Engineering Feasibility of a Grid Mesh Structure in a Traveling Wave Direct Energy Converter

SHU Liyong and TOMITA Yukihiro*

The Graduate University for Advanced Studies, Nagoya 464-01, Japan
*National Institute for Fusion Science, Nagoya 464-01, Japan

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Abstract

In D-3He/FRC fusion reactor such as “ARTEMIS-L” [1], a traveling wave direct energy converter (TWDEC) was proposed to recover the energy of fusion protons of 15 MeV. In this paper, engineering feasibility of grid meshes in TWDEC is studied. The fusion protons are guided from burning plasma to the direct energy converter, where the incident power is as high as 3.5 MW/m². In order to remove incident heat to grid meshes, a radiative cooling without liquid flow is ineffective because of the high heat flux. The method by the flow of the pressurized water of 15 MPa with a flow velocity of higher than 10 m/sec is feasible to remove the incident heat. However, it is necessary to exchange grid meshes attributed to the irradiation effect, such as displacements of atoms, several times during a lifetime of a reactor.

Keywords:
D-3He fueled fusion, field-reversed configuration, traveling wave direct energy converter, grid mesh structure

1. Introduction

D-3He fueled fusion has an attractive feature which produces a small fraction of 14 MeV neutrons [1]. This leads low activation of a structural materials due to the impact of neutrons. For a purpose of demonstrating the attractive characteristics of D-3He fueled fusion, a design study of D-3He/FRC reactor “ARTEMIS-L” [1] has been carried out. At this design, approximately 1/3 of fusion power is carried by 15 MeV fusion protons. Therefore, it is important to develop a direct energy conversion system with high conversion efficiency which brings about a fusion reactor with a high plant efficiency. The energy of 15 MeV, however, is too high to handle with electrostatic method. In case of 15 MV, a gap length is necessary as long as 24~184 m in vacuum of lower than 1 mTorr [2]. This means the conventional direct energy converter with electrostatic method (VBDEC: Venetian Blind Direct Energy Converter) [3~5] is not applicable to recover the energy of fusion protons with 15 MeV. A concept of a traveling wave direct energy converter (TWDEC) for recovering the energy of fusion protons has been proposed in 1989 by H. Momota [6] on the basis of the principle of a Linac [7]. A schematic drawing of the TWDEC is shown in Fig.1, where a cusp DEC [1] to recover thermal component of plasma ions is also shown. In order to obtain the high conversion efficiency, the perpendicular energy of fusion protons with respect to magnetic field lines is changed to the parallel one by use of magnetic field expansion, which is performed by the expansion of the radius from 1.68 m (separated; \( B = 5.36 \) T) to 5 m (DEC; \( B = 0.09 \) T). The TWDEC consists of a modulator and a decelerator both of which consist of an array of metallic grid meshes and a transmission circuit. At the modulator, incident protons are modulated with a traveling wave field to form bunched protons at a down stream. At the decelerator, a traveling wave field is excited in the transmission circuit by a flow of bunched protons. The bunched protons are decelerated by the potential of excited traveling wave. In D-3He/FRC burning plasma [1], fusion protons with 545 MW escape directly out of
burning plasma. The expansion of plasma radius from 1.68 m to 5 m makes the incident power density to TWDEC low as 3.5 MW/m², which is comparable with the heat load to the first wall and divertor plate of the D-T fusion reactor (15–20 MW/m²: self ignition, 70–100 MW/m²: steady state). In this paper, engineering feasibility of a grid mesh (copper: Cu or austenite stainless steel: SS) structural under the heat flux with the high energy of 15 MeV is studied. In Section 2, the lifetime of a grid mesh is estimated by the effects of irradiation due to the bombardment of fusion protons. In Section 3, the removal of the incident heat to grid meshes is analyzed. Conditions of a flowed water, such as pressure and velocity, and a structure of grid meshes are determined from these analyses.

2. Irradiation effects

Here, we estimate the irradiation effects of grid material due to the bombardment of high energy fusion protons with 15 MeV. The bombardment of these particles sputters and displaces metal atoms of grid meshes. First, the sputtering effect is estimated. The empirical formula of the sputtering yield \( Y \) for incident ions with energy \( E \) is developed by Yamamura et al. [9]:

\[
Y(E) = 0.42 \frac{\alpha^* Q^* K s_0 (\varepsilon^*)}{U_i [1 + 0.35 U_e s_0 (\varepsilon^*)]} \times (1 - \sqrt{E_m/E})^{2.8} \text{ (atoms/ion),}
\]

(2-1)

where \( \alpha^* \), \( Q^* \), and \( E_m \) are the empirical parameters. \( U_i \) is the sublimation energy in eV, \( s_0 (\varepsilon^*) \) and \( s_0 (\varepsilon^*) \) are Lindhard's elastic and inelastic reduced stopping cross sections, respectively. These functions are expressed in terms of the reduced energy \( \varepsilon^* \):

\[
\varepsilon^* = \frac{0.03255}{Z_1 Z_2 (Z_1^{2/3} + Z_2^{2/3})^{1/2} M_1 + M_2} \sqrt{E (\text{eV})}. \]

(2-2)

where \( \alpha^* \) is the conversion factor from the elastic reduced stopping cross section \( s_0 \) to the stopping cross section \( S_0 \) in units of eV cm²/10¹⁵ atoms:

\[
K = \frac{S_0}{s_0} = 8.478 \frac{Z_1 Z_2}{(Z_1^{2/3} + Z_2^{2/3})^{1/2} M_1 + M_2}. \]

(2-3)
In these equations the values $Z_1$ and $Z_2$ are the atomic numbers of the incident ions and target atom and $M_1$ and $M_2$ are their mass numbers, respectively.

As the experimental data are distributed at the lower energy than 100 keV, we extrapolate the formula (2-1) up to the higher energy of fusion protons with 15 MeV. This gives us the sputtering yield for proton on SS and Cu to be about 7.1 $\times$ 10$^{-7}$ and 1.5 $\times$ 10$^{-6}$, respectively. For the particle flux of 1.4 $\times$ 10$^{18}$/m$^2$/sec with the energy 15 MeV in "ARTEMIS-L" [1], the lifetime of grid mesh with a thickness of 0.5 mm is estimated to be longer than 10$^6$ years. The lifetime of a grid mesh is much longer than a reactor lifetime of about 30 years, if there is an ambiguity of 10$^4$ regarding extrapolation of sputtering yields to high energy of 15 MeV.

The displacement of metal atoms due to the irradiation of fusion protons is considered. For the proton flux of 1.5 $\times$ 10$^{18}$/m$^2$/sec, the displacement rate of stainless steel becomes about 10$^{-7}$ dpa/sec or 3 dpa/y [8], which is almost the same as that due to the irradiation of 14 MeV neutrons with flux of 1 MW/m$^2$. Note that these protons deposit only the surface of a grid material of range of 15 MeV proton $\sim$ 100 µm, which has a straight structure without any stress except for low pressure of liquid flow (10 $\sim$ 20 MPa), therefore, this effect on irradiation damage may be small compared to that due to neutron flux with 1 MW/m$^2$. These displacements, however, may affect the characteristics of grid meshes through embrittlement etc. Accordingly, it is necessary to exchange irradiated grid meshes several times during a lifetime of a reactor. This exchange might be easy because of low fluence of neutrons and a straight structure of a D$^3$He/FRC reactor.

3. Heat removal

3.1 Radiative cooling without liquid flow

First we consider the heat removal of meshes by a conductive and radiative cooling without liquid flow. The temperature of grid mesh at a position of along the length obeys the heat transport equation:

$$\frac{d^2T_g}{d\bar{z}^2} - \frac{2E_g \sigma_{SB}}{r_{out} \varepsilon} T_g^4 + \frac{2q_in}{\pi r_{out}^2} = 0. \quad (3-1)$$

Here $\lambda_g$, $E_g$, and $r_{out}$ are the heat conductivity, emissivity, and outer radius of grid mesh, respectively. The parameter $\sigma_{SB}$ indicates the Stefan-Boltzman constant, i.e. 5.67 x 10$^{-8}$ W/m$^2$K$^4$, and $q_in$ is the heat input density of 3.5 MW/m$^2$. As the heat conductivity of metal is as low as 20 W/mK (SS) and 400 W/mK (Cu), the heat conduction is much smaller than radiative cooling. Therefore, the temperature of grid mesh is determined only by the radiative cooling:

$$T_g = \left( \frac{q_in}{\pi E_g \sigma_{SB}} \right)^{1/4}. \quad (3-2)$$

This temperature rises up to 2105 K even for largest emissivity, i.e. black body radiation: $E_g$ = 1.0, which is much higher than the melting temperature of austenite stainless steal (~ 2000 K) and copper (~ 1300 K). This indicates that it is impossible to remove the heat input only by radiative cooling. Therefore, the heat removal by a liquid flow is inevitable.

3.2 Heat removal by pressurized water

The temperature and pressure of pressurized water in the pipe of grid mesh change along the length according to the following equations:

$$\frac{d}{d\bar{z}} \left( u p_\ell C_v T_f \right) = q_in, \quad (3-3)$$

$$\frac{dp_\ell}{d\bar{z}} = -\frac{1}{2 p_{in}} \frac{u_\ell^2}{2} f_B. \quad (3-4)$$

Equation (3-3) represents the heat transport equation along to the length $\bar{z}$: $u_\ell$, $p_\ell$, $C_v$, and $T_f$ are the flow velocity, mass density, specific heat at constant volume, and temperature of pressurized water, respectively. The quantity $r_{in}$ is the inner radius of grid pipe. The second equation (3-4) indicates the drop of water pressure $p_\ell$ along the length. The coefficient of friction at the turbulent flow is introduced by $f_B$, which is represented by Blasius equation using Reynolds number $R_e$:

$$f_B = 0.316 / R_e^{1/4}, \quad (3-5)$$

$$R_e = 2 r_{in} u_\ell / \nu, \quad (3-6)$$

where $\nu$ is kinematic viscosity of water. In these equations, the conductive and radiative effects of a grid mesh are neglected and the properties of pressurized water, such as $p_\ell$, $C_v$, and $\nu$, are the functions of both the temperature $T_f$ and the pressure $p_\ell$ of water. The temperature of grid pipe at the inner surface $T_{g,in}$ is obtained from the heat transmission relation between fluid and inner surface of pipe:

$$T_{g,in} = \frac{q_in}{\alpha} + T_f. \quad (3-7)$$

The coefficient of heat transmission $\alpha$ is determined from the empirical heat transmission equation of a turbulent flow in a cylinder, i.e. Dittus-Boelter equation:

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\[ N_u = \left( \frac{2 \rho_{w} \alpha}{\lambda_{t}} \right) = 0.023 \times R_{e}^{0.8} \times P_{r}^{0.4}, \quad (3-8) \]

where \( N_u \) and \( P_{r} \) are Nusselt and Pendltke number, respectively. The quantities \( \lambda_{t} \) and \( \eta_{t} \) denote heat conductivity and coefficient of viscosity of pressurized water, respectively. The quantities \( hf \) and \( \eta_{f} \) denote heat conductivity and coefficient of viscosity of pressurized water, respectively. The pipe temperature at outer surface \( T_{\text{out}} \) is obtained from the heat conductive relation to a radial direction of a grid pipe:

\[ T_{\text{out}} = \frac{q_{m}}{\lambda} \left( \frac{r_{\text{out}} - r_{\text{in}}}{r_{\text{out}}} \right) + T_{\text{in}}. \quad (3-9) \]

The pressure of a grid pipe is limited by a maximum shearing stress, i.e. Tresca yield condition, at the inner surface of grid pipe:

\[ P_{\text{lim}} = \frac{\sigma_{t} \left( \frac{r_{\text{in}}}{r_{\text{out}}} \right)^2 - 1}{2 \left( \frac{r_{\text{out}}}{r_{\text{in}}} \right)^2}, \quad (3-10) \]

where \( P_{\text{lim}} \) and \( \sigma_{t} \) are the limit pressure and the tensile strength of a grid metal. In case of water temperature and pressure at inlet are 20°C and 15 MPa with flow velocity of 10 m/sec, the axial change of temperatures of water flow, inner and outer surfaces of a grid pipe (Cu and SS) are plotted in Fig. 2 (a), where the saturation temperature of pressurize water is also shown. The axial change of the flow pressure and the limit pressure are shown in Fig. 2 (b). In these cases, the pipe has inner and outer radii of 4.5 mm and 5.0 mm. Although the flow temperature becomes the highest at the outlet of \( \delta = 10 \) m, it is lower the saturation temperature. The flow pressure is much lower than the limit pressure of Cu and SS. In Fig. 3 (a) and (b), the temperatures and the pressures at the outlet are shown as a function of the flow velocity, where the other parameters are the same in case of Fig. 2. The slower flow velocity than 2.9 m/sec makes the water temperature higher than the

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Fig. 2 (a) Axial temperature profiles of water flow, inner and outer surfaces of a grid pipe (Cu and SS), and also saturation temperature of pressurized water and (b) pressures of flow and limit pressures of a grid pipe: water temperature and pressure at inlet of 20°C and 15 MPa with flow velocity of 10 m/sec, and inner and outer radii of a grid pipe of 4.5 mm and 5.0 mm, respectively.

Fig. 3 (a) The temperatures and (b) the pressures at outlet of a cooling pipe as a function of flow velocity under the same conditions of Fig. 2.
saturation temperature. From these results, by applying a grid pipe of Cu or SS with outer radius of 5 mm and a thickness of 0.5 mm, the pressurized water of 15 MPa with a flow velocity of higher than 10 m/sec is feasible to remove the input heat due to fusion protons. Note that the temperature difference between inlet and outlet falls up to 60 K by the flow velocity of 20 m/sec. From the viewpoint of margin with respect to the limit pressure, stainless steel is preferable as a material of grid meshes.

4. Concluding Remarks

The engineering feasibility of grid meshes in TWDEC of D-3He/FRC fusion reactor, such as "ARTEMIS-L," was studied. The heat input to TWDEC attributed to fusion protons with 15 MeV is as high as 3.5 MW/m². The sputtering effects of grid meshes due to bombardment of fusion protons is estimated negligible small during a reactor lifetime of about 30 years. However, the exchange of grid meshes is necessary due to the displacements of metal atoms several times during a lifetime of a reactor. Regarding heat removal of grid meshes, radiative cooling without liquid flow raises the grid temperature to higher than the melting temperature of a grid metal (copper: Cu or austenite stainless steel: SS). It is possible to remove the heat by use of the flow of the pressurized water with 15 MPa of the flow velocity higher than 10 m/sec in a pipe of 5 mm radius and 0.5 mm thickness. In order to ensure the margin of design, stainless steel is preferable as a material of grid meshes. From the engineering points of view, grid pipes with this flow of the pressurized water work successfully during a lifetime of a fusion reactor.

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References