Predictions of Plasma Behavior Due to Pellet Injection for Future Thailand Tokamak[*]

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Thailand Institute of Nuclear Technology (TINT) was donated HT-6M tokamak by Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP), China. The machine will be upgraded and installed in Nakorn-Nayok, Thailand in the near future to kick start on research and human development in the country. In the first phase of operation there will be no external heating, and hydrogen plasma in ohmic phase will be studied. Pellet injection system will be one of the main components to be developed. In this work, the investigation of injection speed, size of a pellet and the angle of injection is conducted by using simulations for providing initial results of the effect of pellets on the plasma. TASK/TR integrated modeling code is used for predicting the plasma profiles. In the core area, the anomalous transport is computed by either the theory-based current diffusive ballooning mode (CDBM) model or the Multi-Mode-95 (MMM95) model. The interaction of the pellet and the background plasma is analyzed by HPI2 code which employed the neutral gas shielding (NGS) ablation model including ∇B-drift effect. This work only considers the injection of a single pellet whose radius is between 0.2 - 0.4 mm. The injection speed is varied in the range of 100 - 1,000 m/s. Injections from both low-field and high-field sides and also investigated. The results illustrate that the pellet can penetrate deeply into the plasma core.

1. Introduction

HT-6M was a small tokamak (the major radius is 0.65 m, the minor radius is 0.2 m, the plasma current is 150 kA and the toroidal field is 1.5 T) and it was formerly developed and operated by Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP), China [1]. This machine will be donated to Thailand for research and human resource development. Initially, it will be installed with only basics diagnostics and magnetic components, no external heating and fueling yet. Some components, such as additional diagnostic systems, high voltage power supply, and external heating systems, will be re-designed and upgraded before starting the new experimental campaign. An injection system of high-speed frozen pellets of hydrogen or deuterium directly into the plasma core is another key system for efficient fueling. The goal of this work is to investigate the effects of the pellet injection onto HT-6M plasma by using an integrated predictive modeling code

TASK/TR [2]. The results can provide insightful information for planning of experimental campaign and the development of the injection system.

Comparing to gas puffing method, the pellet injection yields deeper penetration depth [3, 4]. Pellet injection has also been demonstrated to improve plasma confinement in several experiments [5–7]. It can be also used to reduce recycling but increase the strong peak of electron density profile and the confinement time which can lead to increase of the fusion power gain. The effect of the pellet injection onto tokamak plasmas depends on many factors such as machine size, pellet size, injection speed and plasma shape [8, 9]. Injection direction also directly affects the response of the plasma after the injection. Based on previous studies, the pellet injection experiments in JET and TFTR had shown slight improvement of plasma density when injected from the low-field side (LFS) [10]. On the other hand, pellets injected from the high-field side (HFS) yields deeper penetration depth. Thus, better fusion performance can be expected by the HFS injection [11–14].

In this work, simulations are carried out with plasma

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parameters based on the previous design of the HT-6M tokamak, including $R = 65$ cm, $a = 20$ cm, $B_T = 1.5$ T, $n_e = 1 \times 10^{19}$ m^{-3} and $I_p = 150$ kA [1]. Since the first phase of the future Thailand tokamak will have no external heating, an ohmic plasma is expected. TASK/TR integrated predictive modeling code is used to carry out this investigation. The core transport calculation used in this work is either the theory-based current diffusive ballooning mode (CDBM) model [15] or the Multi-Mode-95 (MMM95) [16] model. Three different scenarios of the pellet injection in HT-6M plasma are reported. Firstly, the effects of a single pellet with a fixed size injected with various injection speeds are reported. Then we study the sensitivity of varying pellet sizes and injection speeds. Lastly, the investigation of the effect of the inject direction is conducted.

This paper is organized as follows: brief descriptions of modeling and simulation method are given in the next section. In section 3, the simulation results and discussions are presented. Section 4 summarizes this study.

2. Modeling and Simulation Methodology

2.1 TASK/TR integrated modelling code

The TASK/TR code is a one-dimensional tokamak transport code that has been developed to analyze the time evolution of a burning plasma accompanied with fusion reaction [2]. In this work, the plasma transport in the core region is described by using the current diffusive ballooning mode (CDBM) and the multimode (MMM95) core transport model. The CDBM model [15] is based on the theory of self-sustained turbulence due to the ballooning mode [17] driven by the turbulent current diffusivity. The MMM95 model [16] consists of the Weiland model for the ion temperature gradient (ITG) and trapped electron modes (TEM), the Guzdar-Drake model for drift-resistive ballooning modes, as well as a smaller contribution from kinetic ballooning modes.

2.2 Pellet ablation and ∇B-induced drift models

The neutral gas shielding (NGS) model was proposed by Parks and Turnbull [18] to solve the problem of a solid hydrogen pellet ablation in a plasma. It is considered that the pellet is ablated by the mono-energetic electrons energy flux based on a symmetric expansion and the steady state approximations. As a result, the ablation rate (dN/dt) is given by:

$$\frac{dN}{dt} = 1.12 \times 10^6 n_e^{0.3333} T_e^{1.64} r_p^{1.33} M_i^{-0.333}, \tag{1}$$

where n_e and T_e are the electron density in cm^{-3} and temperature in eV, respectively. r_p denotes pellet radius in cm and M_i is the mass of the pellet material in atomic unit.

After the pellet is ablated, the neutral cloud that

formed around the pellet also experiences the apparent drift in the radial direction. This drift is caused by $\vec{E} \times \vec{B}$ effect which arises from the ionized part of the ablation cloud due to $\vec{\nabla} B$ and curvature-induced charged particle drift [19]. The cross-field drift velocity (V_D) can be computed as:

$$\dot{V}_D = \frac{2(p_0 - p_\infty)}{n_0 m_i R} - V_D \frac{2B_\phi^2}{\mu_0 C_A n_0 m_i Z_0}, \tag{2}$$

where p_0 and p_∞ denotes the initial pressure inside the high density blob of plasma and the pressure of the background plasma, respectively. n_0 refers to the initial density of the plasmoid, Z_0 is the initial thickness of the ablatant cloud, m_i is the ion mass, and C_A is the speed of the Alfven wave [20].

The HPI2 pellet fueling code is able to analyze the pellet deposition profile directly. However, it still requires the plasma profile such as the temperature and density as inputs. These information of the plasma before the pellet event can be determined by the transport code. The transport code also allows to study plasma response after the pellet injection. In order to account for the ablation of the pellet material and ∇B-induced drift effect, we employ the predictive simulation code HPI2 developed by Pegourie and co-workers [20] and it is integrated with the TASK/TR code.

3. Simulation Results and Discussions

In this part, we use the TASK/TR code to simulate the plasma in the core of the future Thailand Tokamak. The plasma is assumed to be hydrogen and it has the electron density of 10^{19} m^{-3}. There is no external heating in these simulations. The transport in the core region is a combination of the neoclassical transport which is computed by NCLASS module [21] and the anomalous transport, which is computed by CDBM or MMM95 transport model.

In the previous experiment of HT-6M [22], the machine was equipped with the pellet injector system. It was designed to produce hydrogen pellets in a cylindrical shape with 0.6 - 0.8 mm in diameter, and 0.8 mm in length. The pellets were delivered into the tokamak by using a pneumatic system and it was able to achieve maximum speed of 1.4 km/s approximately. The bulk plasma electron density for normal operations was around 10^{13} cm^{-3} and the central electron temperature was about 500 eV.

Three different scenarios of the pellet injection are conducted and reported: 1) the effect of the injection speeds for a single pellet whose radius is 3.78×10^{-4} m, 2) the sensitivity study of the effect of varying both injection speed and pellet size, and 3) the analysis of the varying injection direction. Note that we only focus on the response of the plasma after a single hydrogen pellet was injected.

3.1 The analyzing of fixed pellet size with varying injection speeds

We first performed simulations of the pellet injec-

tion based on the previous design and compare with the previous experimental results [22]. Based on their design, the cylindrical pellet of size 0.6 mm diameter and 0.8 mm length is equivalent to a spherical of radius size 3.78×10^{-4} m. A single hydrogen pellet is launched from the LFS into the HT-6M plasma with two injection speeds of 100 m/s (low speed) and 600 m/s (high speed).

The electron temperature and density profile are shown in Figs. 1 and 2 as a function of time and normalized minor radius. The CDBM model is used for the core transport. The simulation results from both discharges are in Ohmic mode. These results show that pellets increase the electron density at the center from 0.200×10^{20} m^{-3} up to 0.370×10^{20} m^{-3} and 0.200×10^{20} m^{-3} up to 0.475×10^{20} m^{-3} for the launching speeds of 100 m/s and 600 m/s, respectively.
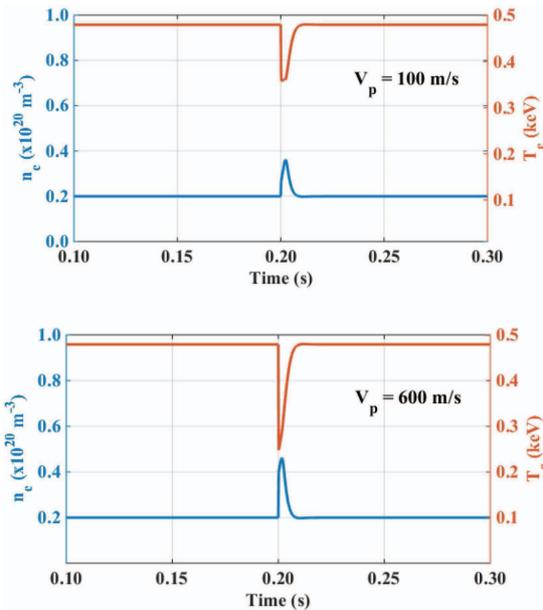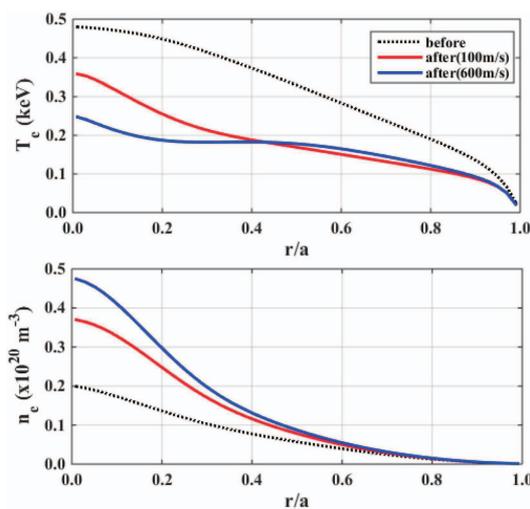
It is also observed that the pellets decrease the central electron temperature from 480 eV to 358 eV for the injection speed of 100 m/s, and from 480 eV to 248 eV for the injection speed of 600 m/s. Both temperature and density of the plasma return to their previous levels after 0.1 ms approximately. The simulation results of the peak value of electron density and temperature agree with the same range of the experimental results [22].

3.2 Sensitivity study of the pellet size and injection speed

It is known that penetration depth and the deposited mass of the pellet depends on the pellet size, injection speed, injection angle, and the background plasma condition as well. This part investigates the sensitivity of the variation of the pellet size and injection speed. A single spherical pellet is launched from the LFS whose size is varied between 0.1 and 0.4 mm and the injection speed is changed between 100 to 1000 m/s.

Figure 3 shows the deposited mass of the pellet on the background plasma as predicted by the HPI2 code for two different core transport models: CDBM and MMM95. As seen in these graphs, the highest deposition fraction that can be achieved from both models is approximately 0.6. Some of the mass that does not remain in the core plasma is lost due to the $\overrightarrow{\nabla} B$ effect in the radial direction.

In Fig. 4, the graphs illustrate the relationship between the penetration depth of a pellet and the injection speed for different pellet sizes. This deposition depth is de-

Fig. 1 The electron temperature and density as a function of time with the pellet velocity of 100 m/s (top) and 600 m/s (bottom).

Fig. 2 The electron temperature (top) and electron density (bottom) profiles as a function of normalized minor radius, before and after pellet injection with the pellet velocity of 100 m/s (red-solid) and 600 m/s (blue-solid), respectively. The core transport model is based on CDBM model.

Fig. 3 Deposition fraction from both simulation of CDBM (Upper) and MMM95 (bottom) as a function of injection speed with pellet sizes of 0.1 - 0.4 mm.
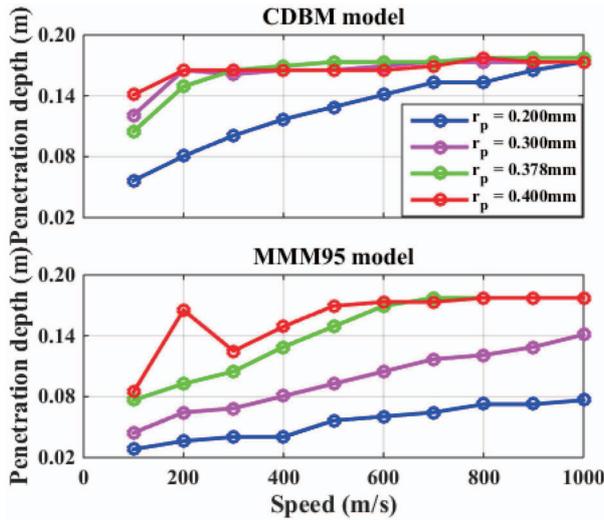
Fig. 4 The penetration depth of deposited mass as functions of injection speed at different pellet sizes. The upper plot is carried out CDBM model and the lower plot is performed by the MMM95 model.

Fig. 5 The electron temperature (top) and electron density (bottom) profiles as a function of normalized minor radius, before and after pellet injection with the pellet velocity of 600 m/s. The core transport model is based on CDBM and MMM95 model.

Fig. 6 The figure shows the tokamak cross section and the launching angles shown in radius.

fined as the distance from the separatrix at which the deposited mass of a pellet is maximum. The lower value of this quantity implies that the pellet cannot penetrate deeper into the core and only deposits their mass near the edge of the plasma. Both simulations from CDBM and MMM95 demonstrate that the deeper penetration depth can be archived if a pellet has larger size or higher injection speed.

In the simulations with CDBM model, when a pellet whose radius is larger than 0.3 mm is launched with speed faster than 200 m/s, the penetration depth is deeper, but the deposition fraction is also decreasing (see Fig. 4). This might suggest that the pellet is partially ablated. Some part of the pellet may still remain in the solid form and leave the plasma without ablation. Results from the simulations with MMM95 model suggest that the most the pellet with a radius of 0.378 mm and speed of 600 m/s is enough for depositing its mass near the middle of the core area. Launching the pellet with higher speed or using larger pellet size would not be necessary and the deposition fraction cannot be increased.

Figure 5 illustrates comparison profiles of electron temperature and density before and after 600 m/s pellet injection using CDBM and MMM95 models. It can be seen that the densities increase while the temperatures drop. Note that the fluctuating results from MMM95 model shown in the figure are caused by numerical perturbation.

3.3 Sensitivity study of injection direction

The magnetic field in a tokamak is non-uniform. Therefore, when a pellet is launched to the plasma from different angle, its penetration depth and deposition fraction may be varied. In this section, we study the injection

of a single pellet to the Ohmic plasma from 10 different launching angles which are illustrated in Fig. 6. The pellet whose radius is 0.3 mm and injection speed is 200 m/s is used in these simulations. This condition is selected based on the results of the previous simulations which suggest that the pellet with these parameters completely ablates before reaching the center. Two core transport models, CDBM and MMM95, are used for comparison.

Figure 7 demonstrates the peak radius of the density profile of the pellets launching from different injection angles. The data in the blue region are from the low-field side $(0 < \theta < \pi/2)$ and the injection data from the high-field side $(\pi/2 < \theta < \pi)$ are shown in the red region. Figure 8 shows the deposition profile of pellets as a function of the normalized minor radius (r/a).
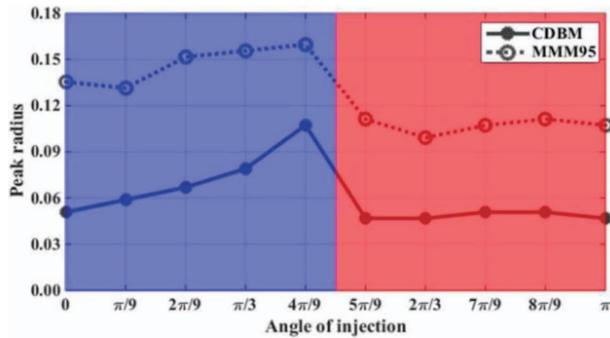
Fig. 7   The penetration depth as a function of angle of pellet injection for different models.
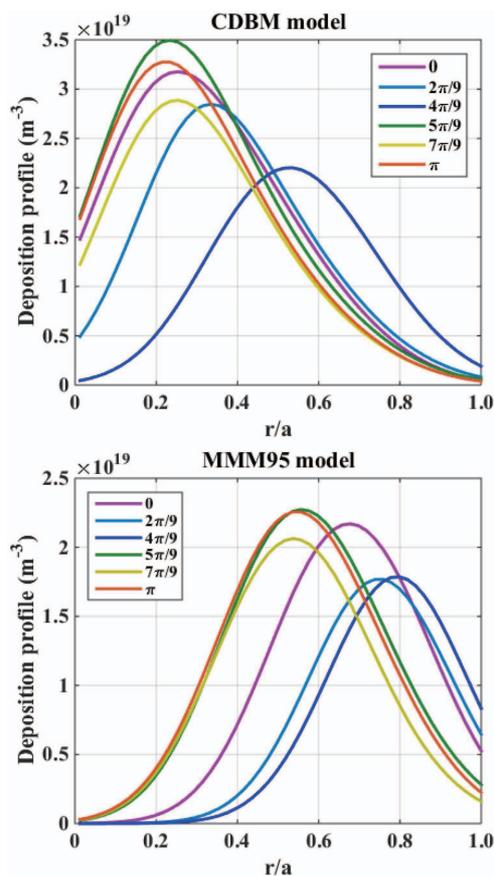
Fig. 8   The deposition profile as a function of r/a with varying launching angles for different transport models.

It is clearly shown in Figs. 7 and 8 that the injections from the high-field side yield the deeper penetration depth for both transport models. These differences are caused by the ∇B drift effect that can directly affect the ablation mass of the pellets. However, the injection results from CDBM model predict that the pellets penetrate deeper than those simulated with MMM model. This might because the temperature profiles predicted by CDBM model is lowered that the other model. Thus, the pellets are able to enter deeper into the core before ablating.

4. Conclusions

Simulations of pellet injections with different scenarios are investigated for the ohmic plasma based on the nominal parameters of HT-6M tokamak. The core transport code used in this work is TASK/TR code. The ∇B-drift effect during the pellet events are considered and are simulated by HPI2 code. The results show that the pellets launched from the HFS yields deeper penetration depth than those injected from the LFS for both CDBM and MMM95 models, but the results from MMM95 model trends to be higher than those CDBM model. When pellets with a radius of 0.2 - 0.4 mm are injected with speed of 200 m/s, the penetration depth is found to be about 5 cm away from the magnetic axis.

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