Numerical tracking of impurities by dust ablation in HT-6M plasma

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Abstract. HT-6M will be officially installed in Thailand in next few years. Some computational studies of possible experiments should be helpful in case of its experiment planning. The authors are interested on the scenario of macro-particle, i.e. dust and droplet, transporting in HT-6M. The study was carried out by the Dust and Droplet Tracking (DDT) code, consisting of basic equations and physical models involving with charging, heating, equation of motion and ablation on macro-particle in a tokamak plasma. DDT implemented a set of HT-6M core plasma profiles from the Transport Analyzing System for tokamak (TASK) code and a set of HT-6M edge plasma profiles approximated from simple SOL model. We observed that relatively small macro-particles, i.e. initial sizes are less than $10^{-6}$ m, significantly involve with impurity generation near plasma facing components (PFCs). In addition, the $10^{-5}$-m macro-particles mostly ablate in SOL. The $10^{-3}$-m and $10^{-4}$-m macro-particles completely ablate if they transport towards core plasma, but some with the inclination with respect to the horizontal direction obtain longer lifetimes. Moreover, few of them can achieve abnormal high speed. The mechanism for this is the acceleration by rocket force due to partial ablation near core plasma.

1. Introduction

Recently, HT-6M, a tokamak owned by Institute of Plasma Physics, Chinese Academy of Science (ASIPP), China, has been officially donated to Thailand Institute of Nuclear Technology (TINT), Thailand. Currently, the tokamak is being refurbished and it will be transferred to and installed in TINT in next few years. However, it is expected that the refurbished HT-6M will not significantly differ from the original one [1]. In order to serve its preparation plan, the authors are believed that the computational simulations on scenarios in HT-6M are unavoidable. One of possible experiments which may be achieved by this kind of devices is macro-particle, i.e. dust, droplet, powder and granule, ablation and transport. For a background, such macro-particles are produced through heat deposition during plasma surface interactions (PSIs). Melting, cracking and flaking on plasma facing
components (PFCs) leads to production of macro-particles [2]. In HT-6M, it should mainly result from disjuction, arc and plasma dislocation. PSIs should be intense at PFCs of a poloidal limiter. After macro-particles are produced, they remain inside a tokamak, so it is possible for them to re-mobilize and continuously degrade a plasma. Macro-particles degrade performance of confinement via dilution of fuel and radiation cooling because macro-particles can penetrate into core plasma and its impurity inventory can be enhanced by ablation of macro-particles. However, it is found that macro-particles made of Li can suppress Type-I ELMs but trigger Type-III ELMs instead, and eventually eliminate ELMs [3-5]. This means that it is valuable to develop understanding of dust transport in aspects of advantages and disadvantages.

The aim of the work is to carry out basic computational study on iron (Fe) macro-particle transport and ablation under the HT-6M plasma profiles. Fe macro-particles should be produced a lot because Fe is a main composition in HT-6M PFCs. The study was conducted via the use of Dust and Droplet Tracking (DDT) code. Section 2 will outline the main HT-6M parameters, the physical models corresponding to charging, heating, equation of motion and ablation on a macro-particle included in DDT, the core HT-6M plasma profiles generated by Transport Analyzing System for tokamak (TASK) [6] and the edge HT-6M plasma profiles assumed by the use of simple SOL model [7]. The following sections will illustrate and summarize the ablation behaviors of Fe macro-particles and the trends of the macro-particle positions and velocities dependent of initial momentum of each of macro-particle.

2. Physical Models

In this section, we aim to outline the physical backgrounds under the Dust and Droplet Tracking (DDT) code. The physical models included in DDT are the theory for determining macro-particle floating potential, the equation of motion in a rotational frame of reference for determining position and velocity of macro-particle, the heating equation for evolving macro-particle temperature, the Modified Young-Laplace Equation (MYLE) for determining net pressure on macro-particle, the models for determining mass loss and size of macro-particle during its flight. DDT was used to perform Fe macro-particle transport in HT-6M under the steady state condition. Therefore, we needed the HT-6M plasma profiles in steady state. Such data for the core plasma profiles were output from the Transport Analyzing System for tokamak (TASK) code [6]. The data were numerically fitted and outlined in this section. The simple SOL model [7] with some assumptions explains the edge plasma profiles. It must be noted that table 1 and tables 2 and 3 show the definition of variables used in the following expressions and the values of parameters used in this study, respectively.

2.1. HT-6M

HT-6M [8-10] is a circular poloidal cross-section tokamak. This is not a divertor tokamak. It is installed by a poloidal limiter. Its PFCs of main vessel and limiter are made of stainless steel mostly consisting of Fe.

2.2. Dust and Droplet Tracking (DDT) code

A phenomenon related to a small object moving in a plasma are generally controlled by ion and electron depositions on its surfaces. This leads to rapid charging. In general, because the charging is very rapid, which is characterized by plasma frequency, we can assume that the charges on its surface are at equilibrium and then the object is occupied by floating potential. The equilibrium floating potential are a potential difference between the object surface and the bulk plasma in steady state. Because macro-particle is assumed to be a small sphere, so DDT includes the Orbital Motion Limited (OML) theory which is well-known as one of theories to determine macro-particle floating potential ($\Phi_d$) [14-18],

$$\exp (-\Phi_d) = \sqrt{\frac{\beta_T m_e}{A m_p}} \left( 1 + \frac{\Phi_d}{\beta_T} \right); \quad u = 0, \quad r_d \ll \lambda_D,$$

(1)
where $\Phi_{sd} = -\frac{1}{2} \ln \left( \frac{2 \pi m_s}{\lambda_{D}^2} \right)$, $\Phi_d = \frac{\phi_d r_d^3}{T_d}$, $u = \frac{v_d}{c_{is}}$, $c_{is} = \sqrt{\frac{\varepsilon T_d (1 + \frac{\rho T_d}{\lambda_{D}^2})}{\lambda_{D}^2}}$, and $\lambda_{D} = \sqrt{\frac{\varepsilon T_d}{n_e e^2}}$. Refs. [14-15] refer to eq. 1 and refs. [16-18] refer to eqs. 2-4. $r_d \ll \lambda_D$ and $r_d \gg \lambda_D$ represent small and large dust sizes. The linear interpolation explains the transition from eqs. 1 and 2 to eqs. 3 and 4, respectively [16-18].

DDT temporally evolves macro-particle temperature ($T_d$) through heat equation,

$$\Delta T_d = \frac{(Q_i + Q_s - Q_{rad}) \Delta t}{m_d c},$$

where $Q_i = 2eT_d \Gamma_i$, $Q_s = 2e \beta_T T_i \Gamma_i$, and $Q_{rad} = \sigma(\epsilon_s T_d^4 - \epsilon_u T_u^4)$. Due to the assumption that rapid charging leads to steady state very quickly, $\Gamma_i = \Gamma_s = n_s^i \sqrt{\frac{e T_u}{2 \pi m_s}} \exp(-\Phi_d)$. If $T_d \geq T_m$, we implement Hertz-Knudsen-Langmuir (HKL) equation and Kelvin term [19],

$$\left| (\Delta r_d)_{\text{vap}} \right| = \frac{(P_{sf} - P_{es})}{\sqrt{2 \pi m k_B T_d}} \exp \left( \frac{2 \gamma m}{\rho k_B T_d} \right) \frac{\Delta t}{\rho},$$

where $P_{sf} = \frac{2 \gamma}{r_d}$ and $P_{es} = \frac{\sqrt{2 \pi m k_B T_d}}{2 \pi r_d^2}$, to evaluate a change in droplet radius during normal vaporization in liquid phase. If $T_d > T_b$, strong and rapid vaporization on droplet by superheating occurs and explain by the following expression,

$$| (\Delta r_d)_{sb} | = \frac{r_d c(T_d - T_b)}{3 H_{\text{vap}}}. $$

By considering Modified Young-Laplace Equation (MYLE) [20-22] a droplet can undergo electrostatic breakups [23] when

$$P_{\text{ele}} = P_{sf} + P_i + P_e - P_{es} \rightarrow 0,$$

where $P_i = 0.5 n_i e \beta_T T_e \left( \frac{\phi_i}{\phi_d} \right) \sqrt{\frac{\Phi_d}{\pi r_d^2}} + \exp \left( \frac{\phi_d}{\beta_T} \right) \exp \left( \sqrt{\frac{\phi_d}{\beta_T}} \right)$ and $P_e = 0.5 n_e e T_e \exp(-\Phi_d)$ [23]. Electrostatic breakups trigger at which $P_{es} \geq P_{sf} + P_i + P_e$. In this case, the whole droplet mass is assumed to be completely vaporized, so $| (\Delta r_d)_{es} | = r_d$. We can find mass loss during the flight of macro-particle by

$$| \Delta m_d | = \frac{4 \pi \rho}{3} \left( 3 r_d^2 | \Delta r_d | + 3 r_d | \Delta r_d |^2 + | \Delta r_d |^3 \right),$$

where $| \Delta r_d | = | (\Delta r_d)_{\text{vap}} | + | (\Delta r_d)_{sb} | + | (\Delta r_d)_{es} |$.

The code temporally solves the equation of a single macro-particle motion for updating $v_d$, i.e.

$$\Delta v_d = \frac{\Delta t}{m_d} \left( q_d (E + v_d \times B) + F_i + m_d g + f + v_d \frac{| \Delta m_d |}{\Delta t} \right),$$

where $q_d = C \phi_d$ and $C = \Delta \varepsilon_0 \varepsilon_0$. Currently, ion drag force ($F_i$) included in DDT is only due to physical momentum transfer between plasma charges and macro-particle [24] as follows.
\[ F_i = \pi r_i^2 A n_i m_p (v_p - v_d) \left( 1 - \frac{\pi \Phi_d}{4 \beta} \right) \sqrt{\frac{8e\beta T_e e V}{A \pi m_p}}. \] (11)

The fictitious force \( f \) is due to the rotational frame of reference. It consists of centrifugal force \( \left( \frac{v_d^2 R}{R^2} \right) \) and coriolis force \( (2v_d \times \left( R \times v_d \right)) \). Rocket force \( (v_d \frac{\Delta m_p}{\Delta t}) \) due to mass loss during its flight is also taken into account.

2.3. Plasma Profiles

TASK [6], solving 1-D diffusive transport equation, together with the main parameters of HT-6M shown in table 2 generated the raw data of core plasma parameters, i.e. \( n_e, n_i, T_e, T_i, E_{tor}, E_{pol}, B_{pol}, v_{p,tor}, \) and \( v_{p,pol} \). Subsequently, the raw data are numerically fitted by the series of the \( n \)th polynomials, \( f(x) = \sum_{n=1}^{N} A_n x^n \) where \( A_n \) is an \( n \)th order coefficient, summarized in tables 4 and 5, and \( x = r'/a \).

Figure 1 illustrates their details. The HT-6M plasma parameters in edge plasma are assumed by the use of simple SOL model [7], \( n_e = n_i = n_e(x = 1) \exp \left( \frac{1-x}{\lambda_n} \right), \) \( T_e = T_e(x = 1) \exp \left( \frac{1-x}{\lambda_T} \right), \) \( T_i = T_i(x = 1) \exp \left( \frac{1-x}{\lambda_T} \right), \) \( E_{tor} = -\frac{2T_e}{\pi R_n}, \) \( B_{pol} = \frac{B_{pol}(x=1)}{x} \), where \( \lambda_T = \lambda_n = 0.056 \) for decay length \( \approx 1.0 \) cm, \( E_{pol} = 0 \) and \( v_{p,pol} = 0 \). Only the function of toroidal magnetic field, \( B_{tor} = \frac{R'B_T}{R^2 + x \cos \theta} \), is applied to both core and edge plasmas, where \( R' = 3.6 \). We assume \( \nu_{p,tor} = 0 \) in core and \( \nu_{p,tor} = \nu_{s,tor} \) in edge.

![Figure 1. HT-6M plasma profiles.](image-url)
### Table 1. Definitions of Variables.

| Variables            | Definition                                                      | Variables            | Definition                                                      |
|----------------------|-----------------------------------------------------------------|----------------------|-----------------------------------------------------------------|
| $v_d$                | macro-particle velocity                                        | $r_d$                | macro-particle radius                                           |
| $\phi_d$            | macro-particle floating potential                               | $\Phi_d$            | normalized floating potential                                   |
| $\Phi_d$            | normalized potential difference between macro-particle and sheath edge | $T_d$                | macro-particle temperature                                     |
| $q_d$                | macro-particle charges                                         | $m_d$                | macro-particle mass                                             |
| $\mathbf{E}$        | electric field                                                 | $B$                  | magnetic field                                                  |
| $\mathbf{F}_l$      | ion drag force                                                 | $g$                  | gravitational acceleration                                       |
| $f$                  | fictitious force                                               | $\nu_p$             | plasma or ion velocity                                          |
| $\beta_T$           | ion to electron temperatures                                   | $t$                  | time                                                            |
| $m_e$                | single electron mass                                           | $n_e$                | ion number density                                              |
| $\epsilon$          | elementary charge                                              | $m_p$                | proton mass                                                     |
| $T_e$                | electron temperature                                           | $T_i$                | ion temperature                                                 |
| $n_e$                | electron number density                                        | $\epsilon_0$         | vacuum permittivity                                             |
| $A$                  | ion mass number                                                | $C$                  | macro-particle capacitance                                      |
| $c_{se}$             | ion sound speed                                                | $u$                  | normalized plasma or ion velocity                               |
| $\lambda_D$         | Debye length                                                   | $c$                  | heat capacity of macro-particle material                        |
| $\Delta r_d$         | change in $r_d$ by normal vaporization                         | $\Delta r_d$         | change in $r_d$ by superheating                                 |
| $\gamma$            | surface tension                                                | $Q_s$                | heat by ion flux                                                |
| $Q_e$                | heat by electron flux                                          | $Q_{s+d}$            | heat by thermal radiation                                       |
| $\Gamma_e$          | electron flux                                                  | $\Gamma_i$           | ion flux                                                        |
| $\epsilon_d$        | macro-particle emissivity                                      | $\epsilon_w$         | wall material emissivity                                        |
| $\sigma$            | Stefan-Boltzmann constant                                      | $T_w$                | wall temperature                                                |
| $\kappa_m$          | molecular/atomic mass                                          | $k_B$                | Boltzmann constant                                              |
| $P_{e,fs}$          | pressure due to surface tension                                 | $P_{e,s}$            | electrostatic pressure                                          |
| $P_i$                | ion pressure                                                   | $P_s$                | electron pressure                                               |
| $P_{net}$           | net pressure on macro-particle                                 | $H_{vap}$            | latent heat of vaporization                                     |
| $T_m$                | melting temperature                                            | $T_b$                | boiling temperature                                             |
| $E_{tori}$          | toroidal electric field                                        | $E_{poli}$           | poloidal electric field                                         |
| $B_{tori}$          | toroidal magnetic field                                        | $B_{poli}$           | poloidal magnetic field                                         |
| $r'$                 | position in minor radius                                       | $x$                  | normalized minor radius                                         |
| $R_T$                | aspect ratio ($=R_B/a$)                                        | $\phi$              | poloidal angle                                                   |
| $\lambda_T$         | normalized $T_e$ and $T_i$ decay length                        | $\lambda_n$          | normalized $\eta_e$ and $\eta_i$ decay length                  |

### Table 2. Main parameters of HT-6M [8-10]

| Parameters                        | Values          | Parameters                        | Values          |
|-----------------------------------|-----------------|-----------------------------------|-----------------|
| Major Radius, $R_0$ (m)           | 0.65            | Minor Radius, $r$ (m)             | 0.20            |
| Center Toroidal Magnetic Field, $B_{tori}$ (T) | 1.0             | Plasma Minor Radius (assumed), $a$ (m) | 0.18            |
| Center Electron Density, $n_e,0$ (m$^{-3}$) | $1.6 \times 10^{19}$ | Electron Density at LCFS, $n_{e,\alpha}$ (m$^{-3}$) | $1.0 \times 10^{18}$ |
| Center Electron Temperature, $T_e,0$ (eV) | 700             | Electron Temperature at LCFS, $T_{e,\alpha}$ (eV) | 10              |
| Ratio Ion to Electron Density (assumed) | 1.0             | Plasma Current, $I_p$ (A)         | $6.5 \times 10^4$ |
Table 3. Additional values of parameters used in this study.

| A | c(J/kg · K) [11] | ε_d = ε_0 [12] | T_m(K) [11] | γ(N · m) [13] | m[kg] [11] |
|---|---|---|---|---|---|
| 1 | 449 | 0.365 | 1810.9 | 1.547 | 9.288 × 10^{-26} |

Table 4. A_n of each core HT-6M numerical fit plasma profiles.

| 9th | 8th | 7th | 6th | 5th | 4th | 3rd | 2nd | 1st | 0th |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| T_e (eV) | 0 | 0 | 0 | 0 | 0.69 | -2.32 | 3.28 | -2.56 | 0.91 |
| T_i (eV) | 0 | 0 | 0 | 0 | 0.048 | -0.098 | 0.056 | -0.091 | 0.089 |
| n_i = n_e (10^{20} m^{-3}) | -38.94 | 160.88 | -278.06 | 260.45 | -143.26 | -46.85 | -8.81 | 0.79 | -0.037 | 0.16 |
| B_pol (T) | 0 | 0 | 0 | -1.33 | 5.00 | -7.78 | 6.55 | -3.27 | 0.88 | 0.012 |
| E_{tor} (V/m) | 0 | 0 | 0 | 0.017 | -0.067 | 0.10 | -0.075 | 0.023 | 0.00099 | 0.30 |
| E_{pol} (10^6 V/m) | -1.294 | 5.17 | -8.592 | 7.664 | -3.97 | 1.205 | -0.207 | 0.019 | 0.0016 | 54.96 × 10^{-6} |

Table 5. A_n of each core HT-6M numerical fit plasma profiles (continued).

| 9th | 8th | 7th | 6th | 5th | 4th |
|-----|-----|-----|-----|-----|-----|
| v_{p,pol} (10^5 m/s); 0 ≤ x < 0.2 | 4932082 | -5461607 | 2652578 | -741258.7 | 131238.7 | -15238.46 |
| v_{p,pol} (10^7 m/s); 0 ≤ x < 0.2 | 1154.854 | -54.28096 | 13.90819 | -6.840530 | 1.351546 | -5.504321 × 10^{-5} |
| v_{p,pol} (10^8 m/s); 0.2 ≤ x < 0.97 | -6.840530 | 13.90819 | -11.05964 | 4.837070 |
| v_{p,pol} (10^9 m/s); 0.97 ≤ x < 1.0 | 0 | 1.215742 | -2.409025 | 1.192937 |

Figure 2. show poloidal trajectories of the $10^{-4}$-m and $10^{-3}$-m solid macro-particles and their radii and velocities with respect to time of flights, where solid line represents $r_{d, init} = 10^{-4}$ m and dash line represents $r_{d, init} = 10^{-3}$ m.
3. Results and Discussions
In this study, we assume that $\text{He}_2$ is discharged in HT-6M. We focus on Fe macro-particles mostly accumulated at the bottom of HT-6M. Therefore, Fe macro-particles are assumed to initially move from the bottom that is far from the poloidal limiter. The magnitude of initial velocity is 10 m/s. The angles of the initial velocities with respect to the vertical direction are $-60^\circ$, $-30^\circ$, $0^\circ$, $30^\circ$ and $60^\circ$. Initial macro-particle phases are solid and liquid. Initial macro-particle radii are $10^{-3}$, $10^{-4}$, $10^{-5}$, $10^{-6}$ and $10^{-7}$ m. In general, the macro-particle motion is not symmetric between inward and outward initial trajectories because of fictitious force in rotational frame of reference. The fictitious force tends to cause macro-particles going back to outer SOL. In addition, initial momentum of macro-particle also indicates how difficult a net force in a tokamak affects its trajectory. Furthermore, initial trajectory of macro-particle which is adjacent to the horizontal direction may lead to longer lifetime in tokamaks.

Overall, the macro-particles with the initial radii of an order of $10^{-6}$ m or less, we found that they completely ablate near PFCs. This leads to the source of impurities accumulated near the surfaces. Their final velocities and positions do not significantly differ from the initial ones. Their temperatures are not remarkably evolved, i.e. near initial temperature (323 K) for dust and melting temperature (1810 K) for droplet. The macro-particles, the initial radius of which is an order of $10^{-5}$ m, can survive longer and then completely ablate in SOL. The final velocities are approximately less than 100 m/s for dust and 40 m/s for droplet, and the final temperatures are approximately less than 1000 K for dust and 2100 K for droplet. From this observation, we anticipate that these relatively small macro-particles contribute to impurity accumulation in edge plasma of HT-6M.

We observed behaviors of relatively large macro-particles, the initial radii of which are in an order of $10^{-4}$ m or more, during their flight in HT-6M plasma. As can be seen in figure 2, the macro-particles with the initial radii of $10^{-3}$ and $10^{-4}$ m and the initial angle of $0^\circ$ completely ablate in core plasma. With the initial angles of $30^\circ$ (and $-30^\circ$), the $10^{-3}$-m macro-particles ablate completely in core plasma but the $10^{-4}$-m macro-particles partially ablate. The trend exhibits for both dust and droplet. With the initial angles of $60^\circ$ (and $-60^\circ$), mostly macro-particles have longer lifetimes in SOL because they avoid intensive vaporization by hot core plasma. They contribute to impurities in SOL plasma. This suggests that the complete ablation of macro-particles in core plasma should be lessen by reductions in their sizes because the net force can efficiently accelerate smaller macro-particles towards outer SOL. In addition, inclination near horizontal direction also contributes to how many macro-particles survive and stay in SOL.

In figure 2, we observed notable transport of macro-particles with the initial radius of $10^{-3}$, and $10^{-4}$ m and the initial angles of $60^\circ$. We found that both dust and droplet drift towards the HT-6M outer wall. During their flights, they partially ablate by core plasma and move back to SOL plasma. Mass loss by partial ablation provides extra momentum through rocket force to the macro-particles, the size of which are in an order of $10^{-6}$ m when they come back to outer SOL. Their velocities abruptly increase and exceed a few km/s with longer lifetimes. This can be achieved only by partial ablation and parallel flow towards poloidal limiter. The trend corresponds to the report of high speed dust observed at mid-plane in FTU [25-26], which is also a circular limiter tokamak.

4. Conclusions
By using DDT and HT-6M plasma profiles, we can learn the dynamics of Fe macro-particles inside HT-6M. We found that macro-particles tend to completely ablate if they cannot avoid core plasma. This causes by initial inclination, which is direct towards core plasma, and large initial momentum. Therefore, suitable initial inclination and momentum increase macro-particle lifetime. In addition, it is possible for survived macro-particle to achieve abnormal high speed by rocket force due to partial ablation done by core plasma.
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