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Cooling water system design of Japan's DEMO for fusion power production

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A B S T R A C T

Considering the water cooling system in fusion reactors, there are several fusion-specific challenges in designs of in-vessel components and their cooling water systems (CWS). In this research, solutions of the challenges have been discussed and indicate the CWS concept of Japan's DEMO. The CWS transfers thermal energy of blanket and a part of divertor to a generator system, and thermal energy of the other part of divertor is used as heat utilization in plant. The required performance of system devices such as pumps is expected to be achieved by proven technologies and its extensions. It is also indicated that blanket can work as the low-pass filter, and can suppress the effect of fusion output fluctuation. The designed cooling water system requires 70 MW electric power and generates 620 MW power with a 1.5 GW fusion power plasma. This research indicates the basic concept of Japan's DEMO CWS that can be practically achieved.

1. Introduction

As the coolant of the nuclear fusion reactor cooling systems, helium and water have been mainly considered. Helium cooling systems have the advantages such as multipurpose uses and no corrosion, but they require extremely fast coolant speed, and can dramatically increase pressure loss. Because of this, helium pumps require several hundreds of MW power [1,2]. On the other hand, water cooling systems have the efficient heat removal capability and this means that fast coolant speed is not necessary, and pressure loss and required pump power are much less than that of helium cooling systems. Additionally, water cooling systems have been used widely for a long time in fission reactors such as pressurized water reactors (PWR). Based on these background, water cooling system is adopted in Japan's DEMO. In spite of the proven technology of the fission reactors, handling water in a fusion plant is still premature and there are several fusion-specific challenges. Water cooled in-vessel components should be designed to satisfy the fusion-specific required functions such as tritium breeding in addition to heat removal performances. In such components, pipe arrangement will be complex, and the pressure loss in the components will be high. Thus, allowable pressure loss of pipes from the in-vessel components to pumps are decreased than that of existing fission reactors, and this makes the design of cooling water systems more challengeable. Additionally, the fusion output fluctuation should be considered. The fusion output is sensitive to temporal changes in the plasma parameters such as density or temperature and it is more difficult than existing fission reactors to keep the thermal output from the core constant. Thus, the effect to a turbine system should be evaluated.

This paper describes a way to deal with such issues related with water cooling and presents a feasible concept of water-cooled power plant. Section 2 describes the requirement and design of each in-vessel component. Section 3 shows the basic cooling water system design of Japan's DEMO. Section 4 discusses the effect of fusion output fluctuation to generated power. Section 5 evaluates the performance of Japan's DEMO cooling water system from the viewpoint of required power and the generated power. Section 6 is summary.

2. Water cooled in-vessel components

As the main parameter of Japan's DEMO, major radius is 8.5 m and fusion power is about 1.5 GW are assumed from resent reactor design research [3,4]. This energy is absorbed and cooled in the in-vessel components. The in-vessel components image are shown in Fig. 1. The following 4 in-vessel components are installed, blanket, divertor, back plate, and vacuum vessel. In this section, the design of these in-vessel components are described.

2.1. Breeding blanket

Blanket needs to produce tritium enough to meet self-sufficiency of fuel. In this point of view, each blanket module must be large as possible so as to reduce non-breeding zones such as gaps between the

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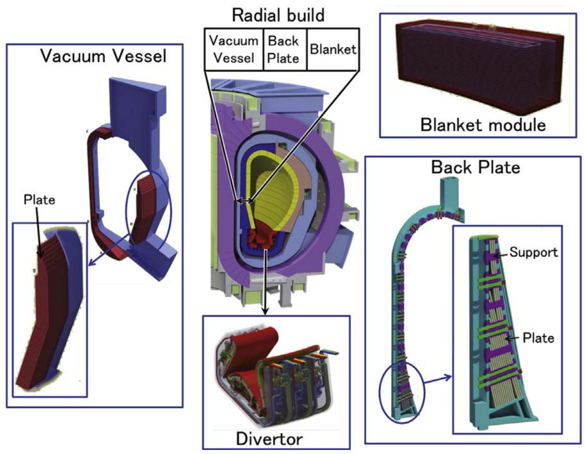

Fig. 1. In-vessel components image of Japan's DEMO.

neighboring blanket modules and rims of the blanket. To the contrary, it needs to be small as possible to withstand electromagnetic forces acting on disruption, as well. In order to balance these conflicting requirements, the blanket of our previous DEMO design SlimCS is segmented into modules with the size of 1.4–2 m (toroidal) × 0.5–0.6 m (poloidal) based on electromagnetic force analysis [5]. Inheriting this, the blanket module of Japan's DEMO has been designed. In addition to the module size, the internal pipe arrangement and the tritium breeding zone should be designed. From the viewpoint of manufacturability and inspectability, mixed Li_2TiO_3 and $Be_{12}Ti$ pebbles are bedded in the space other than the cooling pipe in Japan's DEMO blanket [6]. Cooling pipe are made of reduced-activation ferritic martensitic (RAFM) steel F82H [7]. At lower operation temperature of around 300 °C, irradiation embrittlement of RAFM steel becomes problem, thus, the required temperature is over 300° [8], and the water condition is considered to correspond to that of pressurized water reactor (PWR) [5,6]. The pipe arrangement is designed in order to satisfy the temperature limitation of the materials, the details are shown in Ref. [6].

2.2. Divertor

In 1.5 GW fusion DEMO, nearly 300 MW energy is transported to the divertor. Considering the nuclear heat by the neutron irradiation, the total required removal heat is over 400 MW. In Japan's DEMO, to remove this thermal energy, two different water cooling pipes are used, Cu-alloy (CuCrZr) and RAFM (F82H) [3]. Cu-alloy pipe is used in the inner and the outer divertor targets because of its efficient thermal conductivity. On the other hand, RAFM pipe is used in the other parts of the divertor, considering its lifetime in the neutron irradiation environment. The cooling water conditions in both pipes are determined as 5 MPa and 200 °C in the Cu-alloy pipe part, and 15.5 MPa and 295 °C in the RAFM pipe part. The water condition in divertor RAFM pipe part is same as that of blanket.

2.3. Back plate and vacuum vessel

The back plate is located behind the blanket and supports the blanket modules, and vacuum vessel is located behind the back plate by keeping high contact thermal resistance to the back plate, as shown in Fig. 1. To protect the superconducting coils from the neutrons, 30% of the total volume of the vacuum vessel and the back plate should be water. In the case that high pressure water is used, the problem is how to contain such a plenty of high pressure water in the back plate or vacuum vessel. One possible concept resolving this problem is that the cooling channels are produced by drilled a forged structure material (assumed as SUS316). This concept, however, requires the high cost and the other concept with low cost has not been proposed so far. Because of this, the low pressure water cooling is adopted, and the cooling channels are assumed to be produced by plate welding. In this case, the cooling water pressure of vacuum vessel is assumed to 1.1 MPa and the temperature is below 100 °C. The temperature of the back plate cooling water should be designed between the blanket temperature (about 300–550 °C) and the vacuum vessel temperature, and the pressure should be designed according to the temperature, considering the thermal stress between the in-vessel components. Thus, the back plate cooling water temperature is assumed nearly 200 °C and the pressure is nearly 3 MPa. These parameters will be updated according to the progress of the design researches of other issues.

3. Cooling water system design

3.1. Basic concept

Several concepts of water-cooled plant system have been proposed in Japan [9,10], but the discussion of their feasibility admits of improvement. In this section, the cooling water system (CWS) design of the 5 in-vessel components described in Section 2 is described from the viewpoints of the feasibility, cost and the power generation output. In addition to the water conditions (the temperature and the pressure), the thermal energy to be cooled in each component is necessary for the CWS design. The main factor of the thermal energy is nuclear heat. The neutrons birthed from the nuclear fusion reaction reach and heat each in-vessel component. In this calculation, energy multiplication factor of the neutrons are assumed to be 1.4. Considering the neutron shielding and dumping ratio calculated from the radial build, nuclear heat in the vacuum vessel and back plate is calculated. On the other hand, blanket, divertor RAFM pipe part and divertor Cu-alloy pipe part nuclear heat are calculated from their coverage ratio of the first wall. Additionally, for the calculation of thermal energy of blanket and divertor, surface heat load by the radiation and the plasma heat flux should be considered. Considering these factors, the required removal thermal energy of each in-vessel component is calculated. The water conditions and the thermal energy to be cooled in each component in each component are shown in Table 1.

The water conditions of back plate and vacuum vessel are temporary values. The cooling water conditions in blanket and divertor RAFM pipe part are same as that of PWR, thus, their thermal energy is used for power generation and their CWS are integrated with a heat exchanger (HX). Their thermal energy is not directly transported to a steam generator (SG) but via an intermediate HX (IHX). In this case, IHX is used as a tritium barrier. The diagram image is shown in Fig. 2. Divertor Cu-alloy pipe part CWS is not suitable for the power generation because the allowable water temperature of divertor Cu-alloy pipe part CWS is nearly 200 °C and this is far from the suitable SG water temperature (nearly 280 °C) [11]. Because of this, divertor Cu-alloy pipe part needs individual CWS and its thermal energy should be used as heat utilization in plant. Back plate and vacuum vessel CWS integration also has been considered. Their cooling water conditions are relatively close, and using a flow rate control valve, it may be possible to integrate them. In addition to these CWSs, purification volume control systems (PVCS) are needed to manage the water quality.

Table 1
Cooling water conditions and thermal energy of each in-vessel component.

Component	Temperature	Pressure	Thermal energy
Blanket	290–325 °C	15.5 MPa	1574 MW
Divertor (RAFM)	290–325 °C	15.5 MPa	291 MW
Divertor (Cu-alloy)	200–230 °C	5 MPa	172 MW
Back plate	200–210 °C	3 MPa	16 MW
Vacuum vessel	100–105 °C	1.1 MPa	0.043 MW