Estimation of the Pumping Power of the Liquid Metal Divertor REVOLVER-D for the LHD-Type Helical Fusion Reactor FFHR-d1

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The required pumping power for the liquid metal ergodic limiter/divertor REVOLVER-D (Reactor-oriented Effectively VOLumetric VERtical Divertor), which is considered as an optional divertor design for the LHD-type helical fusion reactor FFHR-d1, has been estimated with a consideration of the change in the strength of transverse magnetic field along the flow channel. It is found that the pressure drop and the required pumping power can be suppressed to an acceptable level by using insulated ducts.

Keywords: liquid metal, divertor, pressure drop, pumping power, heliotron, reactor

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1. Introduction

One of the most critical issues in the design of future fusion reactors is plasma exhaust. Most designs including International Thermonuclear Experimental Reactor (ITER) adopts the divertor components with a solid target. However, the maximum allowable steady-state heat load for such a solid target is limited to less than 10 MW/m^2 even if the combination of refractory target material (e.g., tungsten) and heat sink material with a high thermal conductivity (e.g., copper alloys) is used. Because copper alloys have a short lifetime under the irradiation of fusion neutrons, the use of reduced activation ferritic steel is considered. In this case, however, the allowable heat load becomes even lower. To reduce the heat load on the divertor target, impurity gas seeding is considered. In this case, a large fraction of the heat which flows into the divertor region needs to be radiated and compatibility with core plasma purity thus is not easily achieved. Several issues also remain unsolved: continuous pumping, maintenance and reduction of radioactive wastes. To conquer these issues, a new concept of the liquid metal limiter/divertor, REVOLVER-D (Reactor-oriented Effective VOLumetric VERtical Divertor), has been proposed [1] as an option for the helical fusion reactor FFHR-d1 [2], which is based on the achievements in the Large Helical Device (LHD). In this concept, multiple free-falling jets of liquid tin stabilized by inserted flow resistance (e.g., chain, tape, etc.) are used as a target. The neutralized gas can be easily pumped out through the gap between the jets. The maintenance work is also drastically simplified. On the other hand, there are several issues that need to be solved in order to realize this concept, e.g., heat removal, MHD effect, compatibility with a structural material, etc. Though the effect of tin vapor on the core plasma performance is another concern, the impurity shielding effect found in LHD experiment [3] will be a solution. The details of the design and discussions for the issues of REVOLVER-D are given in Ref. [1]. This paper focuses on the examination of the required pumping power to circulate liquid tin. The geometry of flow channel, calculation method and calculation condition are described in Sec. 2. The result of the calculation is given in Sec. 3.

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2. Geometry of the Flow Channel and Calculation Method

Figure 1 shows the side view of the helical fusion reactor FFHR-d1 equipped with the REVOLVER-D. The major radius of FFHR-d1 is 15.6 m and there is a large space (inner radius of about 6 m) inside the torus. Although the detailed design of the devices required for the REVOLVER-D (liquid metal pumps, vacuum pumps and heat exchangers) has not been completed yet, this space is considered to be able to accommodate these devices. FFHR-d1 has 10 periods symmetry in toroidal direction and jets are placed at the inboard side of 10 sections of horizontally elongated plasma cross-section. The radial position of jets is adjusted to pass the ergodized layer of the magnetic field which surrounds the core plasma. Because the connection length of the magnetic lines of force in this ergodized layer is much longer then the torus perimeter, all plasma particles will hit any one of these jets before entering the region with open field lines. Thus, discrete placement of 10 jets will work for the divertor of the entire region of the torus. Liquid tin is pumped up through a vertical duct (B to C in Fig. 2) located at the torus' inner

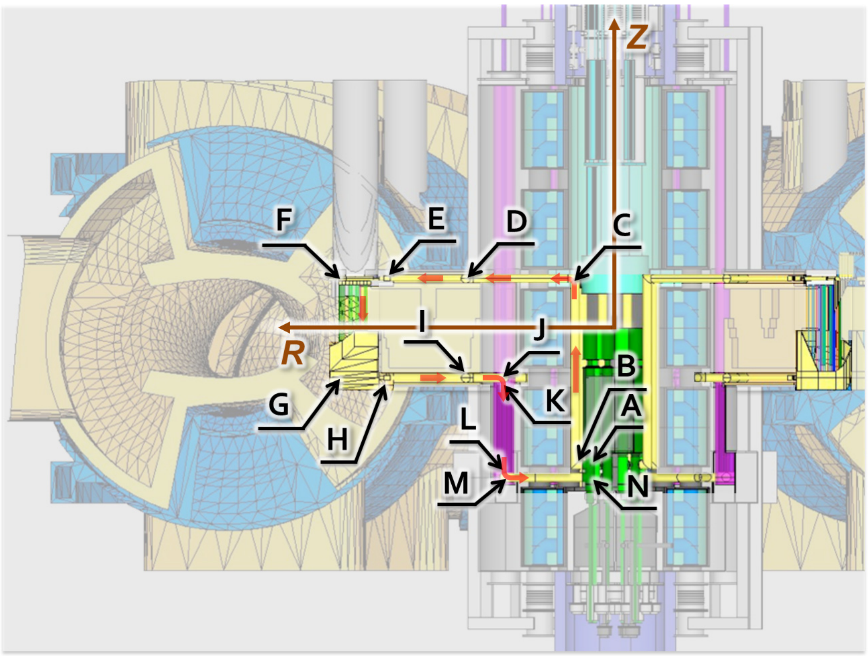

Fig. 1 Side view of the helical fusion reactor FFHR-d1 equipped with the REVOLVER-D. The flow direction of molten tin is denoted by red arrows.

space by electromagnetic pumps (the outlet of the pump is denoted by A) and sent to the top of the jet position through horizontal ducts (C to F). Liquid tin then flows out from multiple nozzles and becomes free-surface vertical jets. All jets are collected into the pool (G). Then liquid tin is sent into the heat exchanger (between K and L) in order to remove the heat from the plasma and the liquid tin is sent back to the pump (N). Because FFHR-d1 is a heliotron system in which confinement magnetic field is generated by the external coils with a steady-state current, there is no time variance in the magnetic field enclosed by the liquid tin loops. In the sections A–D, I–K and L–N the flow channel consists of a single duct with the inner diameter of 0.36 m. In the sections D–E and H–I, the flow channel consists of 5 ducts with 0.18 m inner diameter. In the section E–F, the flow channel consists of 5 ducts with 0.12 m inner diameter. The number and diameter of the jets are 280 and 0.012 m, respectively.

Generally, the power required to pump the fluid with volumetric flow rate $\dot{V}$ is calculated by the following formula

$$P_{\text{pump}} = \Delta p_{\text{total}} \dot{V} / \eta_{\text{pump}}, \tag{1}$$

where Δp_{total} and η_{pump} are total pressure drop and pump efficiency, respectively. The total pressure drop Δp_{total} is described as

$$\Delta p_{\text{total}} = \Delta p + \sum_i \zeta_i \frac{\rho v^2}{2} + \rho g H, \tag{2}$$

where Δp, ζ_i, ρ, v, g and H are pressure drop by duct friction including MHD effect, loss coefficient for the change in the duct geometry and other loss factors (e.g., valves, diagnostic tools, etc.), density of the fluid, flow velocity, acceleration of gravity and static head. For the pressure drop by duct friction, we used two formulae. One is the pressure drop by conductive circular ducts [4]

$$-\frac{\mathrm{d}p}{\mathrm{d}x} = K_{\text{p}} \sigma_{\text{f}} v_0 B_0^2, \tag{3}$$

$$K_{\text{p}} = \frac{C}{1+C}, \tag{4}$$

$$C = \frac{\sigma_{\text{w}} \left(R_{\text{out}}^2 - R_{\text{in}}^2\right)}{\sigma_{\text{f}} \left(R_{\text{out}}^2 - R_{\text{in}}^2\right)}, \tag{5}$$

where σ_{w}, σ_{f}, v_0, B_0, R_{out} and R_{in} are electric conductivity of the duct wall material, electric conductivity of the fluid, flow velocity of liquid tin, transverse magnetic field strength, outer diameter of the duct and inner diameter of the duct, respectively. The other formula is the pressure drop by insulated circular ducts [5]

$$-\frac{\mathrm{d}p}{\mathrm{d}x} = \frac{\frac{3\pi}{8} \mu v_0 \mathrm{Ha}}{\left(1 - \frac{3\pi}{2\mathrm{Ha}}\right) R_{\text{in}}^2}, \tag{6}$$

where μ is viscosity of the fluid and Ha is Hartmann number:

$$\mathrm{Ha} = \left(\frac{\sigma_{\text{f}}}{\mu}\right)^{\frac{1}{2}} B_0 R_{\text{in}}. \tag{7}$$

Note that both equation (Eq. (3) and Eq. (6)) are valid under a certain condition. Equation (3) assumes that the velocity distribution is uniform over the duct cross-section

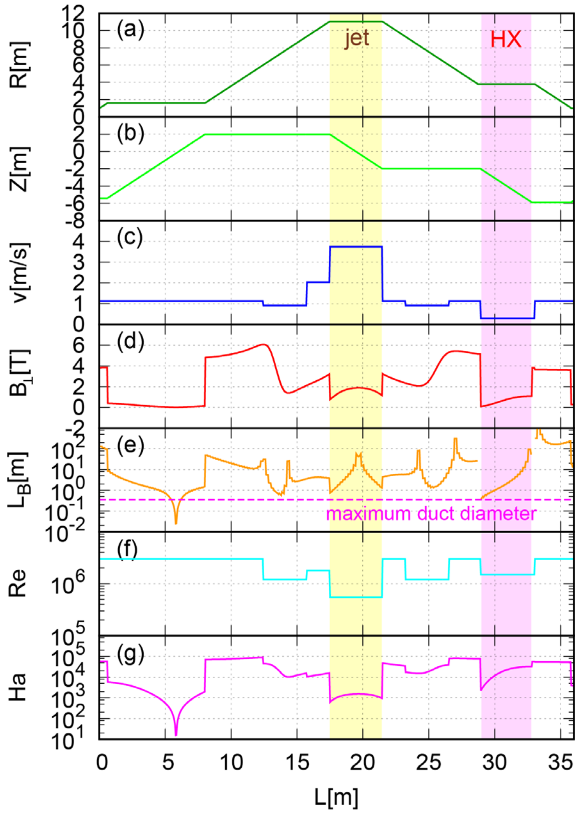

Fig. 2 Distribution of (a) radial position of the duct, (b) vertical position of the duct, (c) flow velocity, (d) strength of the transverse magnetic field, (e) characteristic length of the magnetic field variation, (f) Reynolds number and (g) Hartmann number along the flow channel.

and MHD force is much larger than friction force. Equation (6) assumes the velocity distribution of which direction is perpendicular to both magnetic field and flow velocity, and high Hartmann number (Ha $\gg$ 1). Both equations can be extended to the case of variable magnetic field by integrating along x direction if the change in the magnetic field is gradual, i.e., characteristic length of the change in magnetic field $L_B = B(x)/(\mathrm{d}B(x)/\mathrm{d}x)^{-1} \gg R_{\mathrm{in}}$. For example, Eq. (3) can be transformed into the following formula:

$$\Delta p = -\int_0^x K_{\mathrm{p}}\sigma_{\mathrm{f}} v_0 B(x')^2 \mathrm{d}x'. \quad (8)$$

Figure 2 shows the distribution of radial (R) and vertical (Z) position of the duct, magnetic field strength perpendicular to the flow direction $B_\perp$, flow velocity v, characteristic length of magnetic field variation L_B, Hartmann number Ha and Reynolds number Re along the duct length L. Here we used the following parameters: $\rho = 6990\,\mathrm{kg/m^3}$, $\sigma_{\mathrm{w}} = 1.66\,\mathrm{S/m}$, $\sigma_{\mathrm{f}} = 6.33\,\mathrm{S/m}$ and $\mu = 9.5 \times 10^{-4}\,\mathrm{m^2/s}$. The flow velocity is calculated from the required volumetric flow rate and the inner diameter of the ducts. Because the self-ignition plasma with a fusion output of 3 GW is considered in FFHR-d1, the total amount of the heat flows into divertor regions is 600 MW (the power generated by alpha particles). Considering the radiation loss of 30%, the jets of liquid tin must accommodate the heat load of 420 MW. On the other hand, the temperature increase of the liquid tin should be less than 200 K to suppress the vapor pressure. Considering the heat capacity of liquid tin, the required volumetric flow rate is $0.115\,\mathrm{m^3/s}$ per section. For the outer diameter in Eq. (5), we referred to the value of the commercially available stainless steel pipe for pressurized water that has the closest inner diameter. The thickness of the pipe is 10 mm at the position of which the transverse magnetic field has maximum, 6.1 T. The magnetic field is calculated by the finite volume current element code KMAG [6, 7]. For simplicity, we ignore the effect of the change in the magnetic field along the toroidal direction (corresponding to the sections J–K and M–N). It was found that the above-mentioned condition is met in almost the entire region (except for $L \sim 6$ m where $B_\perp$ passes across zero). Therefore, we used Eqs. (3) and (6) in this calculation. Reference [8] shows that the dependence of experimentally observed pressure drop on the magnetic field can be well explained by Eq. (6) but the absolute value is approximately 1.5 times larger. From a conservative viewpoint, we used the value obtained from Eq. (6) multiplied by 2. For the change in the duct geometry, we used the following formula for the elbow of the duct [9]:

$$\zeta = 0.946 \sin^2 \frac{\theta}{2} + 2.05 \sin^4 \frac{\theta}{2}, \quad (9)$$

where θ is the bending angle. Although additional loss factors (changes in the radius, branches, valves, bends inside the heat exchanger and the pump, etc.) exist in the flow channel, we ignore these effects because the result strongly depends on the detailed design of the flow channel, however, such a detailed analysis is beyond the scope of this study.

3. Calculation Result

Figures 3 and 4 show the distribution of the pressure drop, integrated pressure drop and the required pumping power for one section along the flow channel with conducting and insulated ducts, respectively. Here we assume the pumping efficiency is 20%. As shown in Fig. 3, almost all of the pressure drop is caused by the MHD pressure drop with conducting ducts. The total pressure drop is larger than 30 MPa and the required pumping power per section exceeds 40 MW, i.e., the total required pumping power exceeds 400 MW. Considering that the expected electric output of FFHR-d1 is ~ 1 GW, it is not acceptable to consume such an amount of electricity only for the pumping power in order to achieve as a large net electricity production or engineering Q value as possible. On the other hand, the total pressure drop is suppressed to ~ 0.7 MPa with insulated ducts. Consequently, the required pumping power is less than 10 MW. The result indicates that the use of insulated ducts is necessary.

There exists strong vertical magnetic field (~ 5 T)

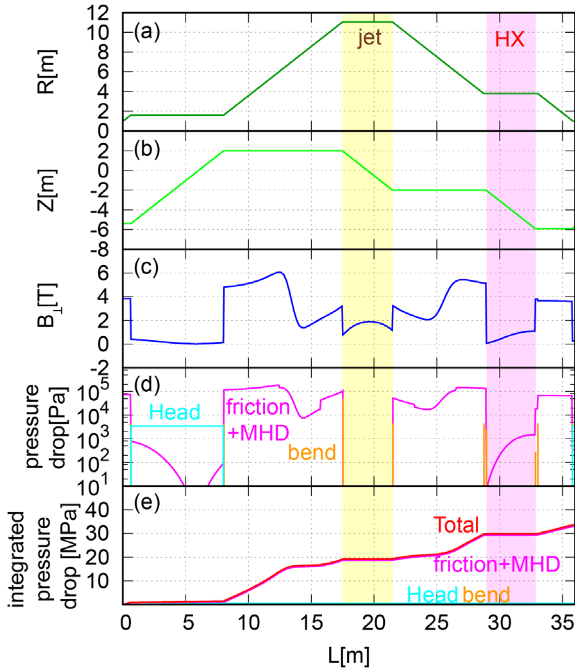

Fig. 3 Distribution of (a) radial position of the duct, (b) vertical position of the duct, (c) strength of the transverse magnetic field, (d) pressure drop and (e) integrated pressure drop with conducting ducts.

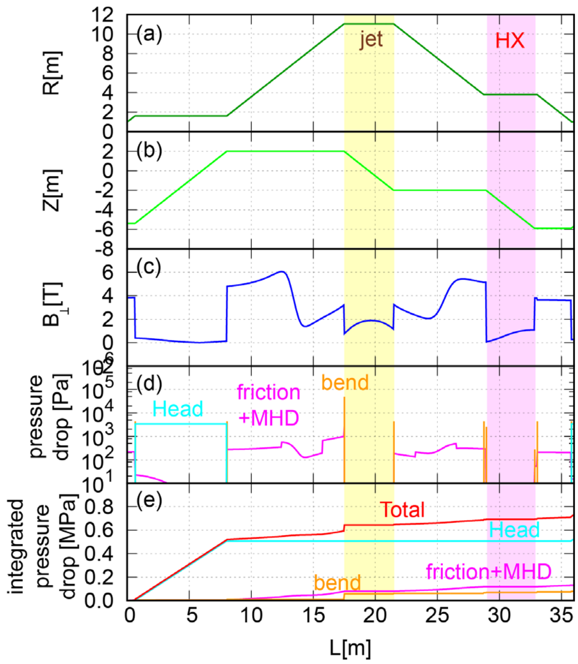

Fig. 4 Calculation result with insulated ducts. The meaning of the parameters is the same as in Fig. 3.

inside the torus' inner space. To reduce this magnetic field and enable a flexible placement of equipment for REVOLVER-D (e.g., electromagnetic pump, vacuum pump), placement of solenoid coils is considered as an option. As shown in Fig. 2, flow direction is parallel to the magnetic field (i.e., vertical direction) in most of the region in the torus' inner space. Thus, the result does not change significantly with the placement of the solenoid coils.

4. Conclusion

Pressure drop and the required pumping power for the circulation of liquid tin of the liquid divertor concept REVOLVER-D for the LHD-type helical fusion reactor FFHR-d1 was examined. The pressure drop is dominated by MHD pressure drop and exceeds 30 MPa with conducting ducts, resulting in the required pumping power of more than 400 MW. On the other hand, the pressure drop is suppressed to ~0.7 MPa (less than 0.2 MPa for the MHD pressure drop) with the insulated duct. Therefore, the required pumping power is less than 10 MW, which is much smaller than the expected electric output of FFHR-d1. Although further detailed analysis on the pressure drop (e.g., effect of the geometrical change in the flow channel, effect of other components on the flow channel including valves and diagnostic tools, effect of the change in the flow characteristics near the point at which the magnetic field passes across zero, etc.) is required, it is concluded that the liquid metal divertor REVOLVER-D is feasible from the viewpoint of the pressure drop or the required pumping power.

Acknowledgments

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