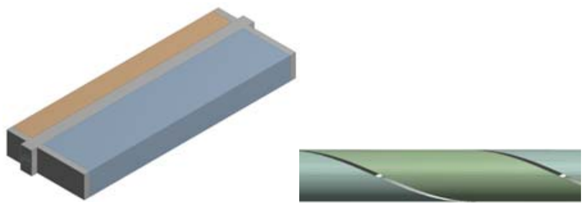
(a) Case 1, simple channel (7 mm)



(b) Case 2, channel with a screw surface (7 mm)



(c) Case 3, simple channel (8.23 mm)



(d) Case 4, channel with a twisted tape (7 mm)

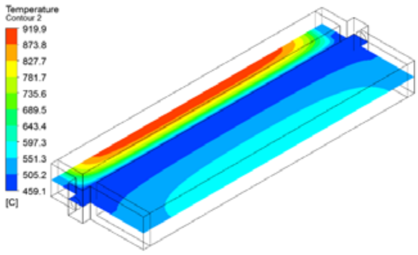
Fig. 2. Geometry of the channels

2.2 boundary condition

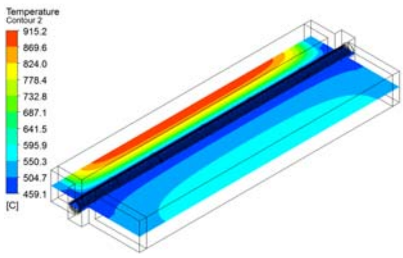
Mass flow of the He coolant is designed as 1.064 kg/s. It is equivalent to about 75 m/s in the present design channel. The inlet velocity is set to 75m/s and 7.5m/s. The inlet temperature of the He coolant is 459.1 °C. A small square box means the component including the breeder. A relatively large box means the beryllium component. 3 surfaces of each box is restricted as the interface. The boundary condition of others is set to a symmetry surface. The power was generated in two box. The specific power density value was set with reference to the nuclear heating data [9]. The reduced activation Ferritic/Martensitic (RAFM) steel is used as structural material for TBM. All thermo-physical properties of the material was generated by using the described reference [10]

2.3. Result and discussion

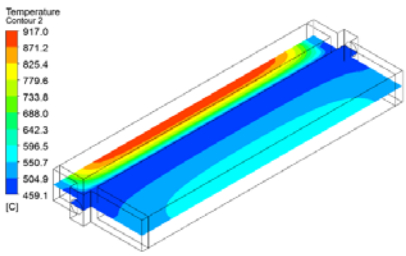
Temperature distribution on the cross-section is depicted based on the channel in Fig. 3. Table 2 shows the summary of the analysis results for all cases. The allowable temperature of the breeder is 920 ^oC. In case 1 and 3, there is no margin to the required temperature in the breeder material. The enlarged heat transfer area is minor in comparison with Case 1 and case 3. The pressure drop is noticeable decrease when the flow channel is enlarged at the same velocity condition. The results of case2 is interesting. The maximum temperature is about 915 ^oC which is lower about 5 Kevin compared with that of Case 1. The maximum temperature of the case 4 is 907 ^oC.



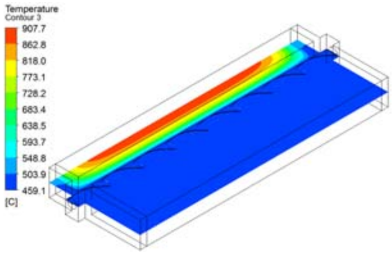
(a) Case 1, simple channel (7 mm)



(b) Case 2, channel with a screw surface (7 mm)



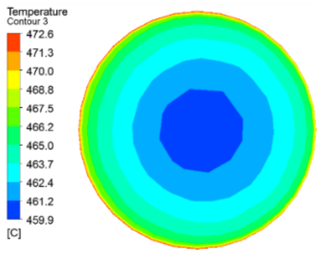
(c) Case 3, simple channel (8.23 mm)



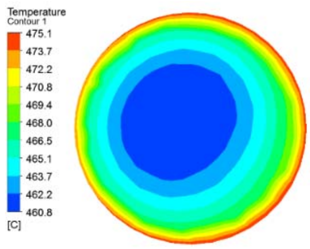
(d) Case 4, channel with a twisted tape (7 mm)

Fig. 3. Temperature distribution on the cross-section

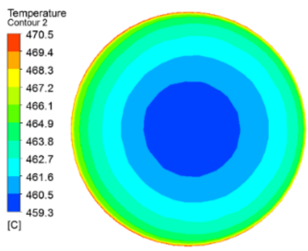
Figure 4 shows the temperature distribution on the outer surface of the channel. High temperature region was concentrated on the edge in case 1 and 3. High temperature region was relatively widely distributed in case 2 and 4 by considering the temperature range. Figure 5 show the why the temperature of the breeder material falls. The tangential vector to the flow direction was generated due to the swirl flow. The swirl flow accelerates the mixture flow in the channels. It leads the decrease of the temperature in BZ region.



(a) Case 1, simple channel (7 mm)



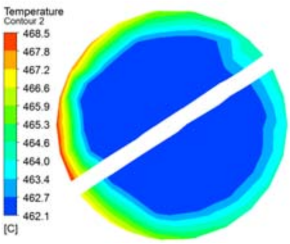
(b) Case 2, channel with a screw surface (7 mm)



(c) Case 3, simple channel (8.23 mm)

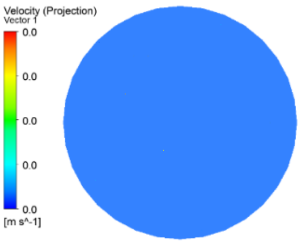
Table II: Summary of the results for all cases

	Case 1			Case 2			Case 3			Case 4		
	Max. Temp. in Li material (ºC)	Max. Temp. in Be material (ºC)	Pressure drop (Pa)	Max. Temp. in Li material (ºC)	Max. Temp. in Be material (ºC)	Pressure drop (Pa)	Max. Temp. in Li material (ºC)	Max. Temp. in Be material (ºC)	Pressure drop (Pa)	Max. Temp. in Li material (ºC)	Max. Temp. in Be material (ºC)	Pressure drop (Pa)
75 (m/s)	919.9	579.8	8924.1	915.2	581.2	37993	917.0	576.6	7439	907.8	468.8	21605
7.5 (m/s)	986.5	657.5	146	968.4	648.7	885.3	974.2	642.5	118	951.6	638.8	432.8

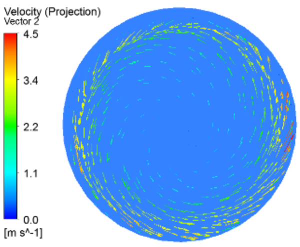


(d) Case 4, channel with a twisted tape (7 mm)

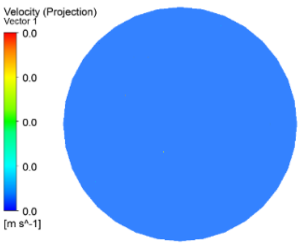
Fig. 4. Temperature distribution on the outer surface of the cooling channel



(a) Case 1, simple channel (7 mm)



(b) Case 2, channel with a screw surface (7 mm)



(c) Case 3, simple channel (8.23 mm)

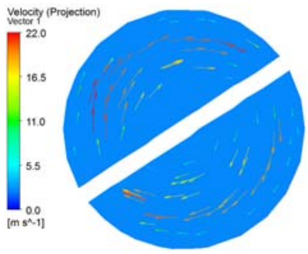


Fig. 5. Tangential velocity vector on the outer surface of the cooling channel

3. Further works

The thermal-hydraulic analysis was performed in the He cooling channel in the BZ region of the HCCR TBM. The maximum temperature in the breeder material is equal to the limit temperature in the present design cooling channel. New designed cooling channels were proposed to improve the cooling performance. The swirl flow accelerates the mixture flow in the channels. Additionally, the effects of the enlarged heat transfer area is effective. It leads the decrease of the temperature in BZ region. However, the temperature drop is minor. The continuous study to improve the cooling performance is required to ensure the thermal margin in the BZ zone.

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