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Analytic treatment of distributions of lithium neutrals and ions in linear devices

Kyu-Sun Chung[a,*], Yoshi Hirooka[b], Naoko Ashikawa[b], Soon Gook Cho[a], Heung Gyoon Choi[a], In Je Kang[a], Hayato Tsuchiya[b]

[a] Department of Electrical Engineering, Hanyang University, Seoul, South Korea
[b] National Institute for Fusion Science, Toki, Japan

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ABSTRACT

Neutral lithium (Li) has been used for the mitigation of heat flux to the plasma facing components and for the control of hydrogen of fusion plasmas. Radial and axial variations of densities of Li neutrals and ions are obtained analytically for a cylindrical chamber by assuming the classical diffusion with or without the magnetic field (B). Neutrals and ions without B can be expressed as a linear combination of the modified Bessel functions of order zero (I_0 and K_0), while ions with B are to be expressed as the square root of them. Analytical solutions of Li neutral densities with Dirichlet and Neumann boundary conditions are compared to those using Monte Carlo simulation and experimental values of the LIGHT-1 (Lithium Injection Gettering of Hydrogen and its Transport experiments) device. Proper combinations of the relaxation length and size of the source would produce well fitted profiles similar to those observed experimentally and those using Monte Carlo codes.

1. Introduction

Control of the recycling of hydrogen in the International Thermonuclear Experimental Reactor (ITER) and other advanced super-conducting or steady-state fusion devices has become an important area. Core plasma performance is usually improved when recycling is reduced. Lithium could be a particle pump and a trap for hydrogen isotopes [1]. For the long term operation of future fusion devices, the heat flux to the divertor and the first wall should be mitigated, and liquid plasma facing components such as lithium (Li) and molten salts would be the favorable materials for the heat dissipation, among which Li is more favorable due to its low atomic number.

From the realization of a Li emitter-collector concept in Tokamak-11M [2], a renewable plasma facing component (PFC) of steady-state tokamak has been investigated, where emitted Li neutrals enter the plasma and return to the PFC with hydrogen [3]. Visible reduction (~50%) of physical sputtering has been observed for deuterated Li surfaces in NSTX [4]. Flowing liquid lithium limiter has been developed for Experimental Advanced Superconducting Tokamak (EAST) after the success of Li coatings in EAST and liquid Li limiters in Hufei Tokamak-7 (HT-7) [5,6]. Improvement of the efficiency of recycling or pumping by Li injection is very important, but in order to get the consistent picture of the role of the lithium neutrals, the way the Li neutrals should be distributed should be considered since it affects the recycling. Besides, the effect of Li particles on the diagnostics cannot be neglected.

For the proper installation of Li evaporators for fusion devices and the practical quantification of Li deposition and recycling effect, one should know the following: (1) the distributions of Li neutrals with or without collisions besides the rates of LiH recombination such as $Li^0 + H^0(H_2^0) \rightarrow LiH$, $Li^+ + H^0(H_2^0) \rightarrow Li^0 + H^+$: $Li^0 + H^0 \rightarrow LiH$, or $Li^+ + e \rightarrow Li^0$; (2) the dominant process among Li^0, Li^+ in H^0, $H_2^-H^-$, H_2^-; (3) the probability of forming lithium hydroxide (LiOH), lithium carbonate (Li_2CO_3), or a lithium-helium molecule (LiHe) due to graphite tile, oxygen at the edge, and/or helium ashes, if there is any; and (4) the effect of magnetic field and background plasmas on the distribution of Li neutrals and ions, if Li atoms are ionized at the instant of injection in the edge of current tokamaks/stellerator ($n \sim 10^{18}$–$10^{20}\,m^{-3}$, T_e~10–100 eV). Based upon Hirooka [7] and Chen [8], one could roughly deduce the rate of recombination of lithium, while one could deduce the rates of ionization and excitation ($e + Li(2s) \rightarrow 2e + Li^+$ and $e + Li(2s) \rightarrow e + Li^*(2p)$ according to the work of Curry [9] and Boeke and Winter [10].

* Corresponding author.
E-mail address: kschung@hanyang.ac.kr (K.-S. Chung).

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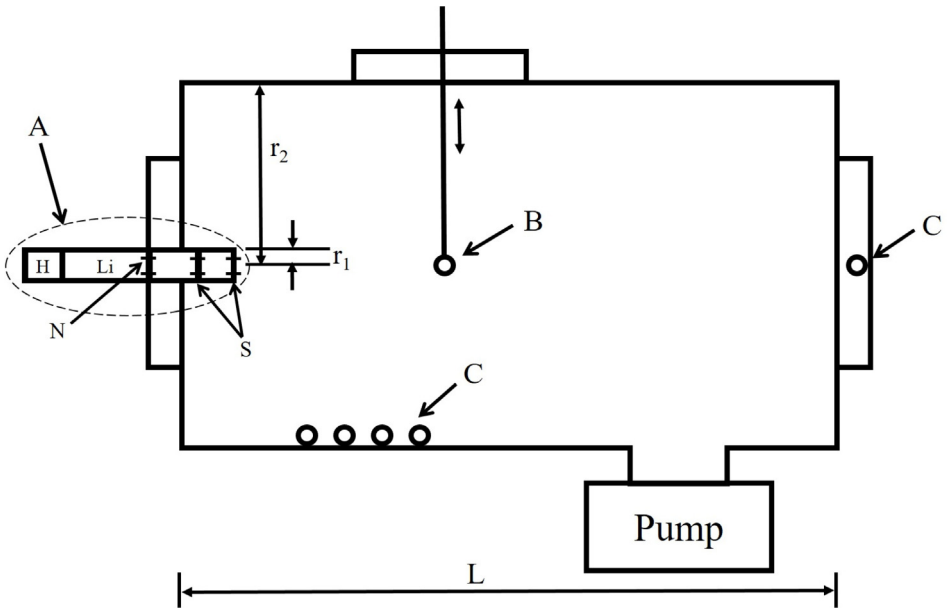

Fig. 1. Schematic drawing of a neutral lithium beam experiment (LIGHT-1 device) [11]. A = lithium beam generator (H = Heater, Li = Li vapor, N = Nozzle, S = Slits), slit radius of A (r_1) = 2.5 cm, B = movable real time deposition probe (a quartz micro-balance for lithium beam profile), which is located at 50 cm from the nozzle, C = fixed deposition probe, r_2 (radius of LIGHT-1 device) = 50 cm, L (length of LIGHT-1 device) = 100 cm.

To test the concept of recycling control in a fusion device like the Large Helical Device (LHD) of the National Institute of Fusion Science (NIFS) by injecting lithium (Li) vapor at a divertor area of the LHD, we test our models by comparing the analytic distribution to the experimental distribution of neutral Li coming out of an evaporator in a cylindrical device, called LIGHT-1 (Lithium Injection Gettering of Hydrogen and its Transport experiments) device [11].

2. Model

Lithium atoms ejecting from a beam source will diffuse through the plasma and atomic/molecular hydrogens into the plasma volume, although the absolute intensity of the initial beam flux would be dependent upon the structure of the beam generator as detailed by Tsuchiya et al., [11]. Fig. 1 shows the schematic drawing of the LIGHT-1 device of NIFS.

When the Li beam is injected into the plasmas of fusion and linear devices, the following processes may occur simultaneously: excitation, ionization, recombination, etc. Especially, LiH (or LiOH, Li_2CO_3, LiC_6 due to graphite tile and small amounts of oxygen at the edge) can be formed at the edge of fusion plasmas. If one considers negative hydrogen ions (H^-) due to electron dissociative attachment (DA) of the hydrogen molecules, one should include the reaction of Li ions and negative hydrogen ions too. If we focus on the behavior of the lithium neutrals and ions, the following continuity equations may hold:

$$\frac{\partial n_s}{\partial t} + \nabla \cdot (n_s \vec{V}_s) = (\sigma_{esg} - \alpha_{esr}) n_b n_s, \tag{1}$$

where n_s indicates density of neutrals (s = n) or ions (s = i) of lithium and n_b is the density of the background particles, g = generation, r = recombination, α_e = effective loss rate and σ_e is effective generation rate. Here, the detailed reaction rates are defined as σ_{eng} = lithium generation from the beam source + dissociation of lithium compound (LiH, etc.) ≈ lithium generation from the beam source, σ_{eig} = ionization of lithium neutrals with electrons of plasmas + charge exchange of lithium neutrals (CER) with lithium ions, α_{enr} = lithium neutral recombination with hydrogen and oxygen, $\alpha_{eir} n_i$ = lithium ion recombination with electrons of plasmas and oxygen (negative) ions (dissociative recombination: DR).

Before solving the whole problem, one should consider the collision property of lithium neutrals by checking the mean free path and lithium flux. First, a formula for the mean free path (λ) of the lithium neutrals could be given as follows [12]:

$$\lambda = \frac{1}{\sqrt{2} n_{\mathrm{Li}} \pi D^2} = \frac{GT}{\sqrt{2}\pi D^2 N_A P}, \tag{2}$$

where n_{Li}, D, G, N_A, P are the density of Li atoms, diameter of Li atoms, Gas (law) constant, pressure of lithium vapor. Using the relevant numbers such as $G = 8.3145\,\mathrm{J/(K\,mol)}$, $N_A = 6.02 \times 10^{23}$, and $D = 3\text{–}4 \times 10^{-10}$ m, the mean free path is ~15 – 20 cm at $T = 823$ K for $P = 1$ mtorr = 0.13 Pa. However, the observed pressure is one-order lower than the ideal vapor pressure of Li, and, as a result, the actual mean free path becomes 150–200 cm. Hence, for the chamber of a general laboratory experiment (length and diameter is one meter or so), the Li neutrals would behave as if they were a collisionless molecular flow. Furthermore, the farther from the nozzle the particles are, the lower the flux (or density) they would have [11]. So, comparing the experimental mean free path (λ_{ex}) to the size of the device (L) for the determination of the likelihood of collisions for the model, there is a case for choosing a collisionless model ($\lambda > L$), although the theoretical estimation of mean free path (λ_{th}) would indicate that the model could be collisional ($\lambda < L$), since experimental mean free path (λ_{ex}) is ten times longer than the theoretical one (λ_{th}).

Second, the initial flux from the beam source can be given as the following: Using the equation of state of gas ($P = nkT$) and the result of the Clausius-Clapeyron Equation

$$P = P_0 \exp\left[\frac{-h}{RT}\right],$$

where h is heat of evaporation of Li ($h = 146$ kJ/mol), P_0 is a constant ($= 3.7 \times 10^9$ for Li) [13], the following can be calculated: $n_{\mathrm{Li}^0} = P/kT = [P_0/kT] \exp[-h/RT] \approx 1.765 \times 10^{20}\ \mathrm{m}^{-3}$; $V_0 = \sqrt{2kT/m} = 1.5 \times 10^3$ m/s; $\Gamma_0 = n_{\mathrm{Li}^0} V_0 = 2.7 \times 10^{23}/\mathrm{m}^2\,\mathrm{s}$; and $A_1 = \pi r_1^2 = 0.00196\,\mathrm{m}^2$. Then the generation rate of particles from the lithium beam source (S_i) is calculated as S_i