Helium Permeability of SiC/SiC Composite Used for Blanket First Wall

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Abstract. SiC/SiC composite is a candidate structure material for solid breeding blankets. A high energy conversation efficiency is expected for this blanket since the operation temperature is taken high, about 1100 K. One of concerns in use of SiC/SiC composite is helium gas permeation from helium gas coolant pipes into plasmas. The helium gas permeability was measured for numerous SiC/SiC composites using a vacuum system consisting two chambers. The SiC/SiC composite made by NITE process showed very low gas permeability, 10^{-11} m^2/s. The helium gas permeability was also measured after heat cycles. The permeability remained the same when the heating rate was taken below 10 K/s. These results suggest that the blanket can be made by using only SiC/SiC composite. Required condition for this blanket to avoid fuel dilution is discussed.

1. Introduction

The use of low activation materials has been desired for blankets and first walls in fusion demonstration reactors. As the low activation materials, the candidates are low activated ferritic steel such as F82H [1], vanadium alloy [2] and SiC/SiC composite [3]. The effects of neutron damage on the changes of mechanical and thermal properties have been investigated so far. The operation temperature regime determined by ductile-brittle transition temperature and creep occurrence temperature has been discussed based upon the experimental results. Since these materials are used for first blanket walls, the influence of these materials on fusion plasmas has to be clarified. In the blanket made by SiC/SiC composite [4], very high energy conversion efficiency is expected since the coolant outlet temperature is taken high, approximately 1100 K. High pressure helium gas will be employed as the coolant in this blanket concept. SiC/SiC composite is a ceramics material, so that one of concerns is a leak of helium gas into the fusion plasma. The leak rate has to be lower than the helium production rate by fusion reactions in order to avoid the fuel dilution [5].

Numerous SiC/SiC composites have been developed for the fusion and fission applications by the group of Kyoto University and Ube Industries [6]. The helium gas permeabilities of these SiC/SiC composites were measured at room temperature using a vacuum apparatus consisting of two chambers in Hokkaido University. The SiC/SiC composite recently developed by NITE process showed a very low permeability [4]. It suggests that the blanket is produced using only the SiC/SiC composite without use of metals. There is another concern on the permeability. The blanket module receives heat cycles owing to start up and shut down in the fusion reactor. Hence, the change or increase of the permeability due to the heat cycles has to be investigated. In the present study, the helium gas permeability is measured for numerous SiC/SiC composites. In addition, the heat load is applied for the SiC/SiC composite and the change of helium gas permeability after the heat cycles is measured. The heat load condition for the permeability not to increase is presented. Based upon these results, the conditions required for the SiC/SiC blanket module are discussed.

2. Experiments

The helium gas permeabilities were measured for SiC/SiC composite samples made by several methods, HP: hot pressing, PIP: polymer infiltration and pyrolysis, PIP+MI: PIP and melt infiltration, NITE: nano powder infiltration and transient eutectoid. As the samples made by NITE process, three SiC/SiC composites (NITE commercial, NITE lab.(M/N), NITE lab(N)) and bulk SiC (NITE bulk) were employed. The SiC/SiC composites except HP consist of two layers, SiC fiber bundle layer and SiC matrix layer. The fiber bundle layer consists of unidirectional SiC fiber bundles with SiC matrix. As the SiC fiber, Tyranno SA fiber tows coated by pyrolytic carbon (Ube Industries) was used. The sample of HP consists of only fiber bundle layer. The samples made by HP, PIP and PIP+MI have relatively a large pore structure. The bulk SiC (NITE bulk) was made using only nano powder of β-SiC. The nano powder of β-SiC was used for the matrix layer in every SiC/SiC composite sample made by NITE process. The nano powder of β-SiC was used for the matrix of the fiber bundle layer in NITE lab.(N). The micro powder of β-SiC was used for the matrix of the fiber bundle layer in NITE commercial and NITE lab.(M/N). NITE commercial is a commercial pilot grade of NITE lab.(M/N). The shape of every sample was a flat plate with a size of 15 x 15 x 2 mm.

The helium gas permeability was measured using a vacuum device consisting two chambers, high pressure chamber and low pressure chamber, as shown in *FIG 1*. The sample was fixed on a stainless steel pipe between two chambers using a vacuum seal, epoxy resin. The sample temperature was a room temperature, RT. The direction of helium gas flow was taken perpendicular to the fiber bundle and matrix layers. The low and high pressure chambers were evacuated using diffusion and rotary pumps. The pressure in the high pressure chamber was adjusted using mass flow controller, ionization gauge and mercury manometer. The pressure was taken in the range from 1×10^2 to 5×10^5 Pa. The pressure increase in the low pressure chamber was measured after adjusting the pressure in the high pressure chamber. Since the range of the pressure rise is very broad, numerous vacuum gauges, spinning rotor gauge, BA ionization gauge and quadruple mass spectrometer, were used according to the pressure rise. The helium gas permeability, K (m^2/s), was determined using

$$K = P_L \, d \, S_{eff} \; / \; P_H \, A, \qquad (1)$$

where P_L and P_H are pressures rise in the low pressure chamber and the pressure in the high pressure chambers, respectively, d and A are thickness and area of sample, and S_{eff} is the effective pumping speed in the low pressure chamber. Equation (1) is applied if the helium flow is a molecular flow, not a viscosity flow. In this case, the permeability becomes constant for the pressure in the high pressure chamber. The heat load was applied using a resistive heating for a tantalum (Ta) container with the sample in the other vacuum device. The highest temperature in the surface facing the Ta container was taken in the range from 1000 to 1400 K. The operation temperature in the SiC/SiC composite is assumed to be 1100 K. In the present experiment, the temperature range covers the operation temperature. The heating rate was taken 6, 8 and 10 K/s and the holding time at the highest temperature was 5 min. In the operation of the SiC/SiC composite blanket, the heating rate can be adjusted by using helium gas flow. The number of heat cycle was taken as large as 120. After the heat cycles, the sample was transferred to the permeability measurement device.

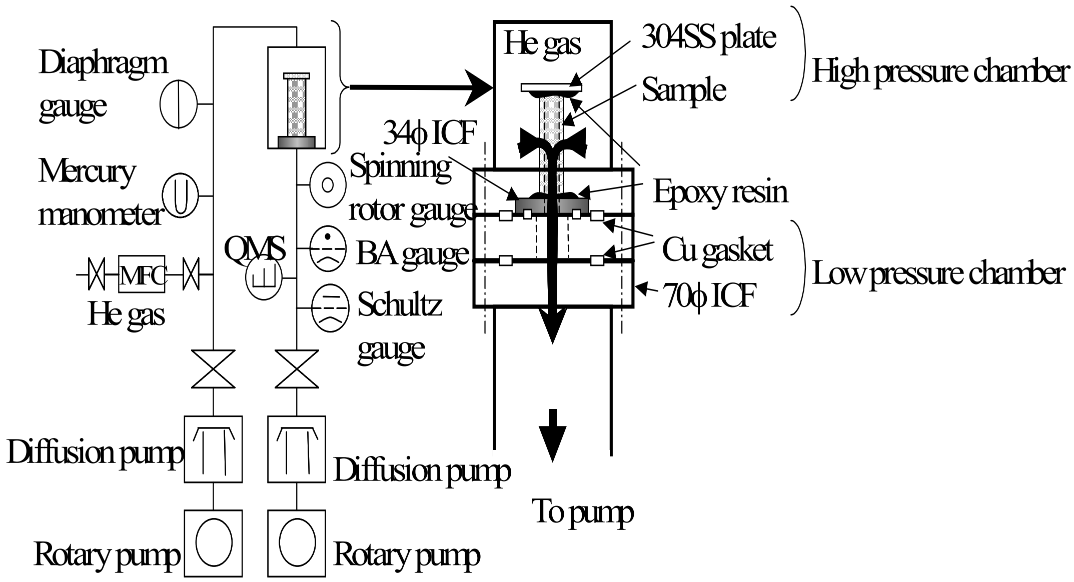

***FIG 1** Vacuum device for measurement of helium gas permeability.*

3. Results

The permeability was measured for numerous SiC/SiC composites before applying the heat load. *FIG 2* shows a plot of the helium gas permeability against the pressure in the high pressure chamber. The permeability was approximately constant to the pressure in the high pressure chamber. The samples made by PIP, HP and PIP+MI had relatively high permeability, 10^{-6} – 10^{-4} m^2/s. The surface morphologies of these samples were observed using scanning electron microscope. The pores of micron size were observed in these samples. There is a tendency that the permeability becomes large with the porosity. In the samples made by NITE process, the permeability was very low, in the range from 10^{-13} – 10^{-7} m^2/s. The bulk SiC, NITE bulk, made by only nano powder of β-SiC, had a lowest permeability. As the SiC/SiC composite, NITE lab.(N) using only nano powder of β-SiC for the matrix both in the fiber bundle layer and matrix layer, had a lowest permeability, 10^{-11} m^2/s. NITE lab.(M/N) or NITE commercial had the permeability several order of magnitude higher than that of NITE lab.(N). The NITE samples had a dense structure without pores of micron size. The helium permeation thus can be significantly suppressed by the dense structure.

The permeability was measured for NITE commercial after applying heat cycles. The permeability of NITE commercial before the heat load depended on the sample, and the permeability was in the range from 4 x 10^{-8} to 10^{-7} m^2/s. The heat cycles with highest temperature from 1000 to 1300 K and heating rate from 6 to 10 K/s were applied. The increase of the permeability was not observed for the heat load with heat cycles of 120, highest temperature of 1200 K and heating rate of 10 K/s. At the highest temperature of 1300 K and the heating rate of 10 K/s, the increase of the permeability was not observed for the number of heat cycles smaller than 90. However, the increase of the permeability was observed when the number of heat cycle was 120. This reason is discussed later based upon the photographs taken by scanning electron microscope. *FIG. 3 (a)* and *(b)* show the helium gas permeability versus pressure in the high pressure chamber for the cases with heating rate of 10 K/s and highest temperatures of 1200 K and 1300 K, respectively.

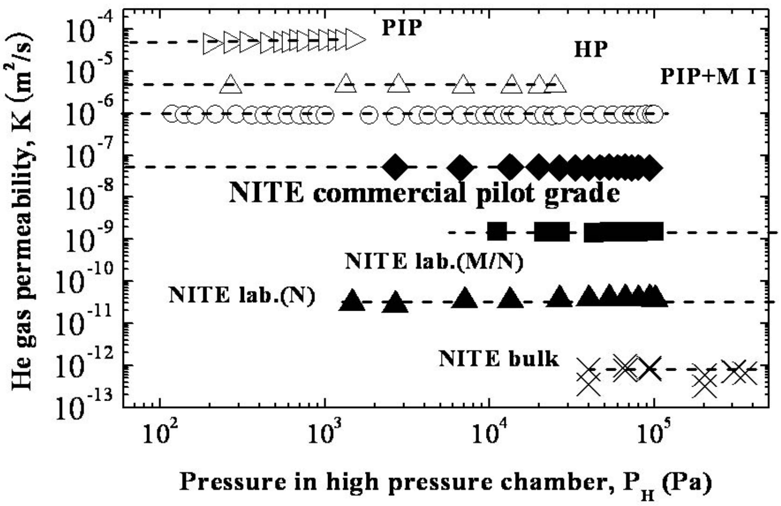

FIG. 2 *Helium gas permeability versus pressure in high pressure chamber for numerous SiC/SiC composites.*

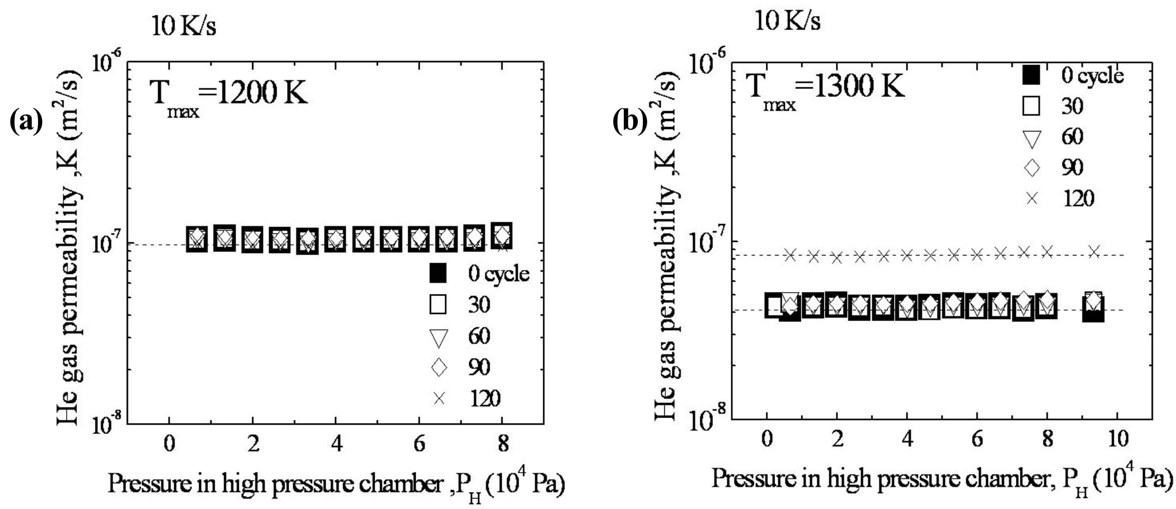

FIG. 3 *Helium gas permeability of SiC/SiC composite, NITE commercial, versus pressure in high pressure chamber, after heat cycles with heating rate of 10 K/s and highest temperatures of 1200 K* ***(a)*** *and 1300 K* ***(b)****.*

FIG. 4 shows the increasing ratio of the permeability, $\Delta K/K$, versus number of heat cycle, for different highest temperatures, T_{max}, when the heating rate was 10 K/s. Here, ΔK is the increase of permeability after the heat cycles. *FIG. 5* shows the increasing ratio of permeability versus number of heat cycle for different heating rate when the highest temperature was 1300 K. In the case of 1300 K and 10 K/s, the increasing ratio of permeability was not large, only approximately 1.6. The highest temperature was increased to 1400 K, and the increase of the permeability was measured after 120 heat cycles. In every case, the increase of the permeability was observed. *FIG. 6* shows the region without increase of permeability in a diagram of highest temperature versus heating rate. In this figure, open circle and cross show no increase and increase of permeability, respectively. This figure is useful to design the maximum operation temperature and the heating or cool down rate of the SiC/SiC composite blanket. The increase of the permeability is easily avoided if the operation temperature is kept lower than 1100 K.

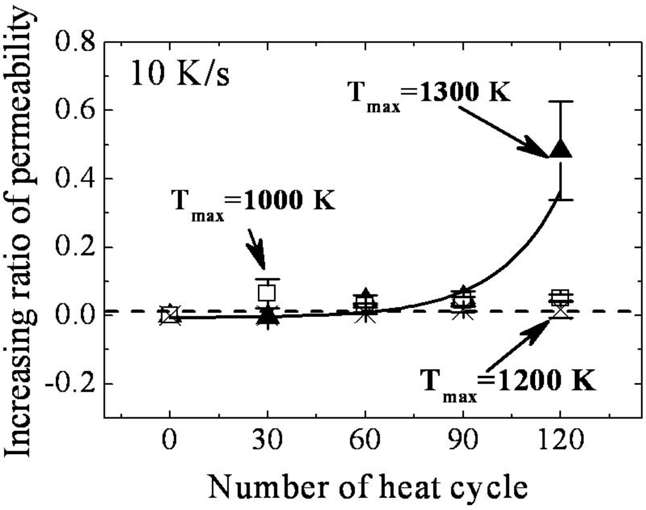

FIG. 4 Increasing ratio of helium gas permeability versus number of heat cycle for heating rate of 10 K/s at different highest temperatures.

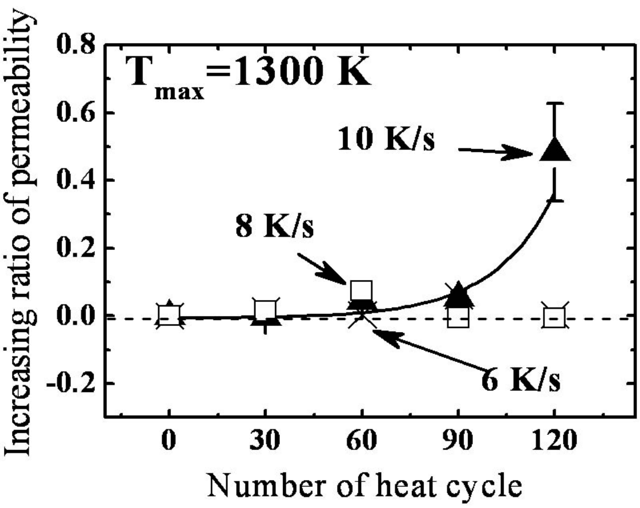

***FIG. 5** Increasing ratio of helium gas permeability versus number of heat cycle for highest temperature of 1300 K at different heating rates.*

In order to consider the reason for increase of permeability, the surface morphologies of the sample before and after the heat load were observed using scanning electron microscope. *FIG. 7* shows the parts of fiber bundle and matrix layers after 120 heat cycles with highest temperature of 1300 K and heating rate of 10 K/s. After the heat cycles, the matrix was lost in the fiber bundle layer and the matrix with a micron size was lost in the matrix layer. The small fragments remained on the tantalum container were also observed using scanning electron microscope. The size of the lost piece or fragment was in the range from 1 to 100 μm. Most of the fragment had a size from 2 to 8 μm. The cracking might have been caused by the thermal stress during the heat load.

In order to apply the SiC/SiC composite to a blanket, one of concerns is the leak of helium gas coolant into the fusion plasma. The leak rate has to be taken lower than the helium production rate by fusion reactions to avoid the fuel dilution. For this sake, the blanket module has to be evaluated to reduce the helium pressure inside of the module, and the heating or cooling down temperature has to be taken to avoid the increase of helium gas permeability. We now discuss on the helium gas permeation into the plasma.

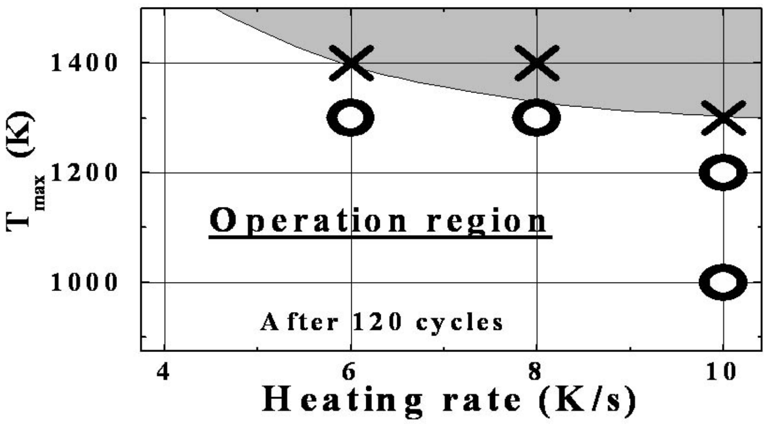

FIG 6 *Operation region of SiC/SiC composite blanket in diagram of highest temperature and heating rate.*

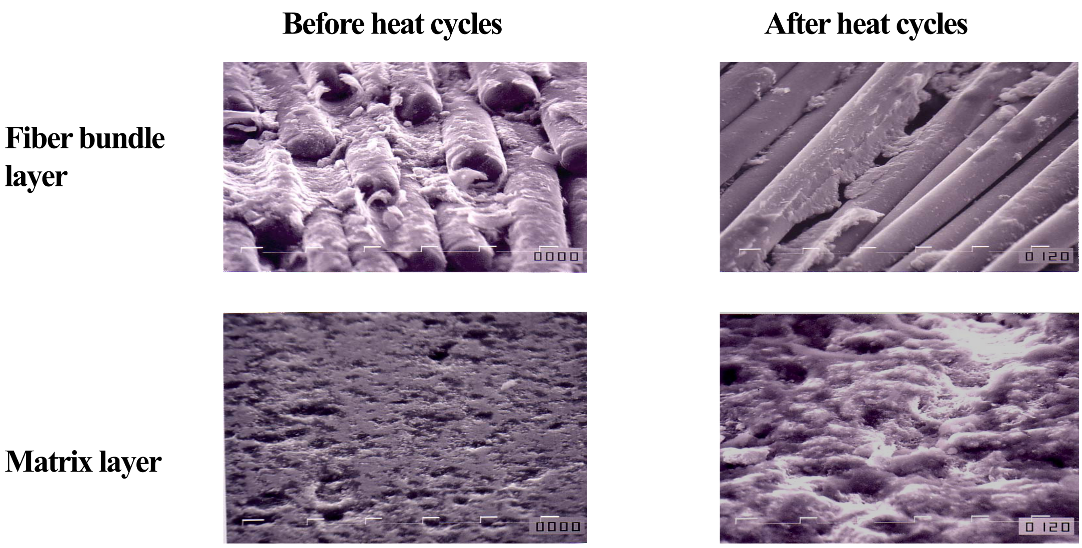

FIG 7 *Surface morphologies of fiber bundle layer (upper) and matrix layer (bottom) before and after heat cycles with cycle number of 120, highest temperature of 1300 K and heating rate of 10 K/s.*

Since the permeability of SiC/SiC composite made by NITE process can be kept low, we examine the requirements for NITE Commercial with a permeability of 10^{-8} m^2/s. For this analysis, we assumed the apparatus of SiC/SiC composite blanket shown in *FIG 8*. Here, all components such as coolant pipe and first wall are the SiC/SiC composite. The leak rate through the first wall into plasma has to be lower than the helium production rate of fusion reaction

$$n^2_{DT} <\sigma v>_f V_p / 4 > K\, n_B\, S_f / l_f, \quad (2)$$

where n_{DT} = 10^{20} m^{-3} is the plasma density, $<\sigma v>_f = 10^{-22}$ m^3/s fusion reaction rate for DT plasma temperature of 10 keV, Vp = 2πR x πa^2 plasma volume, R = 7m major radius, a = 2 m plasma radius, l_f = 0.02 m thickness of blanket first wall, S_f = 2πR x2πa surface area of blanket first wall and K helium permeability. In a steady state, the helium leak rate through the blanket first wall is balanced with the helium leak rate from the coolant tubes into the inside of the blanket module as follows

$$K\, n_B\, S_f / l_f \simeq K\, n_C\, S_C / l_C, \quad (3)$$

where n_C = 1.4 x 10^{27} m^{-3} the helium density of the coolant for the helium pressure of 200 atm at 1100 K, lc = 0.01 m thickness of coolant pipe and S_C total area of coolant pipes. The permeability has to satisfy the condition

$$K < a\, l_C <\sigma v>_f n^2_{DT} / 8\, n_C. \quad (4)$$

We then obtain K < 2x10^{-12} m^2/s. Thus, it may be difficult to suppress the helium leak.

In order to satisfy the condition given by eq. (2), the additional pumping for the blanket module is required as shown in *FIG 8*. It is desirable for the pumping speed to be low. The helium density inside of the blanket module is determined by

$$Q = P_B\, S^B_{eff}, \quad (5)$$

where Q = 110 Pa m^3/s flow rate from coolant pipe to the inside of blanket module, P_B helium gas pressure inside of blanket module and S^B_{eff} effective pumping speed. When S_{eff} = 100 l/s = 0.1 m^3/s, P_B becomes 10^3 Pa. Thus n_B becomes 9 x 10^{22} m^{-3}. If K < 10^{-8} m^2/s, n_B has to be lower than 5 x 10^{23} m^{-3} from eq. (2). Thus, the pumping speed of 100 l/s satisfies the condition given by eq. (2). Namely, the increase of helium density due to the leak into plasma can be kept lower than the helium density produced by fusion reaction. Even if the permeability increases up to 10^{-7} m^2/s, the required pumping speed is 1000 l/s, not large. The present analysis shows that the blanket module can be made by using only SiC/SiC composite, if the vacuum pumping with relatively low pumping speed is attached to the blanket module.

4. Conclusion

In the use of SiC/SiC composite in the blanket, one of major concerns is a helium gas leak into the fusion plasma. For numerous SiC/SiC composites, the helium gas permeability was measured using a vacuum device consisting two chambers. The helium gas permeability of the SiC/SiC composite made by NITE process showed a very low permeability, as low as 10^{-11} m^2/s. This reason is owing to the very dense structure without micron size pores. The helium gas permeability was also measured for the SiC/SiC composite, after applying the heat load with a number of heat cycles up to 120, highest temperature during a heat cycle up to 1400 K and heating rate up to 10 K/s. The increase of the permeability was observed under the severe condition, highest temperature of 1300 K, heating rate of

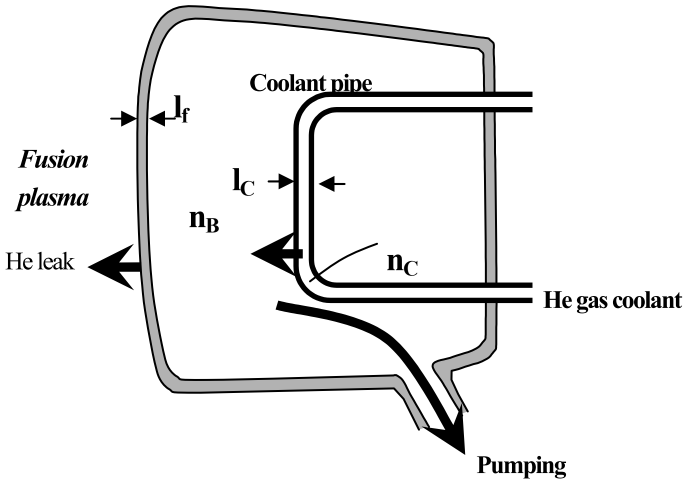

FIG 8 *Schematic diagram of SiC/SiC composite blanket module.*

10 K/s and number of heat cycles of 120. The matrix parts with a micron size were lost both in the fiber bundle and the matrix layers due to the thermal stress. The operation region without increase of permeability, in the diagram of highest temperature and heating or cooling down temperature, was obtained. The operation temperature of the SiC/SiC composite blanket is regarded 1100 K, so that the increase of permeability can be avoided if the heating or cooling rate is suitably chosen. Although the additional pumping is required for SiC/SiC composite blanket module in order to avoid fuel dilution in fusion plasmas, the pumping speed required for the evacuation system is very low. Thus, the additional pumping does not increase the cost of blanket modules.

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