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Numerical simulation of a blanket cooling system for fusion reactor based on PWR conditions

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HIGHLIGHTS

► A reduced blanket module could match the PWR condition for a fusion reactor.
► There is a temperature rise (TR) issue in the blanket cooling system.
► FW channel plays an important role on the temperature rise.

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ABSTRACT

The simulations of a blanket cooling system were presented to address the choice of cooling channel geometry and coolant input data which are related to blanket engineering implementation. This work was performed using computer aided design (CAD) and computational fluid dynamics (CFD) technology. Simulations were carried out for the blanket module with a size of 0.6 m × 0.45 m in toroidal plane, and the nuclear heat was applied on the cooling system at P_n (neutron wall load) of 5 MW/m^2. The structure factors and input data of hydraulics were investigated to explore the optimal parameters to match the PWR condition. It was found that the inlet velocity of first wall (FW) channel should be within the range of 2.48–3.34 m/s. As a result, the temperature rise (TR) of the coolant in the FW channel would be 24–25 K. This leads to the remaining space for TR within the range of 15 K in the piping circuits. It also indicated that the FW plays an important role in TR (reaches 60% of the whole cooling system) due to its high level of P_n and heat flux in the zones. It was predicted that the nuclear heat inside blanket module could be removed completely by the piping circuits with an acceptable pipe bore and the related input data. Finally, a possible design range of cooling parameters was proposed in view of engineering feasibility and blanket neutronics design.

1. Introduction

Many candidates of coolants were considered for breeding blanket of fusion reactor [1,2]. Presently, the researchers proclaimed the PWR (pressurized water reactor, 290–330 °C, 15 MPa) water could be used as the coolant for solid breeding blanket, and they found the blanket tritium breeding ratio (TBR) of PWR condition could be sufficient for reactor tritium self-sustain [3,4]. However, whereas its range of TR was within 40 K, the major concerns would be focused on thermal hydraulics due to the consideration of blanket heat removal capability. Therefore, an effective design of blanket cooling system is required.

In this paper, a P_n value of 5 MW/m^2 was taken into account from the point of view of a fusion reactor, which could be used to check the cooling capability of PWR condition for a reactor. Its detailed analysis was presented both on the FW (first wall) channel and the piping circuits which play the main role of heat removal. The simulations were combined both with CAD and CFD technology using the codes like AUTOCAD, FLUENT, etc., which could provide a design methodology of the cooling system for a water-cooled blanket system.

2. Blanket cooling system

The cooling system of a water-cooled blanket consists of FW channel, piping circuits (pipe1 and pipe2), and header (water flow distributor), as shown in Fig. 1 [5,6]. The one layer cooling system is 0.6 m span in the toroidal direction, and the width

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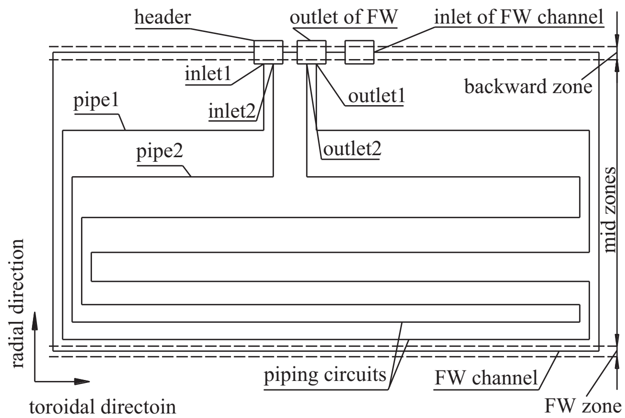

Fig. 1. Cooling system of water-cooled blanket.

is 0.45 m in radius direction. The height of blanket module is important for engineering design, because it is related to layout of blanket modules and the cooling system design of one whole sector inside vacuum vessel. In the blanket concept, a height of 0.5 m has been recommended, as shown in Fig. 2. The study would like to confirm the heat removal capability of the cooling system and the water conditions, so only one row pipes in a horizontal plane (radial–toroidal plane) were chosen.

The module size was determined based on the engineering consideration with an inlet velocity of 2–6 m/s and to match the PWR water condition. FW channel surrounds the blanket module from inlet to header. Inlet flow would go along with the FW channel to the header and was distributed into two branches, entering the pipe1 and the pipe2. Ignoring the header, the main function of the heat transfer capacity of the cooling system is dependent on the FW channel and the piping circuits. It is because of the heat exchange taking place in the coupled surfaces of the FW channel and the cooling tubes.

2.1. Key concerns and tasks

For the blanket cooling system, main concerns are focused on the followings: (1) whether the cooling circuit could match the PWR condition, (2) the feasible structure parameters, such as the size of FW channel, the cooling pipe bore, (3) the suitable input data, for example, the inlet velocity, the mass flow rate, etc. Thus, to determine or choose the optimal pipe bore and improve the capability of heat exchange efficiency would be more important for blanket design activities.

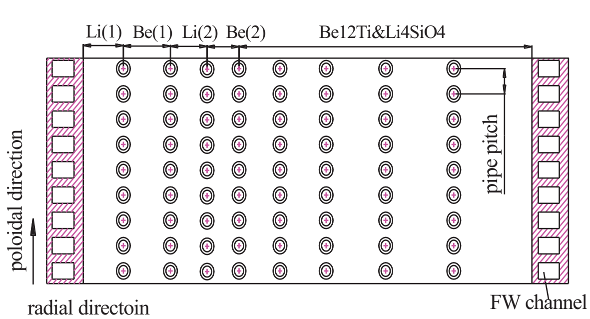

Fig. 2. A cross-section scheme for blanket interior.

3. CFD simulation

3.1. CFD models

The CFD models include the FW channels at first, whose total length is 2020 mm. The other one is the cooling tubes, which is divided into two piping circuits: the pipe1 and the pipe2, as shown in Fig. 1. The total length of the two piping circuits was 2894 mm and 2757 mm respectively, they were marked with the inlet1/oulet1 and the inlet2/oulet2. The equivalent diameter of FW channels were noted as the FWi (i = 6, 7, 8, 9, 10) which was arranged for the range of pipe bore of 6, 7, 8, 9, 10 mm (the wall thickness of pipe is 1.5 mm) corresponding to the equivalent inlet velocity (m/s) or the mass flow rate (MFR, kg/s) in the cooling tubes. They were designed based on parameter design method by using CAD technology.

To establish the CFD net model, the element hex/wedge was chosen in gambit (CFD pre-processing) for the regular zones, meshing with cooper method is one kind of net elements for the grid division, especially for those cylinder structures, such as cylinders and cylinder pipes.

Boundary layers are set for the fluid–solid coupled analysis between the solid zones of RAFM tubes and the coolant zones. The first node from the solid wall was located inside the log zone by using the wall functions method [7]. The absolute roughness was chosen as 0.05 for the inner surfaces of the cooling channels. For the calculations, the double precision calculator was chosen for the slenderness ratio model. The realizable K-epsilon model was adopted for the turbulence calculation with high Reynolds number ($Re \geq 2.88 \times 10^5$) model. The discretization of pressure was applied with "PRESTO!" scheme, because it can effectively inhibit the gradient of pressure in the discrete element.

3.2. Boundary condition

The water properties, such as the density (kg/m^3), the specific heat capacity (J/kg K), the thermal conductivity (W/m K), and the viscosity (Pa s) were assigned with the variable value of pressure and temperature correspondingly which could describe the dynamic properties of the water condition.

The nuclear heat (both neutron and gamma) was deduced by P_n equal to 5 MW/m^2. Since the distribution of the nuclear heat is as a downtrend from the FW surface to the backward area [8], for loading the nuclear heat in a simplicity way, an average value of the heat was thought of by applying in the three typical zones, the FW zone, the mid zone and the backward zone (as shown in Fig. 1), which assumed 60.5, 31 W/cm^3, and 1.83 W/cm^3 respectively. The heat flux on the surfaces of FW would be 1 MW/m^2 at this case. The inlet velocity of the FW channel was ranged from 2 to 6 m/s.

3.3. Analysis results

Generally speaking, the inlet temperature of the piping circuits would be the outlet temperature of header. So the calculations were divided to two phases, the first phase is for FW channel, and the second one is for piping circuits.

For the FW channel, it is shown the outlet temperature decreases with increasing equivalent diameter and with increasing inlet velocity. The overall range for the cases examined is from 330 °C to 300 °C, as shown in Figs. 3 and 4. The difference of the outlet temperature would be reduced when the equivalent diameter of FWi was broadened. But this effect would be shrunk at the case of FWi equal to FW8, and it is almost a law for all the cases of FWi of this blanket module. For example, this reduction would be very small and could be no difference between FW9 and FW10, as shown in

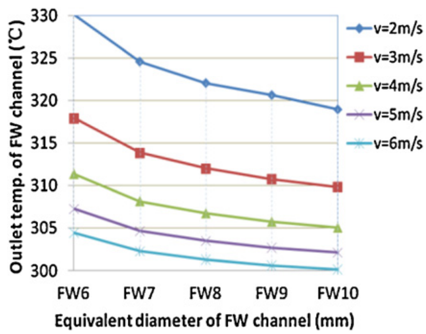

Fig. 3. Outlet temperature of pipe1.

Fig. 3. The TR trend and the variation of piping circuits would similar to the FW channel's, just the temperature values are different. This shows a case that there is a design limitation on the size of coolant channel (both FW channel and pipe bore). Next, the difference of the outlet temperature between the pipe1 and the pipe2 was found within 1 K due to the different pipe length. Since the pipe1 is longer, so the following comparisons would be based on pipe1's results.

To match the PWR condition, TR in the whole cooling system must be in the range of 40 K, and must be guaranteed the outlet temperature of piping circuits closed to 330 °C. In terms of this, the inlet velocity of FW channel should be suitable for the TR, and then the outlet temperature should not be so high to lead no reserved space for TR in the piping circuits. For example, when the FW channel is FW6 at an inlet velocity of 2 m/s, the outlet temperature of the FW channel reaches 330 °C, it is impossible taken a TR in the piping circuits keeping a normal PWR condition, because it has been break down due to outlet temperature far from 330 °C. To reckon the requirement, it was found when the outlet temperature of the piping circuits is around 330 °C, the outlet temperature of the FW channel must be controlled closed to 314 °C. The simulation results also confirmed this, and it is almost a law for all the cases of FW*i* of this blanket module, as shown in Figs. 3 and 4. And in this case, FW channel would occupy about 60% of the TR in the whole cooling system.

Next, to complete the TR both in the FW channel and the piping circuits, and also to match the PWR water condition, an required inlet velocity of the FW channel should be within the range of 2.48–3.34 m/s in theoretical calculation (as shown in Figs. 4 and 5), and resulted in the corresponding mass flow rates (MFR, kg/s), as shown in Table 1.

For the pressure drop, both the FW channel and the piping circuits play a non-linear growth along with the inlet velocity increase, as shown in Figs. 6 and 7. And also, it was found that the pressure drop would be decreased with the pipe bore expansion. But once the inlet velocity was less than 4 m/s, the downtrend would become more flat, especially for the case of 6 m/s, as shown in Fig. 7. In addition, the difference of the pressure drop of pipe1 and pipe2 is only around 1 kPa due to the difference of pipe length.

Based on these results, it is deduced that the lower pipe bore with a higher inlet velocity would assume higher pressure drop compared to the bigger pipe bore with a lower inlet velocity. For example, the pressure drop of pipe1 is 0.014 MPa for the pipe bore of 6 mm at an inlet velocity of 6 m/s, as shown in Figs. 6 and 7, but for the case of pipe bore of 10 mm at an inlet velocity of 2 m/s, the pressure drop would be lower than 0.015 MPa. If the pressure drop of the FW channel and the piping circuits was combined together, namely, FW channel plus pipe1, its value is 0.200 MPa, which is the maximum value of all the CFD combinations. However, for the

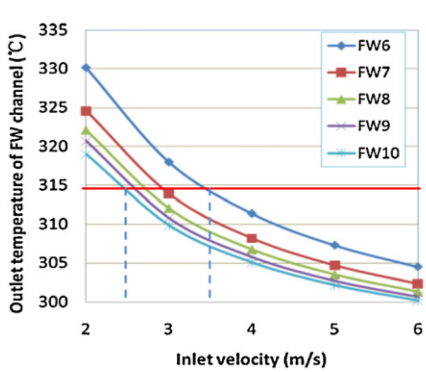

Fig. 4. Outlet temperature of FW channel.

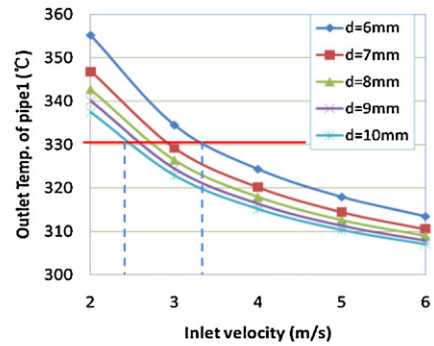

Fig. 5. Outlet temperature of pipe1.

Table 1
RP for PWR condition.

RP	Pipe bore				
	6	7	8	9	10 (mm)
FW*i*	8.5	9.9	11.3	12.7	14.1
Inlet velocity (m/s)	3.34	2.94	2.74	2.6	2.48
Required MFR (kg/s)	0.14	0.17	0.2	0.25	0.29

RP: required parameters.

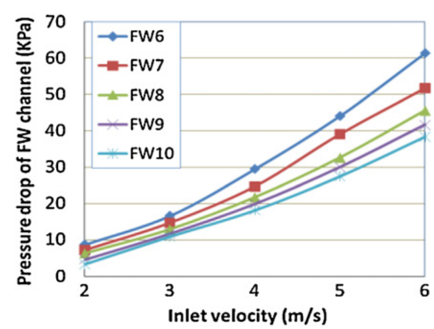

Fig. 6. Press drop of FW channel.

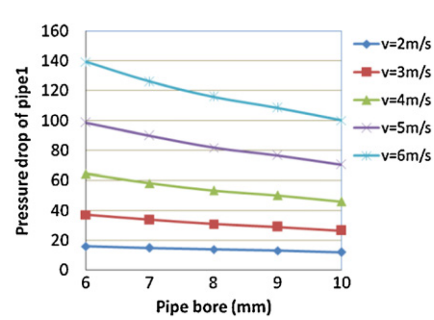

Fig. 7. Press drop of pipe1.

Table 2
ΔP (FW channel + pipe1, kPa).

d (mm)	V (m/s)				
	2	3	4	5	6
6	24.5	53.5	93.8	142.5	200.7
7	22.0	48.3	82.8	128.9	177.6
8	20.1	43.8	75.1	114.4	161.4
9	17.5	40.6	70.0	106.5	150.2
10	17.2	37.3	63.9	97.7	138.2

cooling system of a water-cooled blanket module, the pressure drop of the FW channel and the piping circuits would occupy the 96% or more of the total [5]. In proportionally, the maximum pressure drop of the cooling system was estimated on 0.2 MPa according to its total length. Coincidentally, the value is the design limitation of this blanket cooling system. Table 2 shows the total ΔP (pressure drop) of the FW channel and the pipe1 (d—diameter of pipe bore) for all cases.

3.4. Discussion

To accommodate the PWR water condition, the whole TR (40 K) would be distributed both in the FW channel and the piping circuits. It means when the inlet temperature of FW channel is assigned to 290 °C, the final outlet temperature of the two piping circuits must be controlled around at 330 °C. According to Table 1, if only consider the TR under PWR condition, all cases of the pipe bores would be acceptable with a reasonable inlet velocity. However, from the point of view of reducing pressure drop and the effect of the blanket TBR, the pipe bores must be reconsidered again although the TR issue of PWR condition was solved.

Firstly, for the pressure drop, it would be affected largely by the inlet velocity at high level ($\upsilon \geq 4$ m/s), as Figs. 6 and 7 shown, but for the cases of lower velocity, the effect is small. At the same time, the variation of pipe bore would influence the pressure drop at higher inlet velocity. It indicates when the inlet velocity is dropped to 3–4 m/s, the pipe bore factors to the pressure drop would be reduced to the lowest level. In practical, the case of pipe bore of 10 mm at an inlet velocity of 2 m/s has reached the design limitation. So, a pipe bore about 7–8 mm with an inlet velocity of 3–4 m/s would be more preferred in terms of engineering design.

On the other hand, once the heat removal capability is suitable for the blanket module, the lower pipe bore would have the priority. Since TBR issue is concerned related to the structure material occupation in the blanket module, thus the lower occupation of FW channel and the pipes would be benefit to obtain the TBR gain due to the amount of breeding material or multiplier material enhanced. In view of this, a relative low value of the pipe bore would be welcome as long as the heat removal capability could be guaranteed.

By the way, the input data of fluid parameters was limited in the case of this paper, once the layout of cooling system was changed, the results would be vary correspondingly. For this reason, a pipe bore in range of 7–8 mm and with an inlet velocity about 3–4 m/s were recommended based on the blanket module for the discussion. In other words, once the blanket module is outside the range of 0.6 m × 0.45 m in the toroidal plane, the possible diameter of pipe bore would be more than 8 mm and beyond the velocity of 4 m/s (P_n of 5 MW/m^2). Similarly, if the P_n value is less than 5 MW/m^2, the required input data would also be lower than the case of P_n of 5 MW/m^2.

4. Summary

(1) A cooling system size about 0.6 m × 0.45 m in toroidal plane could satisfy the heat removal for the blanket module based on PWR condition at P_n of 5 MW/m^2.
(2) When the equivalent diameter of FW channel or pipe bore is increased to 7 mm or more, the difference of outlet temperature would be decreased, and the diameter factor of coolant channel would be reduced.
(3) There is a TR issue in the blanket cooling system. For the PWR condition, the FW channel occupies about 60% of the total TR in the cooling system, and its outlet temperature would be required around 314 °C which could leave the TR space of 16 K for piping circuits.
(4) For the input data, a required inlet velocity of FW channel would be within the range of 2.48–3.34 m/s in theoretical calculation. In practical, a pipe bore of 7–8 mm with an inlet velocity of 3–4 m/s would be recommended for the blanket module in view of TBR or the pressure drop requirement.
(5) An optimization approach of a breeding blanket cooling system was established combined the CAD technology and the CFD method. It is not only for PWR condition, but also could be used for other coolant conditions.

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