Fuel Particle Balance Study in FFHR DEMO Reactor*)

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Tritium particle balance in the FFHR DEMO reactor is investigated with consideration of the fueling efficiency by pellet injection system, retention loss in a vacuum vessel and permeation loss from the fuel processing system. In order to satisfy the fuel balance and the tritium safety management, it was necessary to suppress the tritium retention rate to be 10^{-5} and the DFs in the tritium cycle systems to above 10^{7} with the tritium breeding ratio of 1.08. The processing throughput for the tritium processing system is estimated to be about 400 mol/h, which is almost same as the throughput of the fuel stream for the ITER. Therefore, the tritium processing system for vacuum exhaust gas for the DEMO will not be necessary to improve the system for the ITER further. On the other hands, the significant development of the tritium processing system for the effluent disposal and the waste materials from the safety aspect and the social acceptance will be required toward the DEMO reactor.

Keywords: particle balance, DEMO reactor, tritium processing system, fueling efficiency, tritium retention, tritium permeation, decontamination factor, tritium safety handling

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1. Introduction

Conceptual design studies of the LHD-type helical DEMO reactor FFHR-d1 have been conducted by integrating wide-ranged R&D activities on core plasmas and reactor technologies [1]. As for the reactor systems, the establishment of the fuel cycle system is one of key issues for a fusion DEMO reactor. The first step to consider the fuel cycle system would be estimated the fuel particle balance and the flow in the fusion reactor system. The scenario of steady state fuel particle balance is as follows: the fuel particles are supplied into vacuum vessel via the fueling system such as pellet injection, gas puff, etc. A part of supplied fuel particles is ionized and burned in the core plasma, and the rest of fuel particles transports to the edge plasma region. Then, although the fuel particles and the helium ash are exhausted from the vacuum vessel, various interactions between plasma, neutral particle and material are occurred in the edge and the diverter plasma region. As the results, a small amount of the fuel particles is trapped in the wall by the retention and it is the loss of fuel particles [2]. The exhausted fuel particles and helium ash are separated and purified by fuel processing system. On the other hand, tritium from the blanket system and external deuterium are supplied for fuel cycle system to replenish burned fuel particles. Then, the fuel particles from both the fuel processing system and the blanket system are temporarily stored in the fuel storage bed and supplied to fuel injection system according to demand. In the fuel cycle loop, however, a part of the fuel particles are loss from the fuel processing system and the wall by permeation. These fuel particle losses are considered to affect on the fuel balance. As an inevitable consequence, tritium loss causes the requirement of higher tritium breeding ratio in the blanket system.

In order to consider the fuel balance in fusion reactor system, hence, the fueling rate or burning rate in core plasma, the tritium breeding ratio (TBR) and the tritium loss rates both the permeation from the wall and the retention in the vacuum vessel would be critical parameter. In previous studies, the steady state and the dynamic analytical model of fuel balance have been reported with regard to the tritium inventory in the fuel cycle, the flow rate information throughout the fuel cycle, the efficiency of a tritium processing system, fueling scenario, the effect of tritium loss, and TBR, etc [3–9]. In this report, in order to understand the behavior of tritium balance, the simple steady state tritium particle balance model which takes into account the fueling efficiency into core plasma and loss of tritium was developed.

2. Analytical Model

The tritium particle balance model on FFHR2m2 is based on Takenaga *et al.* [5]. In the model of Ref. 5, however, the particle loss in the fuel cycle processing system, tritium retention and loss were not considered in detail. In this report, the simple particle balance model considered both main plasma and fuel cycle systems is prepared. Figure 1 shows the schematic diagram of tritium balance analysis model. In this model, to discuss the effects of fueling efficiency and the tritium loss due to the permeation

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and the retention, it is assumed that tritium is fueled by only pellet injection in the main plasma. Then, we introduce a parameter of the fuel efficiency "α" of pellet injection. It is defined as the ratio of the number of hydrogen atoms in the plasma and the total number of hydrogen atoms from external fuel sources [10]. The detailed analysis of pellet injection is in progress under the FFHR design activity [1]. Additionally parameters of tritium loss ratio by permeation "R_p" from the wall and retention in the vacuum vessel "R_r" are also introduced in the model.

In the steady-state tritium balance, the total numbers of tritium in the main plasma and the balance of fueling and pumping are expressed as

$$N = \tau_c[\alpha S_F - S_L] + \tau_e[S_R + (1-\alpha)S_F], \tag{1}$$

$$f_{pump}\Phi_{div}(1 - R_r) = S_F - S_L - \Phi_{div}R_r, \tag{2}$$

$$\Phi_{div} = S_F - S_L + S_R, \tag{3}$$

where N is the total number of particles in the main plasma, S_L is the sink rate due to fusion reaction in the main plasma, S_F is the fueling rate in the main plasma, and S_R is the recycling rate, τ_c and τ_e are the particle confinement times for the main and edge plasma, f_{pump} is the divertor pumping fraction, Φ_{div} is the flow rate to the divertor plates. Equation (1) indicates the particle balance in the main plasma. Equations (2) and (3) express the balance of fueling and pumping. According to the results of the Large Helical Device (LHD) experiments, the fueling efficiency of 0.5-0.9 is observed [11] and the divertor pumping fraction has dependence on the divertor plasma density and temperature [12]. Thus, the pumping fraction in the helical type DEMO reactor might be in the range of less than 10%. The detail divertor design for the FFHR is now in progress [13]. In this paper, since particle balance in a steady-state operation with the fixed number of particles is discussed, the divertor pumping fraction is fixed at 5% in this model.

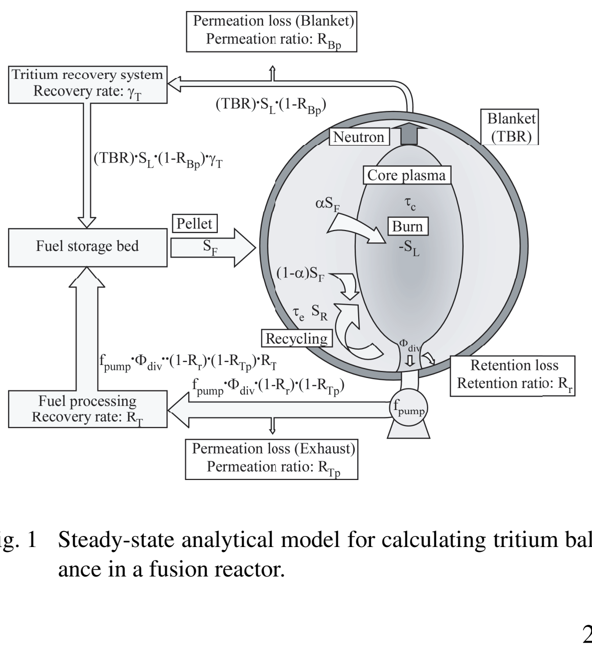

Fig. 1 Steady-state analytical model for calculating tritium balance in a fusion reactor.

In order to consider the flow of tritium processing system, we introduce the tritium balance considering the tritium processing systems for the exhaust gas and the blanket expressed as

$$\begin{aligned} S_F = {} & f_{pump}\Phi_{div}(1 - R_r)(1 - R_{Tp})R_T \\ & +(\mathrm{TBR})S_L(1 - R_{Bp})\gamma_T, \end{aligned} \tag{4}$$

where R_T and γ_T are the recovery ratio for the tritium processing system and the blanket tritium recovery system, and R_{Tp} and R_{Bp} are the permeation ratios from the wall and assumed to be almost equal ($R_P \sim R_{Tp} \sim R_{Bp}$) in this report. For the analysis of tritium balance in a steady-state condition, S_F and S_R are derived from Eqs. (1) through (3). The relation between α and R_T is then estimated from Eq. (4).

The design parameters were adopted from the FFHR2m2 [14]. According to the design parameter for the fusion power of 3 GW, N was 1.48×10^{23} particles, S_L was 1.2×10^{21} particles/s, and τ_c was 2.6 s. The particle confinement time for the edge plasma τ_e is assumed to be 2.6 ms, because the particle confinement in the edge plasma of a helical type device is much smaller than the particle confinement time in the main plasma [15].

3. Analytical Results and Discussion

3.1 Effect of fueling efficiency into core plasma

Figure 2 indicates the analytical results of the dependence of the tritium recovery ratio in the tritium processing system as a function of the fuel efficiency of pellet injection, where it is assumed that f_{pump} is 0.05, γ_T is 0.99, R_r is 5×10^{-5}, and R_p is 5×10^{-5}. The area bounded by the line of analytical results and below the line of $R_T = 1$ represents the self sufficient region to be able to keep the tritium balance. In this case, a high tritium recovery ratio for the tritium processing system is required with a decrease in the fuel efficiency of the pellet injection. For TBR = 1.08, which corresponds to the design parameter of FFHR2m2, a fuel efficiency of more than 0.68 is required to maintain

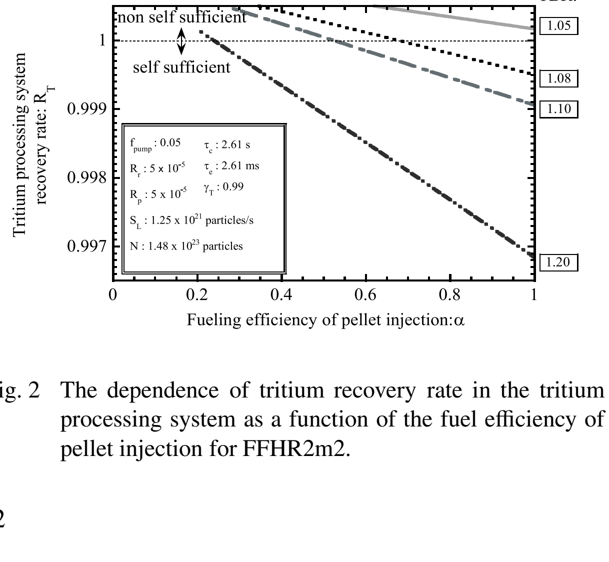

Fig. 2 The dependence of tritium recovery rate in the tritium processing system as a function of the fuel efficiency of pellet injection for FFHR2m2.

the tritium balance under these assumptions. The tritium recovery rate in the tritium processing system and the fuel efficiency of the pellet injection must be as high as possible in order to achieve tritium balance in a fusion reactor within acceptable loss rate. In other words, analysis indicates that the design parameters in the fueling efficiency in the core plasma and the blanket system with reasonable TBR are key factors to keep the tritium fuel balance.

3.2 Effect of recovery rate in the fuel cycle

Figure 3 shows the fuel self-sufficiency condition for the FFHR DEMO reactor system as the functions of TBR and the recovery rate for the tritium processing system and the tritium recovery system for blanket, R_T and γ_T, assuming that f_{pump} is 0.05, α is 0.85, R_r is 5×10^{-5}, and R_p is 5×10^{-5}. It is indicated that the recovery rate satisfied the fuel balance for R_T are required higher value than that for γ_T. For example, in the case of TBR = 1.08, the recovery rate satisfied the fuel balance for R_T is 0.9999 [DF = 10^4] as compared with 0.99 [DF = 10^2] for γ_T. In other words, the required decontamination factor for R_T is much higher than that for γ_T. This difference in the DF values of R_T and γ_T is attributable to the fact that the amount of tritium being processed is much larger in the vacuum exhaust gas than in the blanket processing system, due to the fuel burn-up in the core plasma being as small as few percents. Consequently, when considered from the viewpoint of the tritium fuel balance, the realization of a fuel self-sufficient condition would be premised upon the establishment of a fuel processing technology providing extremely high efficient treatment.

3.3 Safety aspect of the tritium management

From the viewpoint of the tritium safety handling, the amount of the tritium loss from the fuel cycle system and by the retention in the materials should be reduced. Figure 4 indicates the tritium loss per day from the fuel cycle system of both the blanket system and the tritium processing system for vacuum exhaust gas as the functions of the decontamination factor where it is assumed that f_{pump} is 0.5 α is 0.85, R_r is 5×10^{-5}, and R_p is 5×10^{-5}. According to the section 3.2, the DFs of 10^4 for R_T and 10^2 for γ_T are able to satisfy the fuel balance. In these parameters, the tritium loss from the system is estimated to be about 10 g/day. To reduce the tritium loss from the fuel cycle system, the DF for the tritium processing system has to be high, because the processing of vacuum exhaust gas is the main stream for fuel cycle. However, the tritium loss from the fuel cycle is not able to restrain as long as the DF of the tritium recovery system for the blanket is low. From the standpoint of tritium safety management, the DF for both the fuel cycle and the blanket system should be high more than 10^7.

In order to satisfy the fuel balance and protect occupationally exposed workers it is necessary to restrict the amount of tritium retention in the wall. Figure 5 shows the tritium retention in vacuum vessel as the functions of the pumping fraction and the tritium loss ratio, assuming that α is 0.85, R_T is 0.9999, γ_T is 0.99, and R_p is 10^{-5}. The amount of tritium retention increases as the pumping

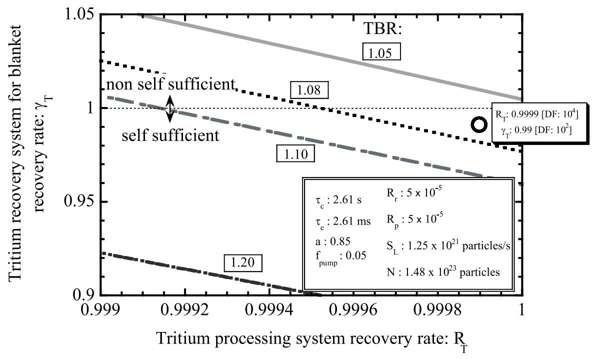

Fig. 3 Fuel self-sufficiency condition for FFHR DEMO reactor system as the functions of TBR and the recovery rate for tritium processing system, and tritium recovery system for blanket, R_T and γ_T.

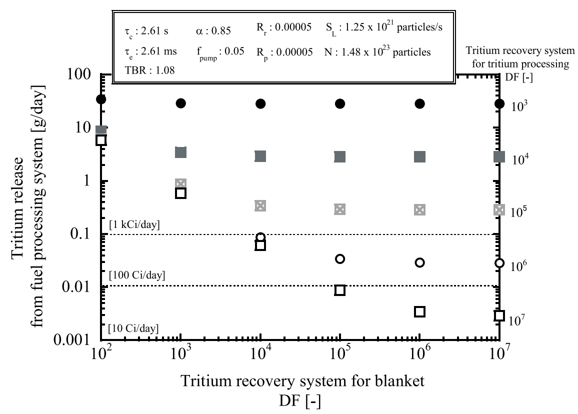

Fig. 4 Tritium loss from the tritium recovery system as the functions of decontamination factor for blanket system and tritium processing system for vacuum exhaust gas.

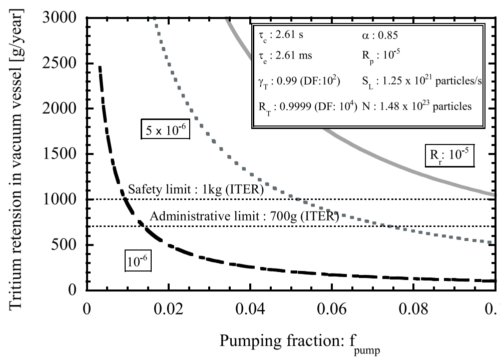

Fig. 5 Tritium retention in the vacuum vessel as the functions of pumping fraction and tritium loss ratio by retention in the vacuum vessel, R_r.

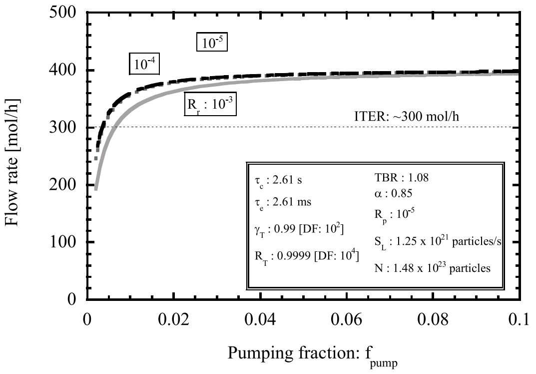

Fig. 6 The estimated flow rate from the vacuum vessel as the functions of pumping fraction and tritium loss ratio by retention in the vacuum vessel, R_r.

fraction is reduced. It means that the recycling in the edge region is enhanced by the reduction of pumping fraction and the particle fluxes to the divertor plate increase. It is important for satisfying the tritium balance in a fusion reactor and the safety aspect to suppress the tritium retention less than the acceptable level. To satisfy the safety limit of tritium inventory in the vacuum vessel, e.g. 1 kg for the ITER, the retention loss ratio R_r has to be less than 5×10^{-6} in the range of between 0.05 and 0.1 for pumping fraction.

The replacement of components such as the first wall and the blanket materials may involve a significant impact of the tritium inventory. Also, tritium could permeate through the wall and eventually into the atmosphere as HT and the cooling water as HTO. Thus the developments of the permeation barrier and the tritium processing for the gaseous and liquid effluents and the tritium decontamination technique of wastes will require improvement toward the DEMO from the viewpoint of the tritium safety management [16, 17].

3.4 Fuel processing system for FFHR DEMO reactor

Figure 6 shows the processing throughput from the vacuum pump. The flow rate from vacuum exhaust gas in the FFHR DEMO reactor is estimated to be about 400 mol/h, where it is assuming that the particles of tritium in the vacuum exhaust gas are equivalent to the particles of deuterium and helium ash is little as to be neglected as compared with fuel particles. Although the thermal output of the FFHR DEMO is six times higher than that of the ITER, the scale of the fuel cycle system would be estimated to be about the same as the ITER, because the processing capacity of the ITER tritium system has the large margin due to various uncertainties [18]. The tritium processing system of the FFHR DEMO reactor will not be necessary to improve the system for the ITER further. In the design activity toward the helical DEMO reactor, FFHR-d1, the development of advanced tritium handling technology is being made for tritium safe handling and effective system to reduce the tritium inventory in the tritium processing system, gaseous detritiation system and water detritiation system [1].

4. Conclusion

The fuel particle balance in a fusion DEMO reactor is investigated using the FFHR2m2 design parameters with consideration of the fueling efficiency by pellet injection, retention loss in the vacuum vessel and permeation loss from the fuel processing system. To satisfy the fuel balance and be safety, it was necessary to suppress the tritium retention rate of 10^{-5} and the DFs in the tritium cycle system of above 10^7 with the tritium breeding ratio of 1.08.

The significant development of tritium processing system for the effluent disposal and waste materials from the safety aspect and the social acceptance will be require toward the DEMO reactor. To investigate the overall fuel particle balance (D, T, He) in the FFHR DEMO reactor, the discussion of fueling scenario for the pellet injection and the reduction of the divertor heat load by radiative divertor are being started.

Acknowledgments

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