Consideration on Nuclear Fusion in Plasma by the Magnetic Confinement as a Heat Engine

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Abstract

In comparing nuclear fusion in plasma by the magnetic confinement with nuclear fission and chemical reactions, the power density and the function of a heat engine are discussed using a new parameter G introduced as an eigenvalue of a reaction and the value of q introduced to estimate the thermal efficiency of a heat engine. It is shown that the fusion reactor by the magnetic confinement is very difficult to be a modern heat engine because of the lack of some indispensable functions as a modern heat engine. The value of G and q have the important role in the consideration.

Keywords: reaction eigenvalue G, practical thermal efficiency, energy loss rate, quantity q, power density, energy carrier, combustion system, explosive combustion, stationary combustion, fusion reactor.

1. Introduction

Power density as well as the function of combustion system is a very important factor estimating an efficiency of a heat engine. Nuclear fusion system as a heat engine should be studied on that basis in comparison with nuclear fission and chemical combustion systems.

We introduce a new parameter G, eigenvalue of a reaction, having a role to describe the power density under the function of a certain combustion system. Here, combustion systems are classified as usual into three types, which are the continuous and explosive combustion, the pulsive and explosive combustion and the stationary combustion. We also introduce the value q to define the practical thermal efficiency as a function of power density together with G. Then we noticed that G values of modern heat engines are very large and nearly about the same value although the G value might not exceed some upper limits to keep nature stable on the earth. Considering these problems, we discuss fusion reaction in the magnetically confined plasma for a heat engine.
2. Eigenvalue of a reaction, \( G \)

2.1 Introduction of \( G \)

The power density \( P \) is, in general, expressed as follows;

\[
P = \varepsilon <\sigma v> n_1 n_2
\]  

where \( \varepsilon \) is the generated energy by a reaction, \( \sigma \) is the cross section of the reaction at a relative speed \( v \) of particles, and \( n_1 \) and \( n_2 \) are the density of the fuel and the auxiliary material, respectively.\(^1\) \( <\sigma v> \) stands for the value of \( \sigma v \) averaged over the Maxwell distribution. This equation is usually used for the analysis of fusion in the magnetically confined plasma, but it is possible to apply it to nuclear fission and chemical combustion to compare the power density. For the thermal reactor, \( n_1 \) and \( n_2 \) are the number density of U-235 and thermal neutrons, respectively. Then the role of \( n_2 \) is to control the combustion. In the case of the usual CH\(_4\) combustion in air, \( n_1 \) and \( n_2 \) are the density of CH\(_4\) and O\(_2\), respectively. O\(_2\) is supplied to the system together with N\(_2\) as air and the supply is enough to achieve the perfect combustion in a short time. Although the process of chemical reaction in a gas state is very complicated, eq (1) is reasonable if \( \varepsilon \) is taken to be the total energy generated in the perfect combustion of a CH\(_4\) molecule. Then the characteristic energy generation of a reaction can be defined for any type of combustion system as follows;

\[
G = \varepsilon <\sigma v> \quad [\text{eV m}^3 \text{ s}^{-1}].
\]  

Power density is a product of \( G \), \( n_1 \) and \( n_2 \). The value of \( G \) is proper to a reaction and varies sensitively with the energy of reaction particles. However, if the reaction temperature is settled in a constant range to keep the combustion stable for each practical system, the power density will be simply controlled by \( n_1 \) and \( n_2 \).

2.2 Calculated \( G \) values for typical reactions

For the evaluation of \( G \), typical reactions are selected in the field of nuclear fusion, nuclear fission and chemical combustion, as follows;

<table>
<thead>
<tr>
<th>Reaction</th>
<th>( \sigma ) ( [ \text{m}^2] )</th>
<th>( v ) ( [\text{ms}^{-1}] )</th>
<th>( &lt;\sigma v&gt; ) ( [\text{m}^3 \text{s}^{-1}] )</th>
<th>( \varepsilon ) ( [\text{eV}] )</th>
<th>( G ) ( [\text{eV m}^3 \text{s}^{-1}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH(_4)</td>
<td>54 \times 10^{-20}</td>
<td>1.1 \times 10^3</td>
<td>5.9 \times 10^{-16}</td>
<td>9.2</td>
<td>0.54 \times 10^{-14}</td>
</tr>
<tr>
<td>H(_2)</td>
<td>24 \times 10^{-20}</td>
<td>3.1 \times 10^3</td>
<td>7.4 \times 10^{-16}</td>
<td>1.3</td>
<td>0.96 \times 10^{-15}</td>
</tr>
<tr>
<td>U-235</td>
<td>5.5 \times 10^{-26}</td>
<td>2.2 \times 10^3</td>
<td>1.2 \times 10^{-22}</td>
<td>208 \times 10^6</td>
<td>2.5 \times 10^{-14}</td>
</tr>
<tr>
<td>D-T</td>
<td>5 \times 10^{-28}</td>
<td>2 \times 10^6</td>
<td>1 \times 10^{-21}</td>
<td>17.6 \times 10^6</td>
<td>1.8 \times 10^{-14}</td>
</tr>
<tr>
<td>D-D</td>
<td>2 \times 10^{-30}</td>
<td>2.4 \times 10^6</td>
<td>4.8 \times 10^{-24}</td>
<td>4 \times 10^6</td>
<td>1.9 \times 10^{-17}</td>
</tr>
</tbody>
</table>

\(^1\) \( <\sigma v> \) stands for the value of \( \sigma v \) averaged over the Maxwell distribution.
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\[ D (0.1) + T (0.1) \rightarrow ^{4}\text{He} (3.5) + n (14.1) + 17.6 \text{ MeV} \quad (3) \]
\[ ^{235}\text{U} + n \rightarrow ^{94}\text{Sr} (90) + ^{136}\text{Xe} (90) + 2n (2) + 208 \text{ MeV} \quad (4) \]
\[ \text{CH}_4 + 2\text{O}_2 = \text{CO}_2 (3) + 2\text{H}_2\text{O} (3) + 210.8 \text{ kcal/mol} \quad (5) \]
where the numbers in the parenthesis are particle energy in MeV for eq (3) and (4) and eV for eq (5). Needless to say, eq (4) is one of the probability of fission process. Table 1 shows the calculated results of G values according to eqs. (3), (4) and (5).

2. 3 G value in nature

The values of \( \varepsilon \) are plotted against \( \langle \sigma v \rangle \) in Fig. 1, where the each oblique line expresses a constant G value. From Fig. 1, it is clear that G\(_1\) (D-T), G\(_2\) (U-235) and G\(_3\) (CH\(_4\)) exist around the value of \( 10^{-14} \text{ eV m}^3 \text{ s}^{-1} \), while G\(_D\) (D-D) is about 1/10\(^{3}\) times as large as G\(_1\) (D-T). The modern heat engine is supported by the large value of G\(_2\) or G\(_3\). G\(_1\) is also large enough to produce the power density as a modern heat engine. However, G\(_D\) is so small that the fuel density \( n_1 \) and/or \( n_2 \) should be increased by 10\(^{3}\) times to obtain the same power density as D-T reaction. G\(_H\) is a little smaller than G\(_3\) but H\(_2\) is still expected to be usable for the fuel of the modern heat engine, since \( n_1 \) can be large enough to obtain the high power density.

2. 4 Power density and introduction of q value

Consider the Carnot cycle, in which energy \( Q_1 \) is given to a system at the temperature \( T_1 \) [K] and energy \( Q_2 \) is removed from the system at \( T_2 \) [K]. Then, the thermal efficiency \( \eta \) is expressed as follows;

\[ \eta = \frac{(T_1 - T_2)}{T_1} \quad (6) \]
When it is provided that a practical heat cycle needs more energy $Q_3$ than $Q_1$ of the Carnot cycle ($Q_1 + Q_3$ is given to the system at $T_1$ and $Q_2 + Q_3$ is removed from the system at $T_2$), then the thermal efficiency of this cycle $\eta_R$ could be expressed as follows:

$$\eta_R = \frac{Q_1 + Q_3 - Q_2 - Q_3}{Q_1 + Q_3} = \frac{Q_1 - Q_2}{Q_1} \times \frac{Q_1}{Q_1 + Q_3} = \frac{T_1 - T_2}{T_1} \left( 1 - \frac{Q_3}{Q_1 + Q_3} \right)$$ (7)

As shown in eq (7), $\eta_R$ is a product of the thermal efficiency for the Carnot cycle and a factor less than unity representing the difference from the Carnot cycle. Supposing that the generated power density $P$ eVm$^{-3}$ s$^{-1}$ and the energy loss rate $L$ eVm$^{-3}$ s$^{-1}$ originated from $Q_3$ are homogeneous and stationary in the burning area $V$ m$^3$, we obtain the following equations.

$$P = \frac{(Q_1 + Q_3)}{(Vt)}, \quad L = \frac{Q_3}{(Vt)} \quad (8)$$

where $t$(sec) is the time for adding or removing energy. Then the quantity $q$ is introduced.

$$q = \frac{Q_3}{(Q_1 + Q_3)} = \frac{L}{P} \quad (9)$$

Substituting $q = L/P$, the relation between $\eta$ and $\eta_R$ can be described by the following equation.

$$\eta_R = \eta (1-q). \quad (10)$$

The temperature of the construction material, including safety factor, could not exceed 900K in general. Assuming that the atmospheric temperature is 300K, the thermal efficiency of the Carnot cycle becomes $\eta = 2/3$. However, $\eta_R$ of the conventional power plants, the obtained value in practice, is about 0.4,5) which is 60% of the ideal $\eta$. On the other hand, the maximum temperature of LWR is limited to be about 600K because of the boiling of the moderator water. When the Carnot cycle ($T_1 = 600K, T_2 = 300K$) is assumed as the LWR system, $\eta = 1/2$ should be obtained. $\eta_R$ of LWR is about 0.32,4) which is 64% of the ideal $\eta$. It is supposed that the difference between 60% and 64% comes from the difference of $q$ related to the power density. The power density of the conventional plant and LWR is about the order of 10MW/m$^3$,7) 100MW/m$^3$,6) respectively. The value of $q$ decreases with increase of $P$, since $L$ is partially a function of $P$ but also includes a constant value regardless of $P$. The power density of a heat engine is composed of two parts, $G$ and $n_1 n_2$ in eq (1). The former is a proper value of a reaction but the latter depends on the combustion system. For a reaction having small $G$ value, special consideration is necessary to obtain the large $n_1 n_2$. Comparing the fusion reaction of D-D with that of D-T, $n_1 n_2$ of D-D must be $10^3$ times larger than that of D-T. Is the magnetic confinement of plasma possible to achieve this difficult task?

2.5 Temperature coefficient of G value

$G$ value varies with the energy of reaction particles. The variation of $G$ in the operation temperature range is shown in Fig. 2. This figure was conducted from Table I and the published data.8) The nuclear fission in eq (4) is controlled by the thermal neutron density, and $G_2$ is supposed to be constant in the operation temperature range, since the thermal neutron cross section complies with $1/v$ law.9) The chemical reaction shown in eq (5) is a combustion in a gas state. The cross section of a molecule was es-
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Estimated by $4 \pi r^2$, where $r$ is the radius of a molecule, and the cross section is proportional to $T^{1/2}$. Therefore, $G$ changes a little in the operation range of temperature, that is, $G_1$ does have the positive temperature coefficient. The nuclear fusion in eq (3) seems to be achieved by the magnetic confinement of the plasma at about 0.001 MeV. However, $G_1$ steeply rises up in the operation range (0.001 to 0.01 MeV) and the temperature coefficient seems very difficult to be compensated by the value of $n_1$ and $n_2$ which increases with increase of the magnetic force. Only the way to control the combustion by the magnetic confinement is to keep the plasma stationary at the top of the curve, that is about 0.08 MeV (Fig. 2). Is it possible to obtain a far stronger magnetic field than the present experimental use?

3 Combustion
3.1 Combustion system

Combustion systems of heat engines can be classified into three types, as follows;
(1) continuous and explosive combustion (boiler burner)
(2) pulse and explosive combustion (internal combustion engine)
(3) gentle and stationary combustion (thermal neutron reactor).
(1) and (2) are the explosive thermal reaction in a gas state and the combustion itself cannot be controlled, in general. Then, the power density should be controlled by $n_1$ and $n_2$. A constant power density is supported and also limited by the total latent heat of the fuel supplied to the combustion area per second. On the other hand, (3) is the solid state combustion and it is possible to control the combustion itself according to the neutron density $n_2$ with the control rods. Fusion by the magnetic confinement of plasma is the thermonuclear reaction in a gas state, and that should be the

Fig. 2 Variation of $G$ in the range of the control temperature
explosive combustion. Provided that the combustion is controlled only by the magnetic confinement, the force should be strong enough to keep the plasma temperature at 0.08 MeV as mentioned before (See Fig. 2).

3.2 Storage fuel in combustion area

A constant quantity of CH₄, sent into the combustion area successively, releases all the latent energy in a short time, but the released energy will be limited to a constant value. However, thermal neutron reactors store the fuel for 3 to 5 years in the combustion area and very small portion burns gently and stationarily because of the solid state combustion as mentioned before. The fuel is necessary to keep the criticality and the power density. Large fuel quantity is also necessary to nuclear fusion as well as fission, although the burning rate per second is only 10⁻⁶ portion of the storage fuel. However, the lack of the guaranty to suppress the power below a constant value is a serious problem, since it is the explosive combustion.

3.3 Share of generated energy

The generated energy is so large that those particles which carry the energy should not directly contact with the construction material. In eq (5), one CO₂ molecule carries about 3 eV, and this is 40 times of 0.075 eV (900K). The molecules of the reaction product repeat collision with other particles, and a cluster is produced around the reaction center. The particles shared the energy in the cluster will diffuse to outside of the cluster, thus the generated energy will be shared among many carriers in small energy in a short time before contact to the wall of the container. In eq (4), a small portion of the generated energy is carried out from the cluster by γ ray, electrons, neutrons and neutrinos, but a major portion of the energy is carried by the two fission products, e.g. Sr and Xe. The cluster thus produced by the reaction products is supposed to be extremely small in size, since they are heavy charged particles. The state, inside of the cluster, may be in an ultra high temperature plasma because the energy should be released only in a short range of sintered UO₂. The energy in the cluster will diffuse within the sintered UO₂ by phonon and transferred to the water flowing outside of the sheath can. The sintered UO₂ fuel and the sheath can is used to be changed every 3 to 5 years. In eq (3), no reasonable carrier can be produced to share the generated energy into small energies because all the particles are already heated up to an ultra high temperature. This mechanism of sharing energy is indispensable to a heat engine but the combustion of the plasma fusion system does not have this mechanism. The failure of the first wall (disruption) is caused by this reason.¹¹ ¹² The problem is not only the energy fluence but the energy of incident particles.

4 Conclusions

Introducing parameter G and q value, we discussed the fusion by the magnetic confinement in terms of function of a heat engine. As the result, it is expected that the fusion system is very difficult to operate as a heat engine for the reasons mentioned below.

(1) Reaction eigenvalue G has a large positive temperature coefficient in the operation range.

(2) The thermonuclear fusion by the magnetic confinement is an explosive combustion, that is similar to the thermochemical reaction in a gas state.

(3) Only a small portion of the storage fuel in the combustion area is burnt in an explosion. There is no guaranty of the power limitation. The power of the chemical combustion is limited by the whole latent heat of the fuel inserted to the burning area, at the time of each explosion.
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(4) In the case of the chemical reaction, sharing the generated energy to the carriers, the small energy of a carrier does not give a serious damage to the wall of the furnace or cylinder liner. This is one of the functions to make the large energy available in a heat engine, and the thermal neutron reactor has the same function. However the fusion system has no such a function.

(5) G value of D-D reaction is about $10^{-3}$ times as large as that of D-T. To obtain the similar density, $n_1 n_2$ of D-D system must be $10^3$ times for D-T system, otherwise the q value becomes large and the thermal efficiency will be too small as a modern heat engine. By consideration of these reasons, Solid State Fusion Fission Combined Reactor (SFCR) is proposed to make nuclear fusion reaction available for a modern heat engine.13

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