Review on Plasma Facing Materials and Suitable Divertor Configuration of a Fusion Experimental Reactor

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The characteristics of the graphite as plasma facing material are reviewed and the problems of the graphite for the plasma performance are pointed out. The capabilities of low atomic number materials such as boron and beryllium are shown briefly and the limits in use of B or Be as the plasma facing component are presented. It is then summarized that the achievement of burning plasma condition with a long time period in a fusion experimental reactor such as ITER becomes difficult only by the development of the plasma facing materials.

In order to successfully achieve such burning plasma, a scheme with the enlarged divertor configuration is proposed for the reduction of the heat flux to the divertor. The present scheme is also compared with other schemes for the reduction of the heat flux.

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I. Introduction

A fusion device of the tokamak type showed very excellent plasma confinement properties in the late of the 1960's⁽¹⁾⁽²⁾. The tokamak size has been scaled up and the heating power was also increased. The plasma stored energy rapidly increased both by the increased input power and the device size. However, the deterioration of the energy confinement time was observed because of the radiation loss power due to the impurities such as oxygen and carbon.

In order to remove the light impurity species such as O and C, developed were several excellent techniques for wall conditionings, *e.g.* Taylor discharge cleaning, glow discharge cleaning and ECR discharge cleaning⁽³⁾⁻⁽⁵⁾. These schemes are very often applied as the wall conditioning methods in the present large devices, *e.g.* JET, TFTR, DIII-D and JT-60U.

As the increase of the plasma stored energy, the metal impurities such as iron caused an extremely large radiation loss since the radiation loss power is proportional to the cube of atomic number, Z^3 ⁽¹¹⁾. The materials with a low atomic number had to be, therefore, placed onto the metal vacuum chamber as the inner wall element. Then, the graphite tiles began to be used both to protect the chamber and to avoid the emission of metal species from the chamber⁽¹²⁾.

Since the graphite has a low atomic number, $Z=6$, the radiation loss power was largely reduced even if the plasma was contaminated by the carbon impurity. So the energy confinement characteristics of the plasma were remarkably improved. Against the high heat flux, the graphite first wall showed good thermal stability. In the present large devices, the graphite tiles have been employed at most of the inner wall region as the plasma

facing components.

In the discharge shot in JET, the energy breakeven, *e.g.* the fusion energy gain greater than unity, $Q>1$, was achieved ($Q=1.14$)⁽¹³⁾, but such a state with high plasma stored energy has been limited by a sudden increase of the carbon impurity concentration called the carbon bloom. The carbon bloom occurs both due to the erosion of the graphite by oxygen impurities, and the large erosion called the radiation enhanced sublimation (RES)⁽¹⁴⁾⁻⁽²⁵⁾ by the emitted carbon impurities at the wall region at elevated temperatures ($\geq 1700^\circ\text{C}$) or normal sublimation. The more suppression of oxygen impurity level has been required as well as the reduction of the graphite wall temperature. In addition, the hydrogen recycling has to be suppressed to obtain the good confinement properties such as the H mode and the hot ion temperature mode. In the next device, an experimental reactor like ITER⁽²⁶⁾, the heat load to the divertor becomes extremely large. Then the controls of the oxygen impurity and the recycling, and the heat removal become more difficult. It is conceived that these problems may not be solved only by the material developments. Thus, in order to obtain the long burning time period in the fusion experimental reactor, a novel approach for these problems should be developed both from, the points of the material developments and the modification of plasma configuration.

In this paper, we briefly review the graphite properties as the plasma facing material (PFM). Then, pointed out are the problems in the use of graphite as PFM. To eliminate the problems associated with the graphite, recently the boron coating technique or the boron doping and the beryllium evaporation technique have been developed. The limits in the use of these lower atomic number materials are also discussed. By taking into account the present status of the above materials, we suggest the

suitable approach, which modifies the divertor configuration, for the fusion experimental reactor.

II. Graphite as Plasma Facing Material

Overall properties of numerous graphite materials have been systematically investigated by the Graphite Project Team organized in 1986⁽²⁷⁾⁽²⁸⁾. Examined were the vacuum engineering properties such as hydrogen retention, gas desorption and effective surface area, the interactions with ions such as erosion yield, and the thermal shock properties. We here briefly review the obtained results.

1. Vacuum engineering properties

The graphite is very porous material, so that the effective surface area is extremely large. The surface roughness factor, which is defined by the effective surface area divided by the geometrical area, takes a value ranging from several hundreds to several thousands. It was observed that the surface roughness factor increased with the bulk density of the graphite. Numerous gas species are desorbed from the graphite by the heating. Major outgassing species are H_2O , H_2 , CO , CO_2 and hydrocarbons. The outgassing amount was observed to increase with the surface roughness factor. These results indicate that the graphite with low bulk density is adequate as the plasma facing material to suppress the light impurity emission and the hydrogen recycling.

In order to reduce the gas desorption and the hydrogen recycling, the wall baking and the discharge cleanings before the plasma discharge shots are quite useful. However, the outgassing can not be sufficiently carried out since the baking temperature is limited below about 350°C , due to the thermal stress caused in the vacuum chamber. It has been also tried to cover the graphite wall by the lower Z metal such as Be, because of the low recycling property. In the high temperature environment, however, the beryllium content largely evaporates.

2. Erosion properties

It is well known that the graphite is eroded in form of hydrocarbon, *e.g.* CH_4 , by the irradiation of hydrogen ions⁽²⁹⁾. This process is called as the chemical sputtering. The yield has a peak around at the temperature ranging from 500 to 600°C . The magnitude of the yield is about 0.1, which is approximately ten times larger than that of the physical sputtering. It is now recognized that the ceramics coatings such as SiC , TiC and B_4C , largely reduces the chemical sputtering yield. There is the problem that the coatings are easily peeled out or cracked by the thermal stress due to the high heat load.

When the graphite temperature exceeds about 1000°C , the carbon interstitials produced by the ion bombardment easily evaporate from the surface even if the temperature is much below the sublimation temperature. The yield is approximately one order of magnitude larger than that of the chemical sputtering. This serious erosion process is called the radiation enhanced sublimation

(RES)^{(14)–(25)}. In the large tokamaks, it is believed that the carbon bloom occurs due to the RES by the emitted carbon impurities, *e.g.* carbon self sputtering. Before the occurrence of this RES process, the carbon level increases by the graphite erosion due to the oxygen impurity. Then, in the region with the elevated temperature ($\geq 1700^\circ\text{C}$), the RES of the graphite due to the carbon impurity becomes dominant, resulting in the carbon bloom.

The metal doped graphite such as the boron doped graphite was evaluated to examine whether the RES can be reduced or not. If the carbon interstitials form a stable carbide before the sublimation at the surface, the RES yield may be decreased. However, the measurement for erosion yield showed no significant difference in the case of the graphite. On the other hand, the RES yield of B_4C ceramics was observed to be very small. On the contrary, the boron evaporation becomes dominant when the temperature exceeds about 1000°C . In addition, the B_4C ceramics is too brittle to the thermal stress.

The graphite is heavily eroded in the form of CO as stated above⁽³⁰⁾. The erosion yield is approximately unity. Thus, the erosion due to the oxygen is considerably serious even if the oxygen impurity level is of the order of 1%. In order to reduce the oxygen impurity, the use of the gettering material such as B or Be is effective. The Si coating is also useful to avoid the oxidation but this material has not low atomic number. The oxygen gettering action of the boron was observed to be limited below 1000°C in the systematic oxidation experiment⁽³⁰⁾. The reason is the evaporation of the boron oxide formed by the gettering action.

3. Thermal mechanical properties

Approximately 10 years ago, the isotropic graphite with the high bulk density began to be employed as the plasma facing material. This graphite, however, was often cracked by the high heat load. In the study of the Graphite Project Team, it was shown that the low density graphite was adequate with respect to the thermal shock resistivity. In the present large device, the carbon-carbon composite (C/C composite) or the carbon fiber composite (CFC) with the low density, high thermal conductivity and high fracture toughness has been used for the region with high heat flux such as the divertor or the limiter. The C/C composite or the CFC showed excellent stability against the high heat load. Up to now, no significant damage has been observed in the large devices.

In the divertor of the experimental reactor, more tough carbon material has to be developed since the heat flux becomes 30 MW/m^2 in the steady state and over 1000 MW/m^2 in the disruption phase. In the neutron irradiation experiment for the graphite, it was observed that the thermal conductivity was much deteriorated by the neutron damage. The post-irradiation annealing may be helpful to recover the thermal conductivity. But, when the dose exceeds 0.1 dpa , the recovery is not sufficient even with the annealing temperature of 1600°C ⁽³³⁾.

Table 1 Methods for problems in use of graphite as plasma facing material.

Problem		Methods or comments
Vacuum engineering property	Large surface area (large outgassing, large recycling)	*Baking (limited below 350°C) *He glow or Taylor discharge cleanings *Deposition of metal species such as Be onto graphite (easy peeling, evaporation due to high heat flux)
	Large chemical sputtering	*Ceramics coatings such as SiC, TiC and B ₄ C (easy cracking and peeling due to thermal stress)
	Extremely large erosion due to RES	*Metal mixed graphite such as B-doped graphite (B content largely evaporates at temp. more than 1000°C) *Ceramics such as B ₄ C (B content evaporates at temp. more than 1000°C)
Erosion property	Extremely large erosion due to oxygen	*B or Si coatings or doping (boron oxide evaporates at temp. more than 900°C. Si has larger Z number)
Thermal mechanical property	Not sufficient fracture toughness	*Use of newly developed CFC (more toughness be required for off normal phase)
Engineering component	More reliable brazing component	*Improvement for brazing method, choice of material and cooling structure

Table 2 Problems to be solved for graphite.

Problems to be solved for graphite	
(1)	Suppression of RES to avoid carbon bloom
(2)	Suppression of chemical sputtering to avoid graphite erosion
(3)	More control of recycling to avoid deterioration of energy confinement time
(4)	More suppression of oxygen impurity to avoid both carbon and graphite erosion
(5)	Development of more reliable brazing component

4. Brazing component

For the divertor of ITER and LHD, the divertor components with active cooling, which consist of C/C composite and copper cooling tube, have been aggressively developed recently. With the improved technologies for the brazing structure, the component which has no damage after the heat cycle test with 1000 cycles, 20 MW/m² and 30 s/cycle, has been developed⁽³¹⁾. So in the normal discharge period of the experimental reactor, this component seems to work very well. The question still remains in the case of the plasma disruption. If the disruption can not be controlled, it is difficult to avoid the damage in the off normal phase. In order to lengthen the life time and to enhance the reliability of the brazing component, further developments are necessary.

The remarks described above are summarized in Table 1. The problems to be solved for the graphite as the PFM is also shown in Table 2.

III. Boron and Beryllium as Plasma Facing Material⁽²⁴⁾

In the tokamaks such as DIID, TFTR, TEXTOR and JT-60U, the boronization experiments showed a large reduction of the oxygen impurity level as well as the decrease of average atomic number of plasma, Z_{eff} . In addition, the boronization contributed largely to achieve the good confinement characteristics, *e.g.* H-mode and hot ion temperature mode shots. In the JET operation, the beryllium evaporation technique and the beryllium limiter in the divertor region have been applied. Then found was the effective suppression both for the recycling and the emission of carbon impurities. Since the beryllium has a lower atomic number compared with that of the graphite, the degree of the radiation loss power is also weakened. By this effort, the energy breakeven condition was achieved.

The advantages of these materials are the oxygen gettering action and the atomic number lower than that of the graphite. The chemical sputtering can be largely reduced in the case of the boron coatings or the boron doping, since the hydrogen retention at higher temperature is reduced compared with the case of the graphite. The degree of recycling in the case of the beryllium is believed to be low, as with the metal chamber wall such as SS. The disadvantages of these materials are the evaporations of metal contents at the temperature higher than 1000°C. In the case of the boron, the boron oxide B₂O₃ formed by the gettering action evaporates at the temperature higher than 900°C. Thus the gettering action is effective only at the temperature below 900°C. In addition, the handling for these materials must be careful because of the toxic.

Table 3 Comparison of B doping/coatings and Be evaporation/bulk.

	Advantage	Disadvantage
B-doping or coatings	*Lower atomic number *Chemical sputtering be reduced *Low hydrogen retention at higher temp. *Oxygen gettering be effective	*Large evaporation of B content at temp. more than 1000°C *Smaller thermal conductivity *Not effective to reduce RES *Gettering be effective only at temp. less than 900°C *Toxic *Resource be limited
Be evaporation or bulk	*Lower atomic number *Low recycling *Oxygen gettering be effective	*Large evaporation of Be at temp. more than 1000°C *Not useful to reduce RES *Toxic *Resource be limited

Table 4 Requirements and comments in use of B or Be material.

Requirements and comments in use of B or Be material
(1) These materials should be used in the region with temperature less than 900–1000°C
(2) For region of divertor, B or Be content is easily lost by the evaporation
(3) Even with the use of Be, the carbon bloom still occurs
(4) For the divertor of ITER, the capability of heat removal is more limited due to the poor thermal conductivity

Compared with the resource of the carbon, these resources are poor.

The advantages and disadvantages of B and Be materials are summarized in Table 3. The requirements in the use of B or Be are shown in Table 4.

IV. Requirements for Divertor of an Experimental Reactor

As described above, only the development of the plasma facing material does not help to solve the problems associated with the carbon bloom, the recycling and the heat removal in the off normal operation. The promising way seems to be the reduction of the heat load to the divertor. Table 5 shows the advantages when the heat flux is reduced.

If the divertor wall temperature is controlled below 1000°C, no RES and no evaporation of B or Be content occurs. In addition, the evaporation of the boron oxide may not to be dominant. The chemical sputtering may be

Table 5 Advantages of reduction of heat load.

Advantages of reduction of heat load
(1) Wall temperature can be kept below about 1000°C
(i) No RES occurs
(ii) B gettering action can work well, e.g. oxygen level be reduced
(iii) B or Be content does not evaporate
(iv) Chemical sputtering also is reduced by B doping/coating
(2) Possible optimization for lower Z materials
(i) These materials can be stably used for the divertor region
(ii) Life time of such material is much lengthened
(3) Easy development for brazing component
(i) Even if thermal conductivity is poor, the requirement for brazing component is not difficult
(ii) Reduction of thermal conductivity due to neutron damage may not cause the problem

Table 6 Summary in scheme of reduction of heat load.

Summary in scheme of reduction of heat load
(1) Plasma facing component consisting with CFC and Cu tube may be applied for the ITER divertor
(2) Optimization scheme for lower Z materials such as B and Be may work well
(3) Problem remains in such scheme for suppression of the recycling
(4) Capability to apply high Z material like W can be considered

able to be suppressed if the boron or the beryllium material is used together with the graphite. Namely, the materials with lower atomic number can be effectively utilized both in the divertor and the first wall regions. Thus, the lifetime of these materials, is considerably lengthened. Even if the thermal conductivity is low or is deteriorated by the neutron irradiation, the handling for the heat removal becomes relatively easier. In other words, the brazing component can be used for the long time operation period without the maintenance.

With the success of the reduction of heat flux, the divertor component with the brazing structure, consisting of the C/C composite or CFC and copper cooling tube, may work during a long operation period. In addition, the optimization for the materials with lower atomic number may be successfully carried out. The scheme of reduction of heat flux is summarized in Table 6.

V. Conclusion: Suitable Divertor Configuration of an Experimental Reactor⁽²⁴⁾⁽³²⁾

For the reduction of the heat load in the divertor, several methods have been suggested as shown in Table 7. Each method has both the advantages and the disadvantages. Even if the heat load is reduced, it can not be accepted if the recycling and/or impurity flow into the core plasma are not controlled. There may be a possibility for the recycling to be enhanced in the schemes of X point swing, gaseous divertor and use of liquid curtain or gas jet limiter. In the scheme of ergotic field configuration, the radiation cooling of the divertor plasma becomes possible only when the edge temperature is of order of 10 eV. If the impurity such as Ar is injected, the cooling may occur in the range of higher temperature since the radiation cooling rate shifts to a higher temperature range. But in this case, the Ar flow to the core

Table 7 Methods for reduction of heat load.

Methods for reduction of heat flux	
Method	Comment
X point swing	*Precise dynamic control be needed *Possibility to enhance the recycling
Gaseous divertor	*Dynamic gas puffing or impurity injection be needed, but not difficult *Recycling be enhanced or impurity flow into core plasma be caused
Ergotic configuration	*Additional coil array be required *Radiation cooling be effective only at low temperature of divertor plasma
Liquid metal curtain or hydrogen jet	*Permeation of gas or metal into core plasma has to be well suppressed *Divertor configuration be complicated
Enlargement or expansion of divertor	*Geometry be simple *Easiest way to reduce the heat flux *Other methods be applicable *Impurity inward flow be well suppressed *TF coil size be enlarged too

Table 8 Summary for elongated/expanded divertor.

Summary for enlarged/expanded divertor scheme
(1) Heat load can be more reduced by adding other schemes
(i) Swing width in scheme of X point swing can be taken large
(ii) Gaseous divertor scheme can be improved because the recycling is suppressed by the long connection length
(iii) Radiation cooling scheme more works since the edge temperature is reduced
(iv) Inward flow of metal species or jet gas is suppressed by the long connection length
(2) Recycling may be suppressed by the elongated connection length or the throat length
(3) Impurity flow from wall to core plasma is suppressed in the high density plasma operation
(4) Even if the high Z material (W or Mo) is used for the divertor, the inward flow can be considerably reduced
(5) Divertor design of ITER should not be optimized only by the point of engineering aspect. Important issue is to achieve the long time burning plasma with adequate divertor configuration

plasma has to be well suppressed.

Most reliable and simple way for the reduction of the heat flux is the enlargement of the divertor configuration. Namely, the divertor geometrical area is expanded and the connection length or the throat length between the wall and the X point is lengthened. Since the divertor size is large, other methods can be relatively easily applied. Due to the long connection length, both the recycling and the impurity flow to the core plasma are largely suppressed because of the effective use of the friction force between the incoming fuel ion flow and the impurity inward flow. Table 8 shows the characteristics of the elongated or the expanded divertor scheme.

If the divertor is enlarged and that the plasma density is kept large, the friction force is enhanced and then the high Z plasma facing material such as W may be used because of the well-suppressed impurity inward flow. In addition, the injection of impurity gas like Ar can be acceptable in the present scheme. It is also easier to apply the scheme of $E \times B$ drift pumping because of the large space.

The problem of the present scheme is the requirement of large TF coils and large vacuum chamber. However, it

is important to design the divertor in order to successfully obtain the burning condition with a long time period in the experimental reactor such as ITER.

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