

CONCEPTUAL DESIGN OF PEBBLE DROP DIVERTOR

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Abstract

A pebble drop divertor concept is proposed for future fusion reactor. The marked feature of this system is the use of multi-layer pebbles that consists of a central kernel and some coating layers, as a divertor surface component. By using multi-layer pebbles, pebble drop divertor have the advantages such as steady state wall pumping with low bulk tritium retention. The performance of whole divertor system depends on the characteristics of the multi-layer pebble. Particularly the maximum heat load of the system is determined by the dimensions, the layer structure and the material of a kernel. A kernel also has an important role to determine surface temperature, which affects the wall pumping efficiency. This paper presents the numerical results of the maximum allowable heat load and the surface temperature of the divertor pebble. From the numerical estimation of thermal stress and surface temperature, it is found that the radius of divertor pebble with ceramic kernel should be 0.5 - 1 mm.

1. INTRODUCTION

Future commercial fusion reactors need to accommodate themselves to higher power density core plasma than those of ITER EDA design [1]. Divertor plates of such high power density tokamaks will be irradiated by very high heat and particle load. Therefore, the removal of high heat load and the reduction of surface erosion of divertor plates become major issues of fusion engineering.

Several concepts of moving divertor are proposed for high heat load application using liquid metal thin film flow [2], droplet [3] and carbon fiber belt [4, 5]. A pebble drop divertor is a new concept applicable to the environment of very high heat load ($> 20 \text{ MW/m}^2$) and particle loading ($> 10^{24} \text{ atoms/m}^2\text{s}$). In the pebble drop divertor, a large number of small refractory pebbles (divertor pebbles) are used as divertor surface. These divertor pebbles are dropped in the divertor space to form a curtain as shielding the striking zone of divertor [6].

Although there was a simple movable limiter concept study by using graphite spheres (10 - 20 mm in diameter) [7], a marked feature of our pebble drop divertor system is the use of multi-layer pebble. The multi-layer pebble consist of a kernel, a Plasma Facing Layer (PFL) and an intermediate Tritium Prmeation Barrier (TPB). Each layer has different functions that are necessary for divertor materials.

At the first phase of conceptual design, we estimated the operation limits of pebble divertor obtained from induced thermal stress in the kernel. The rise of surface temperature, which affects the wall pumping performance were also estimated.

2. OVERVIEW OF PEBBLE DROP DIVERTOR SYSTEM

The pebbles are the essential components of the pebble drop divertor system. The multi layer pebbles consists of at least three layers to satisfy the requirements for plasma facing material (Fig.1a). A kernel is made from graphite or low-Z refractory ceramic like SiC, BeO or Al_2O_3 . The mechanical strength, the thermal stress and the heat capacity of a pebble depend on the kernel. PFL is selected for the compatibility to core plasma. And the continuous wall pumping concept is realized by the hydrogen getter PFL and the regeneration process outside divertor like a carbon sheet pump [8] for the fusion device. The low erosion character is not critical issue for the PFL, because the irradiation

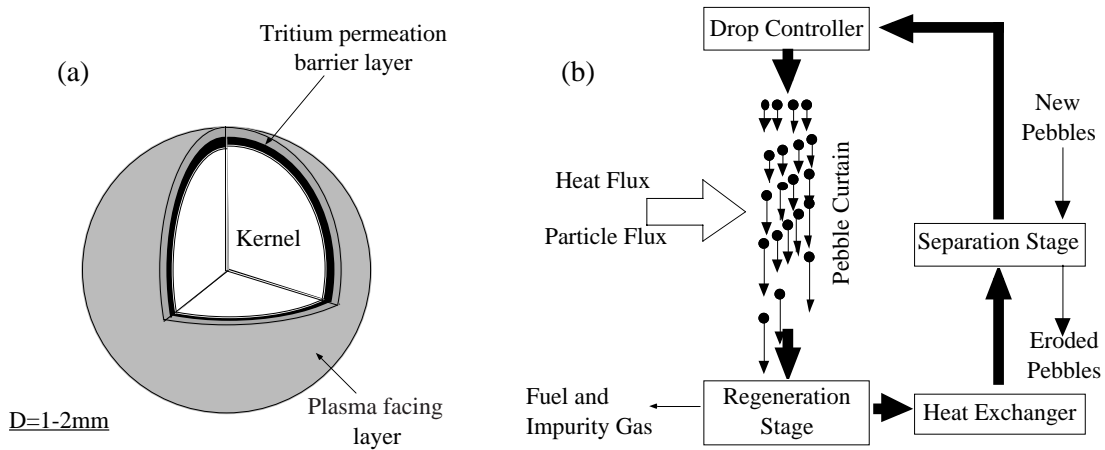


FIG. 1. The pebble drop divertor concepts and the components. (a) multi-layer coating pebble, (b) schematic drawing of pebble cycle

period of falling pebble is very short. Moreover, eroded pebbles can be removed at the outside the divertor. Therefore, conventional low-Z materials and coating techniques can be used for PFL. By using plasma surface interaction characteristics of PFL material, the pebble drop divertor can control divertor plasma; for example, wall pumping and impurity gettering. An intermediate TPB layer prevents tritium diffusing from PFL to the kernel. The TPB realizes both wall pumping function of PFL and low bulk tritium retention in the pebble. The candidate materials of TPB are Al_2O_3 , TiC, TiN [8] or SiC [10]. Additional new layer such as an intermediate high-Z layer can introduce some functions. The layer will quickly cool down plasma when PFL is evaporated in disruption events.

The pebble drop divertor system consists of (1) a drop controller array, (2) pebble processing systems including a regeneration stage, a heat exchanger and the separation stage of eroded pebbles, (3) a conveying system (Fig. 1b). The drop controller array operates to form the seamless pebble curtain at the striking zone of divertor. In the case of typical operational condition, the divertor pebbles of 1 - 2 mm in diameter is dropped from 0.5 - 1.0 m above from striking zone. Each drop controller operates at 50 - 70 Hz and at least 35 - 70 rows of the drop unit in single segment.

After the exposure of pebbles to the divertor plasma, the PFL is saturated by deuterium, tritium and impurities. In the regeneration stage, divertor pebbles are heated and release retained gas to recover the pumping capacity. After that, the divertor pebbles are cooled in heat exchanger. When wall pumping function of pebble divertor is needed, divertor pebble must be cooled to about 500 K. In the separation stage, eroded pebbles are removed and new ones are supplied to the cycle

By using multi-layer pebbles as divertor surface components and the external pebble processing systems, pebble drop divertor system has the following features, (1) pebble conveying without MHD problem, (2) simultaneous removal of incident heat flux and particle flux, (3) both pumping function and low bulk tritium are realized by TPB, (4) the feasibility of divertor plasma control by mixing various pebbles with different PFL, (5) continuous replacement of eroded divertor surface. Furthermore, the fabrication technology of multi-layer coated ceramic pebbles has been developed for High Temperature Gas-Cooled Fission Reactor (HTGCR). The fuel particle of HTGCR consists of UO_2 kernel, carbon layers and SiC layers. Therefore the divertor pebble with carbon and SiC layer can be developed with present technology.

3. MAXIMUM HEAT LOAD OF DIVERTOR PEBBLE

The thermal stress of the pebble induced by incident heat flux limits the maximum heat load. And the rise of surface temperature during irradiation strongly affects the wall pumping performance.

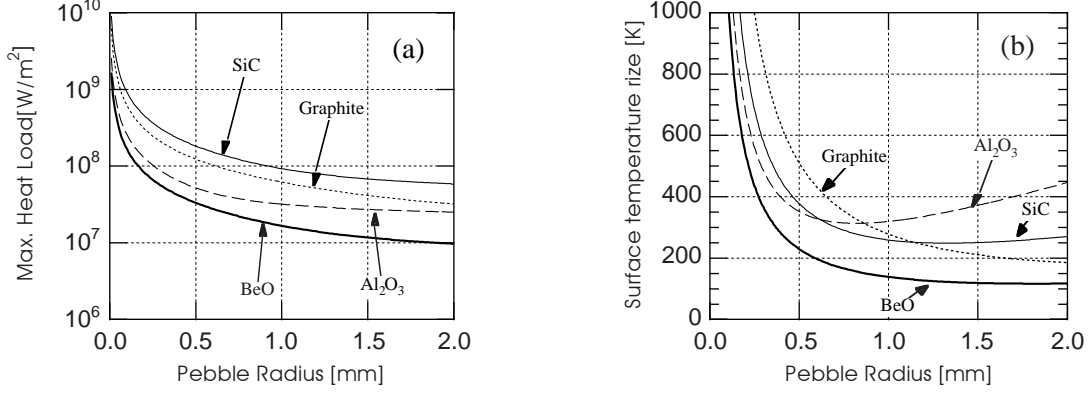


FIG. 2. The maximum heat flux and the surface temperature rise of divertor pebble in typical operation of the pebble drop divertor. (a) Maximum heat flux as a function of pebble radius (irradiation time: 30ms). (b) Surface temperature rise during irradiation at incident heat flux of 30MW/m².

The retained hydrogen in PFL is decrease with the rise of surface temperature. Therefore, allowable maximum surface temperature is determined by the pumping requirement. In the multi-layer pebbles, these thermoelastic characteristics are dominated by kernel material.

When the incident heat flux is distributed uniformly on the surface of pebble, the thermal stress of a solid sphere only depends on its radius. And the radial stress shows the maximum tensile stress at the center of pebble and the angular stress shows the maximum tensile stress at the center and the maximum compressive stress at the surface. The maximum allowable surface heat flux is estimated such that the surface stress does not exceed the compressive strength of kernel material. The surface stress shows the maximum just after the pebbles go out of the striking zone. Therefore, the stress at the point was used in the estimation of the maximum heat flux. In this estimation, the width of striking zone was assumed to be 0.12 m. And the divertor pebbles were assumed to be dropped from 1 m above the striking zone. In this case the irradiation period was about 30 ms.

Figure 2a shows the maximum heat flux *on the surface of pebble* as a function of the radius of the kernel. Although the smaller pebble has higher heat load resistance, the divertor pebble of 0.5 - 1 mm in radius are safe in 30 MW/m² heat load. In the candidate materials, SiC and graphite allow higher heat load. In fact, BeO has the highest heat capacity and shows the lowest temperature rise. However, it's high induced stress prevents high heat load application.

Figure 2b is the rise of surface temperature at the divertor heat flux of 30 MW/m². The results shows the lower limit of pebble size is determined by the allowable surface temperature. From both thermal stress and surface temperature estimation, The optimum size of divertor pebbles is 0.5 - 1 mm in radius.

4. IRRADIATION CONDITION IN TOKAMAK

In previous chapter, the uniform heat load is assumed for the thermal stress estimation, The pebble irradiated in tokamak needs to consider the incident angle of heat flux due to the strong troidal field. If almost all the particles come along magnetic field, the incident angle of these load will be very small. As shown in Fig. 3a, small incident angle irradiation cause to make shadow area on the surface of pebble. To estimate the effect of non-uniform heat load, the 3D stress evaluations were carried out. Figure 3b shows the stress distribution of SiC kernel of 0.5 mm in radius. The incident angle, the distance between pebbles and heat flux on irradiated area were assumed to be 5 degree, 2 mm and 30 MW/m² respectively. The irradiation period was 30 ms.

The thermal stress on the surface is only compressive one. This result shows that the

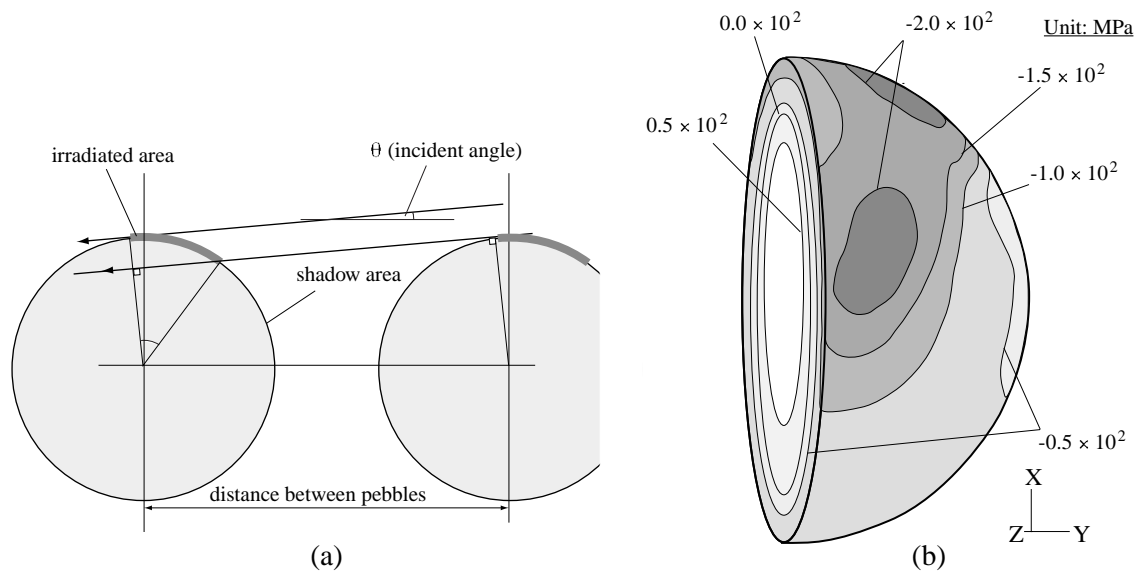


FIG. 3 Thermal stress of divertor pebbles in tokamak irradiation. (a) irradiation condition in strong toroidal field, (b) stress distribution of SiC kernel, 1mm in diameter and heat load is 30MW/m^2 in irradiated area

compressive strength of kernel material can be used for the evaluation of maximum heat load in the non-uniform load condition. The maximum surface stress is 230 MPa and it is lower than 377 MPa obtained from the result of uniform 30MW/m^2 of heat flux. Therefore the maximum heat load estimated by the induced thermal stress of uniform heat load (Fig. 2a) is considered to be useful value for the base of conceptual design.

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