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Direct Energy Conversion of Radiation Energy in Fusion Reactor

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ABSTRACT

Direct energy conversion from plasma heat flux has been studied. Since major parts of fusion energy in the advanced fusion reactor are radiation and charged particle energies, the flexible design of the blanket is possible. We discuss the potentiality of the thermoelectric element that generates electricity by temperature gradient in conductors. A strong magnetic field is used to confine the fusion plasma, therefore, it is appropriate to consider the effect of the magnetic field. We propose a new element which is called Nernst element. The new element needs the magnetic field and the temperature gradient. We compare the efficiency of these two elements in a semiconductor model. Finally, a direct energy conversion are mentioned.

KEYWORD: thermoelectric effect, Nernst effect, fusion reactor, thermoelectric element, Nernst element, direct energy conversion

1. Introduction

Advanced fuel cycle is studied as a safety and environmentally acceptable reactor in the fusion research[1, 2]. Advanced fusion reactor reduces neutron flux further, therefore, fusion energy mainly comes from the radiation and charged particle energy. Moreover, the reactor does not use tritium as a external fuel. Because of these reasons, Li-blanket is not useful to get fusion energy. Here, we discuss the direct electric energy conversion from the heat from the fusion plasma. The main processes to generate electricity are thermoelectric effect and Nernst effect.

The electric field is induced when the temperature gradient appears in conductors, and it is called thermoelectric effect. This effect is studied to apply battery, cooler and heat pump for a long time[3,4,5]. Recently, the space satellites mount nuclear batteries[6] whose heat source is the radioactive matter like ^{238}Pu and ^{90}Sr. The efficiency of thermoelectric element is determined by the operation temperature and the characteristics of the conductor, and the figure of merit is used to discuss the efficiency. The maximum system efficiency is now 10 % in the above nuclear battery system[6]. This value is not high when we compare with the conventional fission reactor at the present time, however, it will be improved in the future and we are also trying to use the thermoelectric element to generate electricity in the fusion reactor.

In order to improve the efficiency, we propose the new thermoelectric element to generate electricity in this paper. A high magnetic field is used to confine high temperature fusion plasma, therefore, it is appropriate to use the effect of magnetic field to convert electricity. The new element depends on Nernst effect that induces the electric field in the presence of temperature gradient and magnetic field. We call it Nernst element. We assume the semiconductor model to estimate the figure of merit for Nernst element and compare the conventional thermoelectric elements. Finally, one of the system design for the direct energy converter is mentioned.

2. Principle of direct energy conversion

At first, we discuss the principle of the direct energy conversion which depends on thermogalvanomagnetic phenomena. This is written by two equations that are the generalized Ohm's law and the heat flux density equations. They are given by [7]

$$\mathbf{E} = \mathbf{J}/\sigma + S\,\mathrm{grad}T + R_H \mathbf{H}\times\mathbf{J} + N\mathbf{H}\times\mathrm{grad}T \quad (1)$$

$$\mathbf{q} = ST\mathbf{J} - \kappa\,\mathrm{grad}T + NT\mathbf{H}\times\mathbf{J} + L\mathbf{H}\times\mathrm{grad}T \quad (2)$$

where **E** is electric field, σ electrical conductivity, **J** current density, S thermoelectric power, T absolute temperature, R_H Hall coefficient, **H** magnetic field, N Nernst coefficient, **q** heat flux density, κ thermal conductivity and L Righi-Leduc coefficient. The first term is Joule dissipation term, the second term is thermoelectric effect, the third term represents Hall effect and the fourth term is Nernst effect in Eq. (1). We take the scalar product **J*E** in Eq. (1), and we find that thermoelectric and Nernst effects can generate electricity, however, Hall effect does not produce electricity because the scalar product is zero. The effect of the magnetic field has been studied so much in thermoelectric effect, however, since the thermoelectric effect does not depend on the magnetic field explicitly in Eq. (1); therefore, it is appropriate that thermoelectric power is a function of magnetic field. Hall effect is studied experimentally and theoretically, and its coefficient is saturated in high magnetic field[8]. This suggests that Nernst coefficient is also constant for a high magnetic field.

The directions of current density and the temperature gradient should be parallel to generate electricity in thermoelectric effect. The effect also transfers the heat flux and it is a reversible process. The schematic structure of thermoelectric element is shown in Fig. 1.

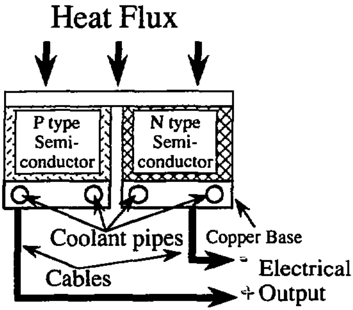

Fig. 1 Set up of thermoelectric element

Heat flux comes down from upper side to the element and this side keeps a high temperature. Opposite side of the element is cooled and this is the low temperature side. The element is composed of p-type and n-type semiconductors, therefore, the signs of thermoelectric power are different. Thus, we can get the electric power from low temperature side. Here, the plasma and its radiation are heat source in our study. If we use the element in the magnetic field, we should consider the effect of the magnetic field for thermoelectric power.

Electric field is induced by Nernst effect when the vector product of the magnetic field and the temperature gradient is not zero. We propose the new element that is shown in Fig. 2. The directions of the magnetic field, temperature gradient and the induced electric field are perpendicular each other and z, y and x in Fig. 2, respectively. The insulation layer is necessary not to make an electrical short for the induced electric field but it can transport heat for the temperature gradient in the semiconductor, and it is set in the low temperature side as shown in Fig. 2. This element needs one type of semiconductor to generate electricity, and it is not necessary to adjust the characteristics of two types of semiconductors like the thermoelectric element. The process transfers the heat flux and is reversible like thermoelectric process. The heat removal is enhanced to generate electricity, in both of the two elements. This effect is convenient for the first wall and divertor to remove the heat in a fusion reactor.

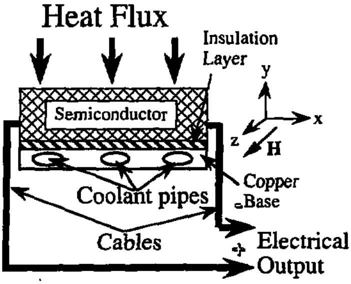

Fig. 2 Set up of Nernst element

3. Model of Semiconductor

The coefficients in Eqs. (1) and (2) are the parameters of materials, however, a conductor model of classical statistical physics[9] can be used to estimate and compare the potentialities of the two types of elements. We suppose a hypothetical substance that has one current carrier. The characteristics of this substance are assumed by Eqs. (3) to (7),

$$\mu_H = \mu_{H0}\left(\frac{T}{T_0}\right)^{-1.5} \tag{3}$$

$$\sigma = \frac{8}{3\pi} n\, e\, \mu_H \tag{4}$$

$$\kappa \approx \text{const.} \tag{5}$$

$$S = -\frac{k_B}{e}\left(2 - \ln\frac{n\, h^3}{4\pi(2m^* k_B T)^{1.5}}\right) \tag{6}$$

$$N = -\frac{\mu_H}{2}\left(\frac{k_B}{e}\right) \tag{7}$$

where μ_H is Hall mobility and μ_{H0} is value in temperature of T_0, n carrier density, e charge of carrier and its sign is negative, h Plank constant, m^* effective mass of carrier, k_B *Boltzmann constant.*

The above model is similar to a semiconductor model, and μ_{H0}, m^*, n, e, κ are given as the material values, and T and H are operation parameters. Thermal conductivity depends on the lattice contribution mainly, and the electronic .contribution is small when the carrier density is low. Figure of merit is used to estimate the efficiency of the element and the figure of merit Z_S for thermoelectric effect is defined by

$$Z_S = \frac{\sigma S^2}{\kappa} \tag{8}$$

Because of the symmetry of Eqs. (1) and (2), the figure of merit for Nernst effect is given by

$$Z_N = \frac{\sigma N^2}{\kappa} H^2 \tag{9}$$

Since the electrical conductivity is not affected by magnetic field so much in high temperature region, the ratio of these two figures of merit is given by

$$\gamma = \frac{Z_N}{Z_S} = \frac{\mu_H^2 H^2}{4\left(A - \ln n + \frac{3}{2}\ln T\right)^2} \tag{10}$$

where A is a function of effective mass.

Figure 3 shows the ratio γ for following parameters;

$\mu_{H0} = 8\ m^2 V^{-1} s^{-1}$
$T_0 = 300$ K
$m^* =$ electron mass
e = electron charge
$H = 5$ Tesla

and

$n = 10^{24}\ m^{-3}$ for case-1,
$n = 10^{25}\ m^{-3}$ for case-2

The value of the ratio is larger than unity, therefore, the new element has high potential to generate electricity in this model. This improvement is a factor of 2 to 5 in the above cases. High magnetic field, high Hall mobility, high carrier density and low temperature is more desirable for Nernst element than thermoelectric element if we use the same materials. The value of 5 T is not difficult to realize even with the present superconducting magnet technology[10]. The design value of magnetic field is 5 to 20 T in fusion reactors. Because of this, we can expect improvement of this conversion efficiency by use of the high magnetic field.

If we choose a high carrier density material, the electrical conductivity is improved but the thermal conduction is also increase and the thermoelectric power is reduced, therefore, the optimum parameters are existed to obtain a high value of Z_S. The carrier density of the semiconductor for the thermoelectric element is selected between $10^{25}\ m^{-3}$ to $10^{26}\ m^{-3}$.

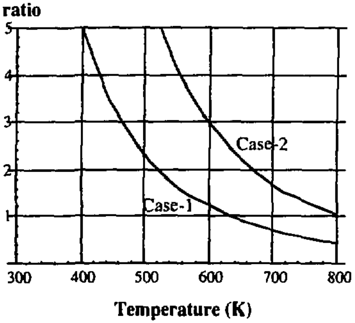

Fig. 3 Ratio of Thermoelectric and Nernst Elements

4. Conceptual Design of Energy Converter

We rewrite Eqs. (1) and (2) to the macro-scale equations that are the circuit equation and heat flux equation to estimate the total efficiency of the system[11]. The total efficiency η_{tot} of the system is given by

$$\eta_{tot} = \eta_c \frac{m}{m+1} \times \frac{1}{1 - \frac{1}{2(1+m)}\eta_c + \frac{1+m}{Z\,T_{hj}}} \qquad (11)$$

where m = (r_{ex} / r_{in}), and is resistance ratio of external and internal resistance in electric circuits, Z figure of merit, T_{hj} high temperature of element and η_c Carnot cycle efficiency.

We optimize the resistance ratio m for Eq. (11), and assume the figure of merit Z to be constant for temperature. Low temperature gives high efficiency, and the low temperature of the element is fixed to be 350 K in Fig. 4. The efficiency is improved for high Z value and large heat cycle temperature, however, it can not exceed the efficiency of Carnot cycle. The value of Z=0.002 is the conventional material's for the thermoelectric element at the present time, and here, we expect 5 6o 20 times improvements for the figure of merit from the calculation result in the previous section.

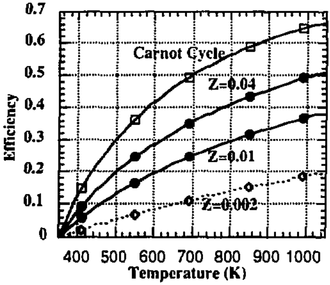

Fig. 4 Efficiency of Carnot cycle, Z=0.002, Z=0.01, Z=0.04 for low temperature of 350 K.

The heat loads of the wall and diverter plate are 1 to 10 MW/m^2 in the present design value of a fusion reactor. These value are too high to use the conventional semiconductor because the thermal conductivity is low. Life time of high carrier density semiconductor might not be so long if fast neutrons bombard the semiconductor. Because of these conditions, we set the energy conversion system out of the reactor. We use He gas and water as the coolants, and high temperature He gas is brought out form the reactor to the energy conversion system. Figure 5 shows the schematic structure for energy converter, and it is called a conversion pipe. High temperature He gas flows in the inner pipe and low temperature water flows in the outer pipe. The semiconductor for conversion is set between He gas and water pipes. Thus the set of the semiconductor generates electricity by the temperature difference. If we use the Nernst element, the magnetic field is needed and the semiconductor should have a gap like Fig. 5 and the electrical terminals are attached to the gap, and the electrical power is brought out from the conversion system. The superconducting solenoid coil is used to generate the magnetic field.

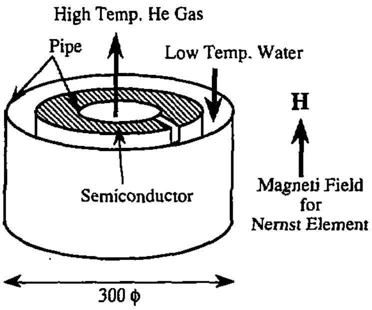

Fig. 5 Schematic structure of energy conversion pipe

One of the set of the design parameters for thermal output of 500 MW fusion reactor is as follows;

Pressure	1 Mpa
high temperature	700 - 750 K
low temperature	300 - 350 K
inner pipe diameter	0.2 mϕ
outer pipe diameter	0.3 mϕ
pipe length	10 m

velocity of gas	7.4 m/s
velocity of water	1.0 m/s
number of pipe	800
magnetic field	5 - 10 T
size of magnet	20 m length
	10.5 mϕ
magnetic energy	26 - 67 GJ
efficiency	14 - 38 %
electric output	70 - 190 MW

High pressure, velocity and temperature of He gas and water coolant give small diameter of the conversion pipe. Finally, its construction cost is reduced. High temperature gas also improve the efficiency. This consideration depends on the design of the fusion reactor.

5. Discussion and Conclusion

When we use the p-type and n-type semiconductors for the thermoelectric element, these figures of merit and other physical parameters should be matched well to make a good thermoelectric element, however, it is not easy to find the couple of the semiconductors in same temperature region. Nernst element needs only one semiconductor, therefore, it is free from this problem. The sign of the Nernst coefficient depends on the types of the semiconductor, and this determine the direction of the current in the semiconductor. This means that the magnetic field is generated by its own current in the conversion pipe system.

Nernst element has high performance in low temperature region from Fig. 3. This may suggest the hybrid element to improve the efficiency, and we use the thermoelectric element in high temperature region and Nernst element in low temperature region. We should study the magnetic effect of the thermoelectric power in this case.

If we can obtain a high figure of merit material in magnetic field, we should consider the whole terms in Eqs. (1) and (2) because Hall and Righi-Leduc effects also are important to transport the heat flux density and electric current.

The thermal and electric conductivities are constant for the magnetic field in the model of section 3. Experimentally, the electrical conductivity is increased by the presence of the magnetic field in low temperature region that means below 80 K. This is called the magnetoresistance, and its value is proportional to the square of magnetic field in the low magnetic field, and is saturated in the high magnetic field.

Effective mass of hole and electron in the semiconductor is not the same as that of electron. This parameter is important to estimate the energy gap and the thermoelectric power of the semiconductor[12] This consideration is not needed for the Nernst element because the Nernst coefficient does not depend on the effective mass in the classical model.

High carrier density material is good for both thermoelectric and Nernst element. If we adopt a high carrier density material, we should consider the contribution of the carrier in the thermal conductivity. If the resistance is affected by the applied magnetic field, its thermal conductivity of carrier also is affected. These two effects will be canceled and proportional to the temperature in figure of merit because of Wiedemann-Franz law. This means that the metals are not good material in high temperature region.

The thermal conductivity of a conventional semiconductor is below 10 $Wm^{-1}K^{-1}$ and its value is too low to use the first wall of a fusion reactor directly, but is available to the conventional reactor. Low thermal conductivity material is used to realize high conversion efficiency in the thermoelectric element[12].

Above considerations need the experiment to study the effect of the magnetic field especially for the Nernst element.

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