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Isotope effects in hydrogen recycling
燃料リサイクリングにおける水素同位体効果

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Burning efficiency in a fusion fuel cycle is, unfortunately, very poor; i.e. only a few % or less of input tritium burns and the majority must be recovered to recycle. This requires huge fuel through-put. In addition, large in-vessel fuel retention rate would result in the huge in-vessel tritium inventory, which is hard to remove and recover. All these are directly related to tritium safety. In this presentation, after summarizing problems on fuel retention and fuel cycles, research proposal which can be done in the deuterium operation in LHD is made.

1. Introduction

Large through-put owing to poor burning efficiency and fuel retention in a reactor vessel concerns us on tritium safety [1]. Before the DT phase of ITER will start, reliable estimations of them must be completed. At the moment, however, no large tokamaks are available to study realistic fuel cycles in a reactor. In this respect, deuterium operation in LHD will give nice opportunity to study fuel recycling and isotopic effect on them. Here, after summarizing problems on fuel retention and fuel cycles, research proposal which can be done in the deuterium operation in LHD will be made.

2. Fuel retention in a reactor vessel

In vessel-tritium inventory and/or tritium accountability in a reactor is the most serious safety concern. In the present tokamaks, there is always significant imbalance between input and output of fuels (mostly measured by deuterium), i.e. 10-20% of the input fuels is continuously retained and immobilized [2]. Although such in-vessel retention is very likely caused by incorporation of fuels in redeposited materials at plasma shadowed area, estimation of tritium inventory even in ITER are scattered more than three orders of magnitude depending on retention models.

Difficulty of quantitative analysis of tritium in the in-vessel components adds additional problems. It is ironical that the accuracy in detecting low levels of tritium (below 10^9 Bq) which utilizes β-electron is better than that in the very high levels which are determined by mass and/or pressure measurements and calorimetry with the accuracy of only 10^{-2} to 10^{-3}. In addition, one cannot measure tritium existing in solid deeper than a few μm. The easy isotopic exchange reactions of tritium with hydrogen in water and hydrocarbons result in easy contamination of the surroundings and can significantly affect the analysis.

Large isotopic effects between D and T would significantly influence their retention rates in PFM, confinement times fuelling efficiencies in plasma and exhausting ratio. Until now no systematic studies on intentionally mixed hydrogen (H and D) plasma have been made.

3. Tritium issues in burning plasma

Burning efficiency in a fusion fuel cycle is, unfortunately, very poor; i.e. only a few % or less of input tritium burns and the majority must be recovered to recycle. In addition, large in-vessel fuel retention rate would result in the huge in-vessel tritium inventory, which is hard to remove and recover. Since exhausted fuel from the vessel includes all hydrogen isotopes (H, D, and T), He and other impurities like water and hydrocarbons, the hydrogen isotopes must be refined and isotopicaly separated with each other to be recycled as fuels.

Figure 1 [3, 4] summarizes the fuel flow in a reactor. In the figure, the burning efficiency and the in-vessel retention rate are assumed to be 1% and 10% respectively. For a total throughput of D/T, as 50/50, only 1/1 fuel is burned to produce 1 neutron, while 5/5 of D/T is retained in the vacuum vessel (VV). Accordingly, D/T of 44/44 is exhausted. In present plasma devices, light hydrogen (H) always remains in the deuterium fuelling operation. The origin is partly residual H_2O in the VV. Since any materials retains some impurity gases in their bulk, their use in vacuum systems always causes out-gassing. Another

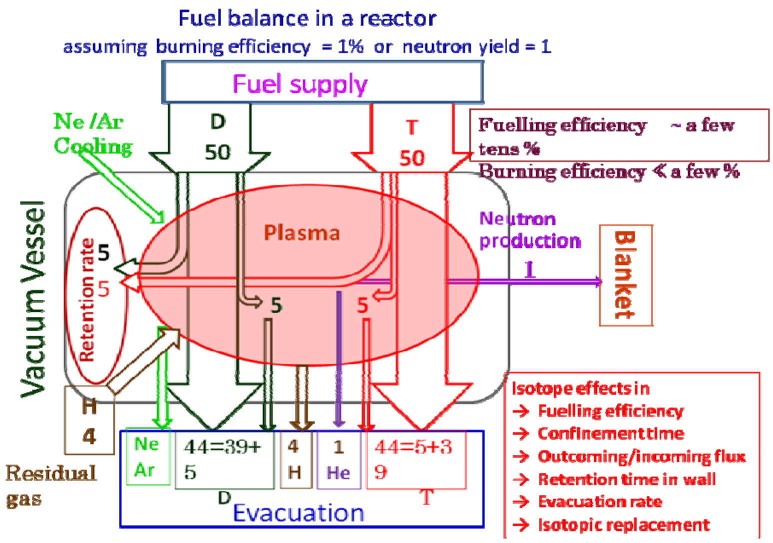

Fig. 1. Fuel balance in a reactor assuming burning efficiency = 1% or neutron yield = 1 [4]

source is back-flow from vacuum pumps. Whatever the sources are, contamination of D and T by H is unavoidable and additional effort to remove H in an isotope separation process is required.

For enhancement of radiative cooling of the plasma and also for disruption mitigation, impurity seeding such as Ne and Ar would be employed, which could significantly dilute the fuels. In addition, various chemical forms of hydrocarbons will be formed from carbon plasma facing materials, if they are used. Thus D and T fueled into the VV are exhausted as a heavily contaminated gas with H, hydrocarbons and inert gasses (He, Ne and Ar). Since only D and T must be recycled, the exhaust gas must be recovered, refined, isotopicaly separated and refueled.

It should be noted that the behavior of D and T are significantly different from each other, not only in the plasma but also in materials [4], owing to their large mass difference; for instance, confinement times, fuelling efficiencies, escaping fluxes from the plasma, retention rates in materials, and evacuation rates from the VV will be different for D and T. [3,4] Simple kinetic theory indicates that the square root of mass ratio of D/T can be correlated with those properties, but more or less no data are available for D and T until now.

In Fig.1, the same fueling rate is assumed for T and D, but the fueling rate is necessarily the same and must be optimized to attain the highest burning efficiency. Therefore, it will not be easy to maintain the appropriate DT ratio in the plasma for continuing the most efficient burning or keeping DT burning efficiency the highest. The concentration of D and T in the burning plasma must be separately measured to achieve feedback fuelling independently. It is, however, quite difficult to measure the concentration of D and T separately. Plasma opacity could disturb optical measurements like Thomson scattering. Separate detection of neutrons with energies of 14 MeV (produced by DT reactions) and of 4.7 MeV (DD reactions) is one of the most promising ways, but the signal does not necessarily give spatial distribution of D/T ratio in the plasmas. Different confinement times of D and T would result in their inhomogeneous distribution particularly in their radial distribution.

Furthermore, retention rates of D and T in the plasma facing wall is not necessarily the same, thus their release rates from the wall. This means that if some local thermal load like an ELM hits the wall, thermal release of D and T are different in their amounts and this disturbs the D/T ratio in the plasma. Owing to the huge wall inventory, a small change in the D/T ratio of the wall retention could cause significant change the D/T ratio of the burning plasma. Thus we are going to face difficulty in controlling the DT ratio in the plasma to attain and keep efficient burning.

4. Proposal in relate experiments in LHD

Since in the deuterium operation in LHD, all exhaust gas will be once stored in surge tanks for tritium safety, quantitative analysis of exhausting H and D becomes possible first time. This makes possible to detailed study on above mentioned problems, such as, fueling efficiency, recycling, fuel retention, and pumping efficiency including isotope effects, required to establish safe and economical DT burning.

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