Simulation of plasma in scrape-off-layer region in Thailand Tokamak 1 using extended two-point model

R Kongkerd¹ and A Wisitsorasak¹

¹ Department of Physics, Faculty of Science, King Mongkut’s University of Technology Thonburi, Bangkok, Thailand

E-mail: apiwat.wis@kmutt.ac.th

Abstract. As Thailand has been preparing to operate a small tokamak in which the device will be upgraded from HT-6M tokamak, the quantitative information about the plasma in the edge and at the surface of a limiter would be insightful for planning future experimental operations. In this work, we employ an extended two-point model to investigate the particle and heat exhausted from the core to the limiter for the tokamak with nominal parameters of HT-6M. The model assumes that the transports of heat and particle from the core enter the scrape-off layer at the outer midplane (upstream point). They then travel to the limiter along the magnetic field line. In this scrape-off layer region, both the conductive and convective transport are considered. The particle sources are only present near the limiter and the conservation of momentum is assumed. Thus, in the steady state, the transport equations can be reduced to a set of nonlinear equations that relates the density and temperature at the upstream to those at the limiter. For Thailand Tokamak 1, as the density at the upstream point is increased from $0.1 \times 10^{19}$ to $3.5 \times 10^{19}$ m$^{-3}$ and power through separatrix is 0.2 MW, it is found that the electron temperature at the limiter surface is reduced from 250 to 10 eV. When the upstream density is greater than $2.7 \times 10^{19}$ m$^{-3}$, the particle flux reaching to the limiter significantly decreases in which this suggests for the plasma detachment.

1. Introduction

All fusion devices consist of a boundary layer that separates the plasma in a confined volume and solid surfaces. In tokamaks, this boundary layer can be established by divertors and limiters [1, 2]. In the divertor configuration, the null magnetic surface is created by current in external coils. The magnetic field outside this surface starts and ends on solid materials. On the other hand, a limiter which is a solid object that protrudes into the plasma for limiting the plasma in the core and preventing direct contact between the hot plasma and the wall. However, this can create an area of open magnetic field lines which exhibit some physical differences with plasma core. Understanding the plasma behavior in this region is thus significantly important as it is a boundary for the core plasma.

While experimental measurements in the scrape-off layer (SOL) are limited, simulations of the plasma transport in this thin region of the SOL may provide more information. The simulation of the SOL plasma is also complicated because it involves complex plasma phenomena and interactions between plasma and solid materials are unavoidable. Advanced simulations such as TOKAM3D [3], BOUT++ [4], NIMBUS [5], B2-EIRENE [6], COREDIV [7], and UEDGE [8] can be used to study the...
transport in the tokamak edge with complex SOL geometry. However, they may require intensive computational time. Less sophisticated simulations also exist such as five-point model [9] and a simple two-point model [10]. This work studies the plasma transport in the SOL region using an extended two-point model which is based on the fluid description of the plasma in the steady state [1, 10].

Thailand has a national plan for conducting research in fusion program and planning to operate a small tokamak. The first tokamak will be upgraded from HT-6M tokamak that was formerly owned by ASIPP, China [11]. The device will have the plasma major radius about 0.65 m and the minor radius of 0.20 m, and it will employ a limiter for creating the separatrix. The goal of this work is to numerically investigate the temperature and density in the SOL by using an extended two-point model [10]. Possibility for plasma detachment will be also explored.

This paper is organized as follows. In the section 2, we describe the extended two-point model in details. Section 3 shows validation of the model with experimental data from TFTR tokamak and presents the predictions of the temperature and density in the SOL for Thailand Tokamak 1 based on the nominal parameters of HT-6M tokamak. This work is finally summarized in section 4.

2. Methodology

The calculation of the temperature and density in the SOL region is based on the two-point model. The model considers parallel transport along a magnetic field lines and relates the temperatures and densities at the midplane separatrix condition (the upstream point) and the target condition (the downstream point) using the fluid equations at the steady state. At the upstream point, particle leaves the core and enters the SOL. The precise locations where the fluxes enter the SOL are still under investigated. Experimental results [12] and simulations [13, 14] suggest that there is the ballooned transport at the edge of the plasma. The transport is found to be localized at the outer mid plane and can enhance the radial transport in the SOL. Therefore, this work assumes that the particle flux enters the SOL at the outer midplane only. The particle fluxes then separate into two parts and finally reach the target points at the limiter surface, see figure 1. For simplicity, the model considers the sources and sinks locally at these two points.

In order to derive a set of equations that relates the temperatures and densities at the two points, the parallel viscosity of the plasma is considered negligible along the SOL. The particles have a non-negligible parallel velocity in a thin region in front of the target due to the sheath potential [1]. The neutral recycling only affects the particle transport in a thin layer near the target surface. The fraction of momentum loss due to recycling is $f_{mom}$. Thus total pressure between the upstream and target can be written as

$$f_{mom}n_u T_u (1 + M_u^2) = 2n_t T_t,$$

where $T$ and $n$ represent plasma temperature and plasma density, respectively. The subscript u refers to the upstream position while t refers to the target. $M$ is Mach number [1] and can be determined as

$$M_u = \frac{1}{2} \left( \frac{n_u c_s (T_u)}{\Gamma_u} - \sqrt{\left( \frac{n_u c_s (T_u)}{\Gamma_u} \right)^2 - 4} \right),$$

where $c_s = 2T/m_i$ is the ion sound speed and $\Gamma$ is the particle flux. The momentum loss factor is relating the ionization and charge exchange process, and can be expressed as follow [15]

$$f_{mom} = 2 \left( \frac{\alpha}{\alpha + 1} \right)^{\frac{\alpha + 1}{2}}, \alpha = \frac{< \sigma v >_i}{< \sigma v >_t < \sigma v >_{cx}},$$

where $< \sigma v >_i$ and $< \sigma v >_{cx}$ represent reaction rate of ionization and charge exchange processes, respectively.
Figure 1. The poloidal cross section and schematic view of the limiter scrape-off layer.

Figure 2. The plot of momentum loss fraction ($f_{\text{mom}}$) as a function of temperature.

Figure 2 shows the plot of momentum loss fraction ($f_{\text{mom}}$) as a function of the temperature. As the temperature decreased, the plasma will significantly lose momentum since the ionization and charge exchange occur more often. Mach number which is the ratio of the flow speed and the sound speed is approximately equal to unity at the target. Thus, the Mach number at the target ($M_t$) equals one.

For the heat transport equation, the convective and conductive transports are considered in the SOL. In the steady state, we can write [10]

$$
\frac{d}{dl} \left(-\kappa_\parallel \frac{dT}{dl} + 5 \Gamma_\parallel T \right) \approx q_{\perp} \delta,
$$

where $\kappa_\parallel = A_K T^{5/2}$ is the Spitzer conductivity, $l$ the direction along the magnetic field line starting the midplane to the limiter, $\Gamma_\parallel$ the particle flux density along the magnetic filed line, and $q_{\perp}$ the heat flux to the SOL.

Integrating equation 4 with boundary condition $d\Gamma/dl = 0$ at $l = 0$ (midplane), we finally obtain [1, 10]

$$
T_c^{5/2} \left( \ln \frac{1 + \sqrt{T_u/T_c}}{1 - \sqrt{T_u/T_c}} - \ln \frac{1 + \sqrt{T_t/T_c}}{1 - \sqrt{T_t/T_c}} \right) = \frac{T_u^{5/2} - T_t^{5/2}}{5} + T_c^{7/2} - \frac{T_c^{3/2}}{3} + T_c^2 (\sqrt{T_u} - \sqrt{T_t}) + \frac{5 l^2 \Gamma_\perp}{4 A_K \delta},
$$

where $T_c \equiv q_{\perp}/(5 \Gamma_\perp)$. Here the SOL width $\delta$ generally depends on the transport properties of particles and heat at the last close flux surface (LCFS). For sake of simplicity, it can be approximated by the following scaling law [16]

$$
\delta = 0.0031 \frac{2}{7} R,
$$

where $R$ is plasma major radius.

The energy loss along the SOL is approximately very small and mostly occur near the limiter. The incoming power flux to the target will partially transferred to the limiter and the ionization of neutral atom in the recycling region. Thus we can write

$$
4\pi R \delta (\gamma T_e + E_i) n_e c_s \sin \psi = q_{\perp} S_{\text{LCFS}},
$$
where \( E_i \approx 30\,\text{eV} \) is the effective energy lost due to the ionization, \( \gamma \approx 7.5 \) the heat transmission factor, the pitch angle, and \( S_{LCMS} = 4\pi^2 aR \) the total area of LCFS.

The limiter surface locates very close to the core and touch the LCFS, see figure 1. This also causes flows of particles from the target to the core. In the steady state these flows must be balanced with the particle fluxes from the core to the SOL \((\Gamma_\perp)\). The particle flux \( \Gamma_\perp \) is approximately equal to

\[
\Gamma_\perp \approx \frac{4\pi R \sin \psi \sigma_n}{S_{LCMS}} \left[ 1 - \exp\left( -n_t \sigma_n \delta \right) \right] \frac{R_p k_i + k_{cx}}{k_i + k_{cx}},
\]

where \( k_i \) and \( k_{cx} \) refer to rates of ionization and charge exchange described as follows [17]

\[
k_i = 0.73 \times 10^{-8} \sqrt{T} e^{-13.6/T} \left( 1 + 0.01T \right), \quad k_{cx} = 10^{-8} T^{0.3},
\]

where \( T \) is given in a unit of \( \text{eV} \), and \( k_i, k_{cx} \) are in units of \( \text{cm}^3/\text{s} \).

Equations 1, 5, and 7 form a set of nonlinear equations that relates the density and temperature at the upstream \((T_u, n_u)\) to these at the downstream \((T_t, n_t)\). In this work, \( n_u \) and \( \psi \) are considered as input parameters. One can reduce these equations to be a single equation which only depends on \( T_t \) and numerically solve such equation by bisection method [18]. Once \( T_t \) is obtained, other variables can be subsequently determined.

## 3. Results and Discussions

### 3.1. Model Validation with Experimental Results from TFTR

In this section, we first validate the extended two-point that takes into account of both conduction and convection transports by comparing with experimental measurement from TFTR Tokamak discharge No. 42456 at the different time snapshots [19]. For this discharge, plasma major radius is \( R = 2.45 \, \text{m} \) and minor radius is \( a = 0.80 \, \text{m} \). The Ohmic heating power in the experiments was set at 1 MW. In order to compare with the developed two-point model, the power through the separatrix is required as one of input parameters. This work assumes that half of the power in the core is lost due to radiation [19]. Thus the power of 0.5 MW enters into the SOL.

Figure 3 plots the temperature at the upstream and target as a function of the upstream density. The experimental data for the upstream temperature, see tables 1, are also presented for comparison. The graph clearly shows the the temperatures decrease as the upstream density increases due to the conservation of pressure along the field line.

| Snapshot No. | Upstream Density \((10^{18} \, \text{m}^{-3})\) | Experimental \( T_u \) \((\text{eV})\) | Simulated \( T_u \) \((\text{eV})\) | %Difference |
|-------------|------------------|------------------|------------------|-------------|
| 1           | 2.65             | 63.79            | 60.19            | 5.6         |
| 2           | 2.66             | 53.84            | 60.19            | 11.8        |
| 3           | 3.66             | 50.36            | 49.45            | 1.8         |
| 4           | 6.02             | 34.60            | 34.98            | 1.1         |
| 5           | 7.94             | 24.16            | 28.91            | 19.6        |
| 6           | 12.21            | 22.04            | 26.50            | 20.2        |
| 7           | 12.47            | 27.40            | 26.80            | 2.2         |

| Table 1. The comparison between the experimental results and simulation from two-point model. The experimental data are taken at seven different times of TFTR discharge No. 42456 [19]. |
The percentage differences of the upstream temperature between the experiment and the simulation (ΔT_u) for these data series are presented in table 1. Based on the comparison, our prediction results agree with the experimental data with the percentage difference less than 20%.

![Figure 3. Temperatures as a function of the upstream density (n_u). Note that the T_t and T_u present the target temperature and upstream temperature respectively. The solid lines are predictions and the dots are experimental data (TFTR discharge No. 42456).](image)

3.2. Simulation Prediction for Thailand Tokamak 1
Thailand Tokamak 1 (TT1) is at the present stage, the first conceptual design that will be operated in Thailand. The machine will be upgraded from HT-6M tokamak which was previously own by ASIPP, China. In this section, the developed two-point model is carried out to predict the upstream, target temperatures, and the target density. These information may help the research team preparing for future experiments.

The nominal parameters of TT1, based on existing parameters of HT-6M tokamak, are as follows: plasma major radius R = 0.65 m, plasma minor radius a = 0.20 m. The machine will use a poloidal limiter which is made of steel for limiting the plasma. There will be no external heating for the first-phase operation. In this work, we assume that the upstream densities are varied between 0.1 × 10^{19} m^{-3} to 3.5 × 10^{19} m^{-3}. The power passing through the separatrix (P_{sep} = q_\perp \times S^{LCFS}) is approximately equal to 0.2 MW [20]. We note that the discharge time of HT-6M tokamak is rather short and the plasma may only be in the transient phase. In this work, however it is assumed that the plasma in the steady state can be for obtained for TT1 tokamak.

![Figure 4. The upstream temperature (T_u) and the target temperature (T_t) as a function of the upstream density (n_u) for Thailand Tokamak 1.](image)

![Figure 5. The relation between the target density (n_t) and the upstream density (n_u) for Thailand Tokamak 1.](image)
Figure 4 shows the upstream and target temperatures as a function of the upstream density, and figure 5 plots the target density versus the upstream density. When the upstream density is less than $0.5 \times 10^{19} \text{ m}^{-3}$, the temperatures at the upstream and target are approximately equal. At the low density, the particle convection dominates the particle transport. The plasma temperature in the SOL is also high so that the heat conduction which is proportional to $T^{5/2}$ is large. Thus the variation of the temperatures along the SOL is negligible. If the upstream density increases further ($0.5 \times 10^{19} \text{ m}^{-3} < n_u < 3 \times 10^{19} \text{ m}^{-3}$), the difference between $T_u$ and $T_t$ becomes more pronounced. The parallel heat flux reaching the target also decreases with increase of upstream density due to radiative cooling effect, see figure 6.

![Figure 6. The parallel heat flux as a function of the upstream density for Thailand Tokamak 1.](image)

![Figure 7. The particle flux reaching to the target as a function of the upstream density for Thailand Tokamak 1.](image)

In figure 7, the particle flux firstly increases and reaches a threshold value at the $n_u \approx 2.7 \times 10^{19} \text{ m}^{-3}$. It then decreases with increasing of the upstream density. This decreasing of the particle flux exhibits the detachment state of the plasma [21]. The detached regime can be occurred in this high density regime since the temperature at the target becomes very low. The neutral particles that are coming from the target are less probably ionized at this low temperature. Therefore, the ionization front moves away from the target, and the particle and heat fluxes decrease [1].

4. Conclusion

The scrape-off layer is important as it provides information at the boundary for the plasma confined in the core. However, the plasma transport in the SOL is complicated because it involves with complex plasma phenomena. This work employs the extended two-point model for the tokamak plasma with the limiter configuration to investigate the densities and temperatures between the midplane point and limiter surface. The model is based on a simple fluid description along the magnetic field line. Both heat conduction and convection are treated explicitly in the energy balance equation. Here the parallel viscosity and velocity are considered to be negligible and the source and sink terms are assumed to be localized near the midplane plane and limiter surface. In the steady state, one can show that the fluid equations reduce to a set of nonlinear equation that relates the densities and temperatures at the upstream and at the limiter. The model is validated with TFTR discharge number 42456 at seven different times. By comparing between the temperature at the upstream point, the percentage differences between the experimental data and the simulations are less than 20%. The developed model is also used to carry out the density and temperature in the SOL for Thailand Tokamak 1 based on nominal parameters of HT-6M tokamak. As the density at the upstream point is varied between $0.1 \times 10^{19} \text{ m}^{-3} - 3.5 \times 10^{19} \text{ m}^{-3}$, it is found that the electron temperature at the limiter surface is in the range of 10 - 250 eV. When the upstream density is greater than $2.7 \times 10^{19} \text{ m}^{-3}$, the particle flux reaching to the
limiter significantly decreases in which this suggests for the plasma detachment.

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