The simulation of \textit{L-H} transition in tokamak plasma using MMM95 transport model

P Intharat\textsuperscript{1,4}, B Chatthong\textsuperscript{2}, T Onjun\textsuperscript{2}, N Poolyarat\textsuperscript{1} and R Picha\textsuperscript{3}

\textsuperscript{1} Department of Physics, Faculty of Science and Technology, Thammasat University, Pathum Thani, Thailand
\textsuperscript{2} School of Manufacturing Systems and Mechanical Engineering, Sirindhorn International Institute of Technology, Thammasat University, Pathum Thani, Thailand
\textsuperscript{3} Thailand Institute of Nuclear Technology, Bangkok, Thailand

Email: pat_int@yahoo.com

Abstract. BALDUR integrative predictive modelling code together with a Multimode (MMM95) anomalous transport model is used to simulate the evolution profiles, including plasma current, temperature, density and energy in a tokamak reactor. It is found that a self-transition from low confinement mode (\textit{L}-mode) to high confinement mode (\textit{H}-mode) regimes can be achieved once a sufficient auxiliary heating applied to the plasma is reached. The result agrees with experimental observations from various tokamaks. A strong reduction of turbulent transport near the edge of plasma is also observed, which is related to the formation of steep radial electric field near the edge regime. From transport analysis, it appears that the resistive ballooning mode is the dominant term near the plasma edge regime, which is significantly reduced during the transition.

1. Introduction

Harvesting nuclear fusion energy from tokamak plasma becomes one of the great challenges among the physicists and engineers. Nuclear fusion reaction requires high energy to overcome the Coulomb’s repulsive force between nuclei. In 1979, it was found in ASDEX upgrade tokamak that when sufficient external heating was applied, the plasma temperature, density and confinement time increased significantly. This new operational regime is called “high confinement mode (\textit{H}-mode)” [1-7]. In \textit{H}-mode, the plasma yields higher performance, which is often measured by quantities such as temperature, density and stored energy. Higher temperature and density can increase the nuclear fusion reactions. The difference between the \textit{H}-mode and a low confinement mode (\textit{L}-mode) is the presence of the steep gradient at the edge region, called edge transport barrier (ETB) [5, 8]. It is most interesting to investigate the \textit{L-H} transition in tokamak plasma.

BALDUR integrated predictive modelling code [9] was developed to simulate time-evolution of plasma current, density and temperature profiles. It includes various phenomena in tokamak experiments, such as sources, sinks, transports of thermal energy and particles, etc. The BALDUR code has been intensively tested against experimental data from various tokamaks, in which the temperature and density profiles yield an RMS about 10% [4, 10]. In this work, both thermal and...
particles transports are described by using a Multimode 95 anomalous core transport (MM95) model. The external heating is applied to the plasma as electron cyclotron resonance heating (ECRH) and ion cyclotron resonance heating (ICRH). Once critical threshold is reached, the plasma makes a transition from L-mode to H-mode, called “L-H transition”. This work studies the L-H transition by using the MM95 anomalous core transport. The H-mode access can be referred from the experiment results using the threshold scaling law and the reduction of anomalous transport near the edge regime of plasma. This work is organized as follows; chapter 2 describes description of simulation, chapter 3 presents simulation results and the conclusion is given in chapter 4.

2. Description of the simulation

2.1. MM95 Anomalous core transport model

In this work, MM95 core transport is used to predict the core and edge transport in BALDUR simulation [10-11, 13] model. It is implemented in BALDUR to predict the profiles of temperature and density. MM95 consists of Weiland models, Guzdar-Drake models and its kinetic ballooning model. The Weiland model described the Ion Temperature Gradient (ITG) and Trapped Electron Modes (TEM), it is a theory-based model derived from the fluid concepts. Generally, the Weiland model is largest contribution in the plasma core regime. On the other hand, the Guzdar-Drake model described both resistive and kinetic ballooning modes (RB and KB, respectively). Their calculation is proportional to the pressure gradient and collision. The resistive ballooning mode has high contribution near the edge of plasma. Whereas, the kinetic ballooning model usually provides a small contribution to total diffusivity throughout the entire plasma, except near the magnetic axis. All of the anomalous transport contributions from the MM95 transport model are multiplied by $\kappa^{-4}$, since the models were originally derived for circular plasmas [11]. Parameter $\kappa$ is plasma elongation which describes the geometry of plasma cross section shape. Both thermal and particle transport parameters in MM95 core transport model are described below:

$$
\chi_i = 0.8 \chi_{i,(ITG,TEM)} + 1.0 \chi_{i,(RB)} + 1.0 \chi_{i,(KB)},
$$

(1)

$$
\chi_e = 0.8 \chi_{e,(ITG,TEM)} + 1.0 \chi_{e,(RB)} + 1.0 \chi_{e,(KB)},
$$

(2)

$$
D_H = 0.8 D_{H,(ITG,TEM)} + 1.0 D_{H,(RB)} + 1.0 D_{H,(KB)},
$$

(3)

$$
D_Z = 0.8 D_{Z,(ITG,TEM)} + 1.0 D_{Z,(RB)} + 1.0 D_{Z,(KB)},
$$

(4)

where $\chi_i$ and $\chi_e$ are ion and electron diffusivities, respectively (m/s²), $D_H$ is particle diffusivity and $D_Z$ is impurity diffusivity. ITG and TEM represent contributions from Weiland model. RB is transport from resistive ballooning model and KB is transport from kinetic ballooning model.

2.2. The H-mode power threshold model

It is found that the L-H transition occur when the total applied heating power exceeds a threshold power. The standard working hypothesis, supported by many observations, is that H-mode occurs when the total power or the power transported across the separatrix ($P_{sep}$) exceeds a threshold value ($P_{sep} > P_{thr}$) [1]. The $P_{sep}$ can be calculated as follows:

$$
P_{sep} = P_{ohm} + P_{aux} + P_{a} \frac{dw}{dt} - P_{loss},
$$

(5)

where $P_{ohm}$ is power in ohmic stage, $P_{aux}$ is auxiliary heating, $P_{a}$ is alpha power, $\frac{dw}{dt}$ is derivative of plasma stored energy with respect to time and $P_{loss}$ is loss power. The threshold power $P_{thr}$ can be calculated based on scaling law as follows [1]:

$$
P_{thr} = 2.15 \kappa n_{e20}^{0.58} B^{0.82} R^{1.00} a^{0.81} M_{ion}^{1/2},
$$

(6)

where $\kappa$ is the elongation, $n_{e20}$ is the electron density ($10^{20}$ m⁻³), $B$ is the toroidal magnetic field, $R$ and $a$ are the plasma major and minor radii, respectively, and the $M$ is the mass of ion species.
2.3. The radial electric field

The physics of edge transport barrier is important for the understanding of the evolution of turbulent transport. At the onset of the $L$-$H$ transition, the turbulent transport is found to decrease near the edge region of the plasma. The key for understanding of the ETB formation is $\omega_{E\times B}$ (flow shear) stabilization. The flow shear is known to be able to quench the turbulent transport. It depends on plasma electric field on radial direction. Theoretically and experimentally the flow shear stabilization [7, 13] is calculated as:

$$\omega_{E\times B} = \frac{(RB_\theta)^2}{B_\theta} \frac{\partial}{\partial \phi} RB_\theta \cdot E_r,$$

where $\omega_{E\times B}$ is the flow shear rate (s$^{-1}$), $R$ is the major radius, $B_\theta$ is the poloidal magnetic field, $B_\phi$ is the toroidal magnetic field, and $E_r$ is the radial electric field for the main plasma ions. The $E_r$ can be used to indicate the plasma mode of the tokamak experiments [7] because the $E_r$ profile is dependent on the pressure gradient at the onset of $L$-$H$ transition. It is calculated as follows:

$$E_r = \frac{1}{Ze_i} \frac{\partial}{\partial r} n_i v_\theta B_\phi + v_\phi B_\theta,$$

where $\frac{\partial p_i}{\partial r}$ is the ion pressure gradient, $v_\theta$ and $v_\phi$ are the poloidal and toroidal velocities, respectively, and $n_i$ is the ion density, $Z$ is the ion charge number and $e$ is the elementary charge. Furthermore, the radial electric field depends on the gradient of temperature, density or pressure of the plasma species.

3. Simulation results

The simulations are carried out using the engineering parameters shown in table 1. For all simulations, an anomalous transport is calculated using MMM95 transport model and the auxiliary heating used the RF heating to induce the $H$-mode on the simulation as the ICRF and ECRH. The auxiliary heating profile is assumed to be a gaussian shape, centralized near the plasma center. The plasma parameters for simulation were chosen based on the $H$-mode plasma experiment on the HL-2A tokamak [14, 15].

| Parameter | Physical Description | Value | Unit |
|-----------|----------------------|-------|------|
| $R$       | Major radius         | 1.65  | M    |
| $A$       | Minor radius         | 0.40  | M    |
| $I_p$     | Plasma current       | 0.48  | MA   |
| $B_T$     | Toroidal field       | 2.8   | T    |
| $K$       | Elongation           | 1.30  | -    |
| $\delta$  | Triangularity        | 0.30  | -    |
| $Z_{eff}$ | Effective charge     | 1.50  | -    |
| $P_{aux}$ | Auxiliary heating    | 3     | MW   |

Table 1. Plasma parameters for the simulation.

Firstly, this simulation is carried out for the behaviours of plasma during the heating phase. Figure 1 shows the plasma stored energy ($W_{TOT}$) as a function of time. The plasma stored energy has similarity to the internal or total energy of the plasma tokamak. It is found that as the auxiliary heating is applied at 0.7 sec, the plasma stored energy is strongly increased, and then after the heating is turned off, it is decreased. The stored energy is strongly increased by around 50% when the auxiliary heating is included and is decreased by around 47% as heating is turned off. When the transport barrier forms, the particle diffusivity is locally reduced near the edge regime. Therefore the electron temperature is increased on the heating phase (t=0.9 sec) as shown in figure 2. The figure shows electron temperature ($T_e$), electron diffusion transport ($\chi_e$) and the temperature gradient (gradient) as a function of normalized radius at a time before (t=0.4 sec), during (t=0.9 sec) and after heating (t=1.2 sec).
Figure 1. The evolution of plasma stored energy ($W_{TOT}$) and auxiliary heating power ($P_{aux}$) as a function of time, from BALDUR simulation.

Figure 2. The electron temperature (top), electron thermal transport coefficient (center) and the electron temperature gradient (bottom) as a function of normalized minor radius at different times, from BALDUR simulation.

In the $H$-mode phase, the electron temperature increases with the strong temperature gradient near the plasma edge as shown in figure 2. Consequently, the $H$-mode plasma is reached, which causes the reduction of the diffusion transport near the edge plasma regime. The difference between $L$-mode and $H$-mode phase can be observed in the electron temperature and total electron transport profiles. During the $H$-mode phase, the turbulent transport is reduced near the edge regime, resulting in the formation of transport barrier.
Figure 3. The radial profiles of the electron transport coefficient in L-mode (t=0.4 sec) and H-mode of plasma (t=0.9 sec), from BALDUR simulation.

In figure 3, the comparison between the L-mode (t=0.4 sec) and H-mode (t=0.9 sec) shows that the total transport decreases near the edge regime on model for the calculation. In the H-mode phase, the Weiland model has the ITG and TEM contribution which dominates near the edge regime. The resistive ballooning mode has the dominant contribution at the edge regime cause by the temperature gradient. The kinetic ballooning mode has smaller contribution than the other models. The total transport is calculated from the summation of the Weiland model and Guzdar-Drake resistive ballooning model. The result shows that the transport decreases near the edge plasma when the plasma undergoes L-H transition.

Next, the results on H-mode formation are compared between the theoretical simulations and the experiments. The H-mode threshold is used as the empirical scaling in the simulation and experimental data. It indicates the power transport across the separatrix ($P_{sep}$) must exceed the H-mode threshold value ($P_{thr}$) and then the L-H transition access. The L-H transition is confirmed with the H-mode threshold scaling during the heating phase. The power transport across the separatrix reaches than the H-mode threshold power for the transition.

Figure 4 shows the power transport across the separatrix in each of auxiliary heating power (0.5 and 3 MW) and the H-mode threshold power for the L-H transition. Before and after heating phase, $P_{sep}$ of both heating is lower than the $P_{thr}$ transition and the transport barrier does not occur in the electron temperature profile. During the heating phase, it is found that $P_{sep}$ ($P_{aux} = 3$ MW) is larger than the threshold power that the electron temperature shows the ETB formation in figure 2 ($T_e$), which indicates the H-mode plasma phase and the turbulent transport.
The power transport across the separatrix ($P_{sep}$) and threshold power for transition (line) as functions of time, from BALDUR simulation.

Figure 5 illustrates the radial electric field and the flow shear stability as functions of normalized radius. When the $H$-mode occurs ($t=0.9$ sec), the radial electric field become more negative, resulting in increases the flow shear rate.

**Figure 4.** The power transport across the separatrix ($P_{sep}$) and threshold power for transition (line) as functions of time, from BALDUR simulation.

**Figure 5.** The evolution of (top) radial electric field ($E_r$) and (bottom) the flow shear rate as a function of normalized radius, from BALDUR simulation.

### 4. Conclusion

The BALDUR integrative predictive modelling code is used to simulate an evolution of plasma profiles during $L$-$H$ transition. It is found that a self-transition from $L$-mode to $H$-mode can be achieved in the BALDUR simulations by using the MMM95 anomalous core transport. This transition can be achieved with the condition that an auxiliary heating power surpasses a certain threshold. The $H$-mode plasma on this simulation can be achieved with the flow shear suppression that causes the reduction of the transition and radial electric field. In the transport analysis, it is found that the resistive ballooning mode is the dominant mode near the plasma edge. When this mode is suppressed during the $H$-mode formation, it results in the transport barrier formation. The reduction of transport near the edge mainly occurs due to the resistive ballooning mode.
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References
[1] Glenn B, Onjun T and Arnold H K 2003 Plasma Physics and Controlled Fusion 45 1939
[2] Glenn B, Miguel A B, Onjun T, Arnold H K and a.A. Pankin 2003 Physics of Plasmas 10 4358
[3] Glenn B, Arnold H K, Jon E. K, Aaron J. R, Jan W 1998 Physics of Plasmas 5 1793
[4] David H, Glenn B, Jon K, Arnold H K, Onjun T and Pankin A 2001 Physics of Plasmas 8 965
[5] Leonard W 2008 Journal of Physics: Conference Series 123 012001
[6] Onjun T, Glenn B, Arnold H K and Hammett G 2002 Physics of Plasmas 5 5013
[7] Schneider P A et al 2012 Plasma Physics and Controlled Fusion 54 105009
[8] Gohil P 2006 Physique 7 606
[9] Singer C E et al 1998 Phys. Commun 49 275
[10] Onjun T, Glenn B, Arnold H K and David H 2001 Physics of Plasmas 8 975
[11] Rafiq T, Arnold H K, Jan W, Pankin Y A and Luo L 2013 Physics of Plasmas 20 1063
[12] Nguyen C N, Glenn B, Arnold H K, Byrom C and Sykes A 2002 Physics of Plasmas 9 3930
[13] Cohen B I et al 2013 Physics of Plasmas 20 05596
[14] Duan X R et al 2010 Nuclear Fusion 50 095011
[15] Liu C H et al 2012 Acta Phys. Sin 61 205201