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A PROPOSAL OF THERMOELECTRIC DIVERTOR BY USING SILICON CARBIDE IN NUCLEAR FUSION EXPERIMENT

Fusion reactor needs a divertor plate to reduce a plasma surface interaction in order to realize long confinement time of high temperature plasmas. The plate is attached on the vacuum vessel, and it should be cooled. The function of the divertor is to control the plasma particle flow, and it is set with the pumping system. The heat flux to the divertor plate is quite high as the order of 10 MW/m^2 in fusion reactor, and the high-energy particles and the radiation from the plasma are bombarded on the surface of the plate. The heat flux on the divertor plate is the same as the inside of the rocket engine, but the heat flux of the rocket engine does not include high-energy particles. In order to remove the heat flux from the divertor plate, the reverse side of the plate is cooled by the water flow, and the plate should be thin to realize the low thermal resistance. Therefore, the temperature difference of the plate is higher than 1500 K. Carbon and tungsten are used in the present experiment as materials for the divertor plate because they possess high thermal conductivity and high melting point temperature. One of authors proposed the thermoelectric divertor to generate electric power in 2002, however, the Seebeck coefficients of these materials are not high and the output power of the thermoelectric divertor is not high. Here, we propose to use silicon carbide (SiC) as a new material for the thermoelectric divertor again because its thermal conductivity is higher than tungsten, the Seebeck coefficient of SiC is the order of 100 μV/K, and it does not melt and its sublimation temperature is 2700 K. In the paper we also propose thermionic emission combined with the thermoelectric conversion system. We discuss the structure of the divertor plate and its performance about the heat removal and electric power generation.

Key words: thermoelectric cooling, energy conversion, nuclear fusion, high temperature materials.

Introduction

Fusion reactor needs the divertor plate [1, 2] to reduce the plasma surface interaction in order to realize the good confinement of high temperature plasmas. The plate is attached on the vacuum vessel, and the vacuum pumping system and the cooling system are connected with the divertor plate in order to control the particle influx and pumping, and the temperature of the plate [3, 4]. Since the energy confinement time of plasma is longer for larger plasma depending on the experimental scaling law [5, 6, 7], the heat flux to the divertor plate is high extremely, and its order is the order of 10 MW/m^2 in fusion reactor [8], and the high energy particles of plasma are bombarded on the plate, too. The heat flux on the divertor plate is the same as on the inner wall of the rocket engine, the heat removal is important to operate fusion experiment and reactors. The material of the divertor plate is carbon and high melting point metals, such as tungsten and molybdenum, and their composite materials [9]. These materials should have high thermal conductivity because of the removal of high heat flux. They should conjugate to the copper plate, and the conjugation technology is also important. Usually the water and helium gas flows cool the copper plate. Therefore, large temperature difference appears between the plasma side of the plate and the copper plate, and it is higher than 1500 K.

This structure and the operation conditions are good for thermoelectric power generation because of high temperature difference, and one of authors proposed the thermoelectric divertor (TED) to generate electric power in 1996 [10] and 2002 [11], and also proposed the thermionic divertor (TID) and its structure in 1996 [12]. However, since the Seebeck coefficients of these materials (carbon and metals) are not high and their figures of merits are extremely low, the output power of the TED is not high. Here, in order to improve the performance of the TED, we propose to use silicon carbide (*SiC*) as a new material for the TED. Thermal conductivity of *SiC* is higher than those of tungsten, molybdenum and the carbon, and moreover the Seebeck coefficient of *SiC* is the order of 100 μV/K [13, 14, 15], therefore we can expect high output voltage of the TED. It does not melt and its sublimation temperature is ~ 3000 K, therefore it is high temperature material. If we install the TED in the fusion reactor, we can also consider the concept of TID with the TED at the same time in order to enhance the electric power output. In the paper, we propose and discuss the new structure of the divertor plate, and estimate its performance about the heat removal, electric power generation, and the perspective of the future experiment in the present device.

Proposal of *SiC* Thermoelectric Divertor

In order to generate high temperature plasma, the plasma-wall interaction should be reduced, and the limiter had been used in tokamaks in 1960's and 1970's. However, the limiter material is going into plasma as the impurities because the surface temperature of the limiter may exceed 2500 K. The radiation loss of the impurity is high, and finally the energy confinement time is limited and not long for fusion reactor. The divertor configuration was developed in magnetic confinement devices, such as the tokamak and the helical system in order to reduce the impurity contaminations in the plasma. This can be called the magnetic limiter, and the magnetic field of the main plasma is not touched to the wall and the limiter directly. Therefore, the high temperature plasmas are realized in the divertor configuration in many experimental devices, and it is the standard magnetic configuration in the present time.

Fig. 1 shows the concept of TED in fusion experiments. This is based on the Fig. 1 (*b*) in ref. [4]. Some of the parts in the figure are changed, such as the cooling channel in the first wall of the divertor. *X* point means the poloidal magnetic field is zero, and the upper parts of the *X* point is the main plasma, and this is called the divertor configuration. The dotted lines mean the magnetic surfaces, and those are composed of the magnetic field lines. The plasma particle flows along the magnetic field line mainly, and the wall where the magnetic field line is crossing must be cooled to keep it. The radiation from the plasma is strong, and the first wall must be cooled. The charged particles of the plasma are neutralized at the wall, and they can be pumped out from the vacuum vessel. This is an important process to control the density of plasma. The thermoelectric modules (TE modules) are added on the original figure and they are connected to the wall of the vacuum vessel where the particle fluxes bombard, as shown in Fig. 1.

The TE module is composed of *n*-type and *p*-type *SiC* semiconductor, and they are connected with the high temperature metallic material such as tungstain in high temperature side. The low temperature side of the semiconductor is connected with the copper and the copper parts are cooled by the water. This configuration is the same as the divertor plate fundamentally. The plasma side of the TE module is hot because of high heat flux of the plasma particle and the radiation, and the other side is cold. Therefore, the TE module has large temperature difference, and can generate electric power.

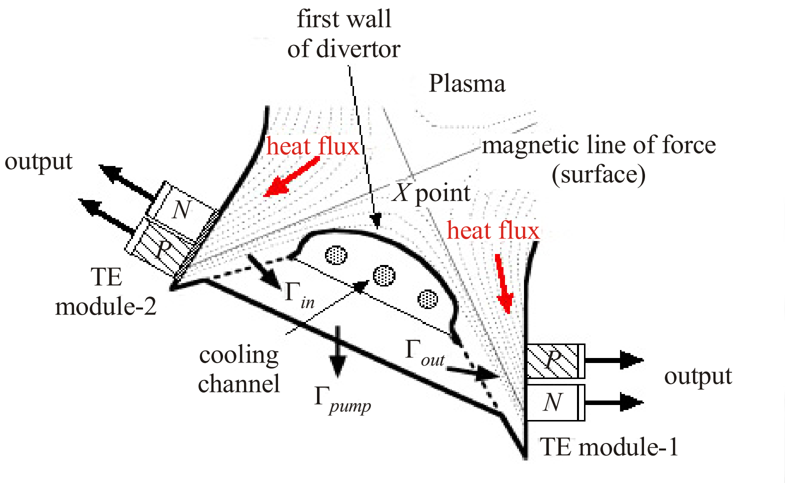

Fig. 1. Setup of the thermoelectric divertor (TED), and the magnetic configuration of plasma.

The functions of the TED should be as

1) to remove the heat at the wall of the vacuum vessel,
2) to pump out the particles from the plasma for controlling the plasma density,
3) to generate electric power.

The first two functions are the same as the original divertor's, but the last one is a new addition. Therefore, the material of TED has high thermal conductivity and strong for the bombardment of high-energy particle from plasma and the thermal shock (rapid temperature change), and in addition its Seebeck coefficient should be high and it is low electrical resistivity in order to generate electric power. The materials of the divertor are tungsten and molybdenum as the first wall because they are high melting points material and have high thermal conductivities. The carbon and the related materials are also used because it can be used in high temperature and their thermal conductivity is also high. However, their Seebeck coefficients are low, and therefore they are not good material from thermoelectric points of view. We cannot expect high electric power output from these materials.

We proposed the silicon carbide, *SiC*, to solve the problem. The thermal conductivity of *SiC* is higher than those of tungsten, molybdenum and carbon, and therefore it is good for cooling and we can keep the same structure of the present divertor. The Seebeck coefficient of *SiC* is also higher than those of tungsten, molybdenum and carbon, and therefore it is good for electric power generation as in Fig. 1. In the present time, we do not have enough data of *SiC*'s parameters at high temperature, but the known parameters are listed in Table 1. The tungsten is a good material to connect the *p*-type and *n*-type semiconductors in the high temperature side because it is strong for the bombardment of high-energy particle from plasma and it is used in the present experiment. *SiC* is a good material as *n*-type semiconductor even in high temperature, but it is hard to make *p*-type. Therefore, B_4C is a candidate of the *p*-type semiconductor at high temperature. Usually we can find *p*-type semiconductor in high temperature. However, since the thermal conductivity of B_4C is low, this is limited to use in divertor.

It is valuable to estimate the electric power generation by using *SiC*. The figure of merit of the *SiC* in Table 1 is expected to be ~ 10^{-5} [K^{-1}], and it is not large as the present *BiTe*, but the temperature difference of the module is high as 1500 K, therefore the efficiency of the electric output power is not low, and can be evaluated by the following equation, where α is the Seebeck coefficient, κ is the thermal conductivity, ρ is the electrical resistivity, T_H is the temperature of high temperature side of the element, T_C is the temperature of low temperature side of the element.

$$\varepsilon = \frac{T_H - T_C}{T_H} \frac{\sqrt{1 + \frac{Z(T_H + T_C)}{2}} - 1}{\sqrt{1 + \frac{Z(T_H + T_C)}{2}} + \frac{T_C}{T_H}}, \quad Z = \frac{\alpha^2}{\kappa\rho} \tag{1}$$

Table 1

Parameters of the high temperature materials

Material	MP(melting point) SP(sublimation point) [K]	Thermal conductivity [W/m·K]	Seebeck coeff. [μV/K]	Resistivity [Ωm]	comments
Tungsten	3695/MP	~ 170 ≅ 300 K	< 10	5.2×10^{-8} ≅ 300 K	for first wall
Carbon	3915/SP	100 ~ 300	< 10	10^{-6} ~ 10^{-2}	high thermal conductivity in diamond
B_4C [16]	2763/MP	30 ~ 42 ≅ 300 K	~ 120 ≅ 1000 K	~ 0.006 ≅ 1000 K	used in fission reactor
SiC	3003/SP	~ 490	> 400	< 0.0001	new proposal

The calculation result of the efficiency is shown in Fig. 2. The efficiency of the thermoelectric conversion is shown as the vertical axis, and the horizontal axis is the figure of merit *Z* [%]. If *Z* exceeds 10^{-5} K, the efficiency is higher than 1%. Therefore, the output power of the TED is several hundred kWatts for the ITER design, and the conversion efficiency may not be low because the temperature difference is larger as 1500 K. Moreover, the cooling of the divertor may be easy because of high thermal conductivity of *SiC*.

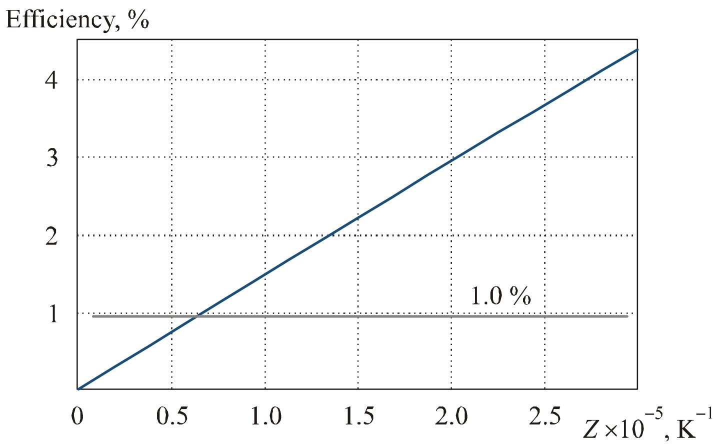

Fig. 2. Efficiency of thermoelectric divertor (TED) by using silicon carbide (SiC) for temperature difference of 1500 K.

Discussions and Future Perspective

The concept of *SiC* TED will be good for the divertor plate, but unfortunately the experimental data is not enough at high temperature for *SiC* and the related materials in the present time. Therefore, it would be good subjects to study. The connection with the metallic material is also important, and the tungsten is used at the high temperature side and the copper should be connected as the electrode in the proposal of Fig. 1. In this meaning, we should develop the connecting technology, and it is not easy because the thermal expansions of these materials are not same usually. The plasma is one of electric conducting media, and the resistivity along the magnetic field line is low because the electron in the plasma can be moved easily along the field line. And it is high for the perpendicular direction of the magnetic field. Moreover, the electrical resistivity is low for high temperature plasma. Therefore, if we can set the TED along the magnetic field line, we may be able to omit the tungsten-plate connection to make the TED. But the magnetic field configuration is controlled by the currents of the magnet current and the plasma. However, when we look at the divertor configuration shown in Fig. 1 carefully, we can find many available settings for the TED.

The other idea is related with thermionic emission [12]. We bring the two electrodes into the vacuum vessel as shown in Fig. 3. One is *W*-plate 1, and the other is *W*-plate 2. These are connecting each other electrically by the magnetic field line and plasma. And we should control that the surface temperature of the *W*-plate 1 is set to be low and the *W*-plate 2's is high. The setting of temperature difference between two plates depends on the design of the plate and the control of plasma and the cooling system operation. The system can operate as the thermionic emission generator if we connect the electrode and the cables as shown in Fig. 3.

The radiation from high temperature plasma is strong, and therefore we can expect the photon enhanced thermionic emission in this case, and the solid angle of two plates for the plasma is not the same in Fig. 3, it means that we can realize the temperature difference of these two surface plates. And if the electrical connection between two plates is realized, we can install the thermoelectric part behind the plates. Because high temperature and/or high radiation flux plate can emit electron and low temperature plate adsorb the electron from plasma, the *p*-type semiconductor should be attached behind the high temperature plate, and the *n*-type semiconductor should be connected to the low temperature plate. Then, we can expect the power from both the thermoelectric and thermionic conversions from proposed schemes. It is also important idea to apply the usual system that is not fusion reactor.

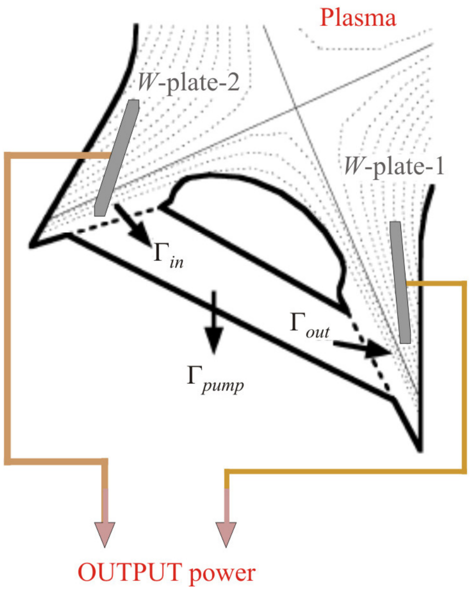

Fig. 3. Concept of thermoelectric and photon enhanced thermionic emission divertor for increasing the output power.

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