Droplet transport from main HT-6M poloidal limiter

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Abstract. The HT-6M is a tokamak installed only with a main metallic poloidal limiter, which may not tolerate energy deposition due to a limited plasma-wetted area. This leads to the production of fresh metallic impurities, including macro-particles, in its main vessel. The macro-particles are transported and then ablated far away from where they were created. Understanding transport and ablation is beneficial to characterize impurity generation in the HT-6M, which will be recommissioned in Thailand in the next few years. A computational study simulated the motion of macro-particles in the HT-6M using the specifically written Dust and Droplet Tracking (DDT) code with the steady state HT-6M plasma profiles produced from the Transport Analyzing System for tokamaK (TASK) code. The results showed that a substantial amount of vapor containing impurities in the scrape-off layer (SOL) plasma was produced by the ablation of the liquid macro-particles emitted from the HT-6M poloidal limiter when the macro-particles were located near the limiter and nearby plasma-facing components (PFCs). Heavy ablation on the macro-particles transported directly towards the core plasma led to complete vaporization locally. The updated DDT code is discussed.

1. Introduction
Plasma surface interactions (PSIs) produce macro-particles. The dominant PSIs in magnetically fusion tokamaks are disruption and arcs [1-2]. Disruption results in permanent confinement loss. Radiation cooling by cumulative impurities in a tokamak chamber is one of the causes of disruption. Heat loss by radiation reduces the plasma temperature which in turn increases the plasma resistance [3]. This leads to confinement instability. Then, all stored energy in a tokamak sinks onto plasma-facing components (PFCs). This results in the erosion of PFCs. Arcs are produced from intensive electron emission under a high electric field. Arcs transfer intense heat onto PFCs, especially rough ones, and produce macro-particles [1-2]. Furthermore, under the effect of the magnetic field in a tokamak, arcs can be moved under $\mathbf{J} \times \mathbf{B}$ force, called retrograde motion [4], to other positions on PFCs. This allows continuous macro-particle production during a tokamak operation.

The HT-6M is expected to be available in Thailand in the next few years. The tokamak is a circular poloidal cross-section tokamak. It will be equipped with a main poloidal limiter and a vessel made of stainless steel during the refurbishment. The earlier phase of its operation is suggested to be in ohmic heating mode, which was successful in the past [5-7].

Due to the limited plasma-wetted area provided by a main HT-6M poloidal limiter, the influx heat by the PSIs might lead to erosion. As a result, macro-particles might be produced from the limiter and be transported by forces in the tokamak plasma. On the way, energy (stored in the plasma) transfer results in heating and ablation on the macro-particles. This produces vapor containing impurities and results in energy drain from the plasma by radiation cooling. From this assumption, a computational study was conducted to simulate macro-particle transport and ablation to characterize the amount of...
vapor containing impurities in the HT-6M vessel when the macro-particles were initially splashed from the main poloidal limiter. The simulation was done using the specifically written Dust and Droplet Tracking (DDT) code with the HT-6M steady state plasma profiles, determined using the code, named Transport Analyzing System for tokamaK (TASK) [8]. A brief overview of DDT and its updates were discussed. The detail of the simulation set-up was provided.

2. Methodology

The Dust and Droplet Tracking (DDT) code is a programming code developed for simulating macro-particle (either dust or droplet) transport in a plasma. With a set of known plasma profiles, the code calculates an equilibrium floating potential \( \varphi_0 \) on a macro-particle subjected to plasma charge deposition. The floating potential is used to calculate the temperature \( T_d \) and net pressure \( P_{\text{net}} \) on a macro-particle. The material phase (solid, liquid or vapor) is considered in the DDT code. Ablation, which produces vapor containing impurities, includes surface vaporization, vaporization under depressurized superheating and electrostatic disintegration, which are temporally controlled by \( P_{\text{net}} \) and the material phase. The current DDT code does not include an impurity diffusion equation to describe impurity transport in a plasma. The HT-6M device parameters, the HT-6M steady state plasma profiles obtained from the TASK code and the details of the physical models in the DDT code are mentioned in a separate unpublished article. However, the updates of the DDT code (bouncing and ablated impurity distribution) and the simulation set-up are reported in this section.

The bouncing of a macro-particle with a vessel wall confines the macro-particle in a computational domain. The current model of the bouncing is explained by

\[
\begin{align*}
\mathbf{v}_{d,f,n} &= -\varepsilon_0 \mathbf{v}_{d,i,n}, \\
\mathbf{v}_{d,f,t} &= -\varepsilon_0 \mathbf{v}_{d,i,t},
\end{align*}
\]

where \( \mathbf{v}_d \) is the velocity of a macro-particle, \( \varepsilon \) is the coefficient of restitution (the ratio of the final to initial speed in a certain direction) and the subscripts \( i, f, n \) and \( t \) refer to initial, final, and perpendicular to toroidal direction and parallel to toroidal direction. In the current study, \( \varepsilon_0 = \varepsilon_i = 1 \) was assumed.

The updated DDT code outputs the cumulative number of vapor containing impurities, which is determined by dividing the ablated mass by the molecular/atomic mass of a macro-particle, at each position in the poloidal and toroidal cross-sections of a tokamak. Subsequently, the 2-D poloidal and toroidal maps can be established to illustrate the impurity distribution in a tokamak.

A macro-particle was assumed to initially start moving from a side of the main HT-6M poloidal limiter. Such movement should be countered by parallel flow in the scrape-off layer (SOL). Therefore, we assumed the toroidal plasma flow velocity \( v_{p,\text{tor}} \) in the SOL plasma as:

\[
v_{p,\text{tor}} = -c_{is}
\]

where \( c_{is} \) is the ion sound speed \( \sqrt{\frac{eT_e[\text{eV}](1+\gamma\beta)}{m_p}} \), \( T_e[\text{eV}] \) is the electron temperature in eV, \( m_p \) is the proton mass, \( e \) is the elementary charge, \( \gamma \) is the ratio of the specific heat capacities at constant pressure and constant volume \( (5/3) \), \( \beta \) is the ratio of the ion to the electron temperature and \( A \) is the atomic mass number. The initial velocity of the macro-particle is mainly in the anti-clockwise toroidal direction of the tokamak.

The PFCs of the HT-6M are mainly made of stainless steel type 1Cr18Ni9Ti (approximately 70%-iron (Fe) [9]), so the macro-particles in the current study were assumed to be made of Fe. Their initial material phase is liquid, so we called them droplets. The main HT-6M poloidal limiter (figure 1) was assumed to be a ring, made of Fe-PFCs, with a defined ring thickness \( (L_1, 0.02 \text{ m}) \), an inner ring radius \( (r_1, 0.18 \text{ m}) \) and an outer ring radius \( (r_2, 0.2 \text{ m}) \).

Two simulations were used, with either a large droplet size \( (10^{-4} \text{ m}) \) or a small droplet size \( (10^{-5} \text{ m}) \). In each simulation, the droplets were launched from the outer, top, inner and bottom positions at the HT-6M minor radius \( (r^*, 0.19 \text{ m}) \) with an initial velocity of 10 m/s, corresponding to the typical velocity of...
Figure 1. (a) Top-view toroidal cross-section of HT-6M and (b) main HT-6M poloidal limiter, where gray area indicates Fe-PFCs, and droplet initial movement directions.

Macro-particles under erosion by the plasma accelerator reported in the literature [10-11]. Sets of injection angles, describing inclination, were defined as: \( \theta = -80^\circ, -60^\circ, -40^\circ, -20^\circ, 0^\circ, 20^\circ, 40^\circ, 60^\circ, 80^\circ \) and \( \gamma = -45^\circ, 0^\circ, 45^\circ \), respectively (figure 1). The sets corresponded to figure 3 in Bazylev B et al 2009 [10], who suggested that it was unlikely to have the macro-particles splashing in a direction near 90° with respect to the normal direction of the tested surfaces.

3. Results and discussion

Figure 2 illustrates the droplet trajectories and the associated impurity distribution due to ablation in the HT-6M poloidal cross-section. Regardless of the initial sizes, the droplets, moving towards the center of the HT-6M (\( \theta < 0^\circ \) and all \( \gamma \) for the outer part of the main HT-6M poloidal limiter; all \( \theta \) and \( \gamma < 0^\circ \) for the top and bottom of the limiter), rarely survived from the HT-6M core plasma. Intensive ablation achieved by high temperature and density plasma in the HT-6M core led to rapid ablation and impurity distribution characterized by the red-to-yellow color range, which represents the number of ablated impurity atoms (N) greater than \( 10^{16} \) atoms for \( 10^{-4} \) m droplets and \( 10^{15} \) atoms for \( 10^{-5} \) m droplets. Some droplets avoided complete ablation in the core plasma, namely \( \theta > 0^\circ \) and all \( \gamma \) for the outer part of the limiter, and all \( \theta \) and \( \gamma > 0^\circ \) for the top and bottom of the limiter. These droplets mostly moved, lived longer (compared to those in the core plasma) and gradually contributed to impurities in the SOL plasma, which has a lower temperature and density. The impurity distribution by such a weak ablation is represented by the green-to-yellow color range. Most of the droplets in the SOL plasma were initially large. The smaller droplets potentially underwent complete ablation near the last closed magnetic surface (LCMS).

Figure 2 also shows the successive bouncing between the droplets and the HT-6M wall. Several successive bouncings delivered the droplets, initialized by \( |\theta| \) slightly > 0° (figures 2 (a) - (b)) and \( \gamma > 0^\circ \) (figures 2 (c) - (d)), to move into the core plasma and led to further droplet ablation. Other droplets stayed mostly in the SOL plasma and underwent less intensive ablation.

Considering figures 2 and 3, every droplet drifted outwardly towards the outer wall of the HT-6M. This was clearly due to fictitious forces, namely centrifugal and coriolis forces. As a result of this, it was noticeable that all droplets from the inner part of the main poloidal limiter rarely survived the ablation because they tended to move through the core plasma (figures 2 (e) - (f)).
Figure 2. Impurity distribution in HT-6M poloidal cross-section produced by ablation of $10^{-4}$ m droplets (a) - (c), and $10^{-5}$ m droplets (d) - (f) initially moving from outer part (a) and (d), top and bottom (b) and (e), and inner part (c) and (f) of HT-6M poloidal limiter, where $N$ is a number of impurity atoms in vapor.

Figure 3. Impurity distribution in HT-6M toroidal cross-section produced by ablation of $10^{-4}$ m droplets initially moving from (a) outer part, and (b) top and bottom of HT-6M poloidal limiter, where $N$ is a number of impurity atoms in vapor.
In general, the impurities tended to localize near the PFCs of the main HT-6M poloidal limiter and spread towards the outer part of the HT-6M vessel (figures 2 (a) - (b) and 3 (a) - (b)). This suggested the formation of either re-deposited or co-deposited layers on the outer part of the limiter and the outer wall. However, for the droplets with $\theta \to 80^\circ$ (figure 2 (a)) and $\gamma \to 45^\circ$ (figure 2 (b)), the successive bouncings led to the spread of impurities towards the inner-part of the HT-6M. However, either re-deposited or co-deposited layers on the inner part of the limiter and the inner wall were most likely due to the accumulation of the vapor containing impurities produced by the ablation of the droplets that originated from the inner part of the HT-6M (figures 2 (c) and (f)).

In practice, whenever a droplet hits a surface, a slight mass of the droplet is left on the surface. This suggests that there is no conservation of mass and momentum during a droplet-surface collision, while the idea is not included in the current DDT code. In addition, it is possible that the mass loss by this collision contributes to the formation of either re-deposited or co-deposited layers, in addition to vapor deposition.

4. Conclusion
The trend of impurity distribution was governed by the inclination of the splashed droplets from the plasma-facing components (PFCs) of the main HT-6M poloidal limiter and successive droplet-wall bouncings. The droplets with inclination directly to the HT-6M core underwent intensive ablation and rapidly produced core impurities. Several successive droplet-wall bouncings recycled some droplets to be additionally ablated in the core plasma. The droplets transported mainly in the SOL plasma had a long lifetime and underwent weak ablation. Due to the centrifugal and coriolis forces, vapor containing impurities tended to spread outwardly and localize near the PFCs on the main HT-6M poloidal limiter and the HT-6M wall. In addition, it was infrequent that successive droplet-wall bouncings transported the droplets from the outer part towards the inner part of the HT-6M. The vapor containing impurities in the inner part of the HT-6M was suggested to originate from the ablation of the splashed droplets from the PFCs of the inner HT-6M poloidal limiter and the HT-6M inner wall.

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