Heat transfer characteristics of breeding zone in TBM of KOREA

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1. Introduction

In South Korea, lithium, Helium cooled ceramic reflector (HCCR) test blanket module (TBM) has been designed to install in ITER and verify the tritium production and the heat extraction [1, 2]. 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 °C. 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. Lithium, beryllium and helium are used as the breeder, the neutron multiplier and the coolant respectively in the pebble bed shaped compound. The group of these components was called as "breeding zone (BZ)" as shown in Fig. 1. The BZ was maintained with the highest temperature due to the nucleate heating on not only breeding material but also structure.

In this work, heat transfer characteristics of breeding zone in TBM was studied. Some ideas was discussed to reduce the maximum temperature of the breeding zone. Thermal-hydraulic analysis was performed with a conventional CFD code, ANSYS-CFX v14.5.

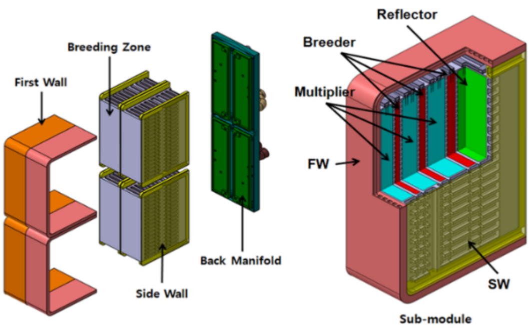


Fig. 1. Exploded and internal view of the HCCR-TBM (CD model)

2. Design Criteria for structural integrity

The required temperature for each material is shown in Table. 1 [3]. 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 34 channels are vertically arranged with two pairs of channels. The margin to the allowable temperature for the breeder have a little with the conceptual design model of HCCR-TBM as shown in Fig. 2. The cooling channels in the BZ should be improved to drop the maximum temperature.

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_2TiO_4 pebble bed	<920 °C
Multiplier	Be pebble bed	<650 °C
Reflector	Graphite block	<1200 °C
Coolant	He (8 MPa, 300~500 °C)	

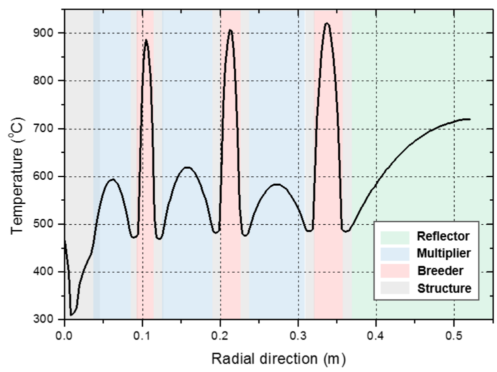


Fig.2 Temperature distribution on radial direction

3. Heat transfer in BZ

Heat transfer in BZ could be described as a thermal resistance circuit as shown in Fig. 3. Heat source of this system is the nucleate heating on the breeding material. Final heat sink is the helium coolant. This heat transfer is expressed like bellow Eq. (1) to Eq. (2). A number of thermal resistance factor is four.

$$Q = h_{al} A(T_s - T_\infty) = \frac{1}{R_{total}}(T_s - T_\infty) \quad (1)$$

$$R_{totla} = R_{con\ 21} + R_{cond\ 2} + R_{C.R} + R_{con} \quad (2)$$

$$R_{totla} = \frac{t}{k_p} + \frac{s}{k_w} + \frac{1}{h_{C.R}} + \frac{1}{h_c} \quad (3)$$

k_p and k_w are effective thermal conductivity of the pebble bed and thermal conductivity of wall. T is absolute temperature. t and s are the thickness of the pebble bed region and the wall. $R_{C.R}$ is contact resistance between the wall and the pebble. $h_{C.R}$ and h_c are heat transfer coefficient on the contact region of pebble beds and the cooling channel.

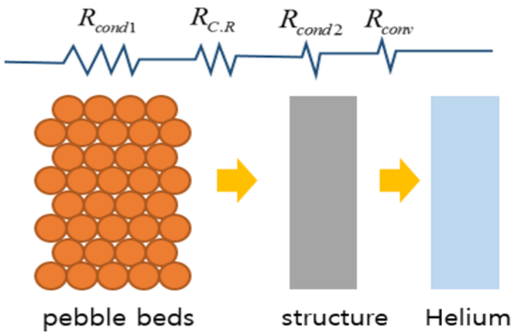


Fig. 3 thermal resistance circuit in BZ heat transfer

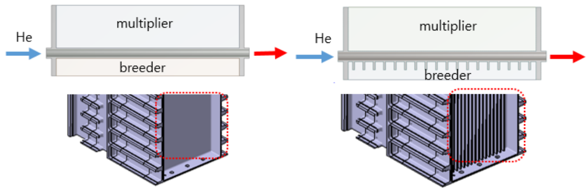
Thermal resistance was calculated based on the temperature of HCCR-TBM CD model in Table II. The major factors of the thermal resistance are R_{con1}, $R_{C.R}$. These are related to the pebble bed. The thermal conductivity of Li_2TiO_2 is about 3.6 W/mK [4]. The one of the pebble bed is about 0.763 W/mK. The heat transfer between the pebble beds and the wall is limited due to the pebble shape [5].

R_{con2} was calculated from the specific value of structure properties. It is difficult to improve the properties. The thickness of the wall is determined to ensure the integrity of the structure of the 8 MPa inner pressure and some loads. The change of R_{con2} is not interested.

R_{conv} was determined by the flow condition of helium coolant and the cooling channel geometry. The flow condition on the inlet flow channel is automatically determined. It is not controllable factor. The enlarged flow channel some devices to accelerate the flow mixing could be considered.

3. Enhancement of heat transfer

The improvement of the thermal conductivity for the pebble bed is limited. The amount of pebble beds is determined from the study of the neutronics analysis [6]. The volume of pebble bed is constant. The attachment of cooling fins was studied to reduce the distance between the heat source and the next heat transfer medium which is wall. This concept was described in Fig. 4.It is the equivalent effect of shortened thickness of s which is the thickness of the pebble bed region. Additionally, the amount of heat transfer between the pebble beds and the wall is increased. $R_{C.T}$ is the factor depending on the thermal conductivity of material. The $R_{C.T}$ would be constant regardless of enlarged heat transfer area. This is the just value of the unit area. The transferable total heat would be increased due to the cooling fins. Consequently, attachment of fins on the wall is positive to reduce the maximum temperature of breeding zone.



(a) Current cooling wall (2) Finned cooling wall
Fig. 4 The geometry of cooling wall in BZ

Some designs were studied to reduce the R_{cov}. Enlargement of heat transfer is positive effect to improve the heat transfer. The mixing effect of He coolant is also effective approach to low the temperature of the helium coolant near wall. However, the effect of these approaches is not noticeable [7].

4. Thermal hydraulic analysis

Figure 5 shows the geometry of analysis model and boundary condition. The 17 pairs of cooling channels is vertically located. Only one pair of cooling channel was determined as the analysis model by using the symmetric wall condition. The minimum mesh quality of this model is 0.249.

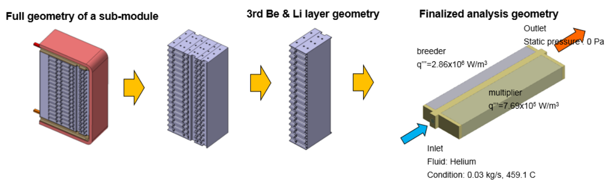
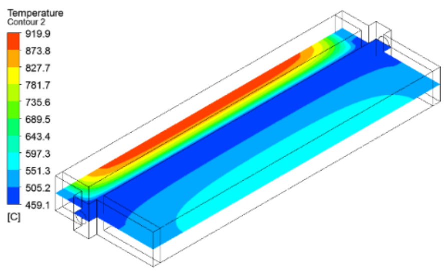
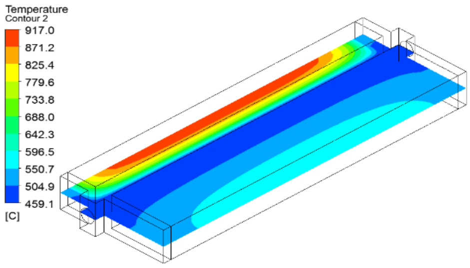


Fig. 5 Analysis model and boundary condition

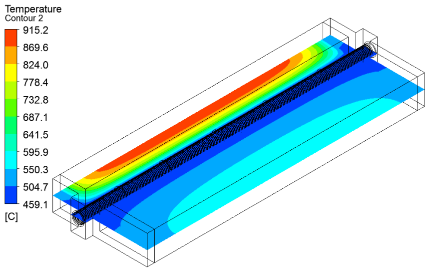
The temperature distribution on the geometry for all models was shown in Fig 6. The maximum temperature of current model is about 919.9 °C. When the twisted tape was inserted in the cooling channel, the heat transfer is enhanced. The maximum temperature of this model is 912.8 °C. Other cases which is focused on the cooling channel design have the negligible improvement on the cooling performance. The finned wall is effective to drop the maximum temperature of the breeder. When the fin is attached on the wall which is contacting with the breeder, the maximum temperature of the breeder is noticeably dropped about 78 °C. The temperature margin to allowable limit for the breeder material could be retained.



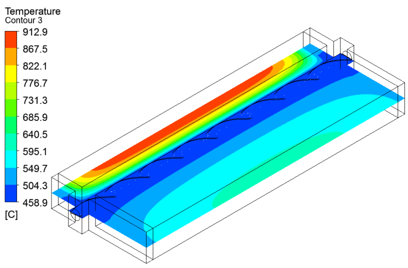
(a) Straight channel, 7 mm (reference model)



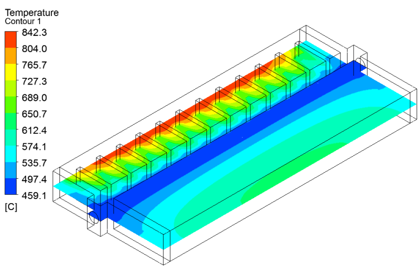
(b) Straight channel, 8.23 mm



(c) channel with a screw surface, 7 mm



(d) channel with a twisted tape, 7 mm



(e) Straight channelwith fins, 7 mm

Fig. 6. Temperatrue distribution on the oveall model

4. Conclusions

The margin to the allowable temperature for the breeder have a little with the conceptual design model of HCCR-TBM. Some feasible methods was discussed to lower the temperature of the breeding zone. The contact resistance between the wall and pebble beds was main factor to determine the breeder temperature. The installation of the cooling fins was considered to reduce the heat transfer resistance between the wall and the pebble beds. Thermal-hydraulic analysis was performed. The maximum temperature of breeder is reduced about 78 °C. It is enough margin to allowable temperature for the breeder material.

Acknowledgment

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