The Behaviours of Plasma during Pellet Injection Using Sandpile Model

W. Kanjanaput[1], B. Kitpitak[1], B. Chatthong[1], J. Promping[3], N. Poolyarat[2], R. Picha[3], T. Onjun[1]

[1]*School of Manufacturing Systems and Mechanical Engineering, Sirindhorn International Institute of Technology, Thammasat University, Pathum Thani, Thailand*

[2]*Department of Physics, Thammasat University, Pathum Thani, Thailand*

[3]*Thailand Institute of Nuclear Technology, Bangkok, Thailand*

Introduction

To obtain high fusion performance in tokamak reactors, high confinement mode (*H*-mode) plasma [1] is needed. The key success of *H*-mode is the formation of a transport barrier near the edge, often called a "pedestal" (see Figure 1). In this work, a sandpile model [1, 2] is used to study the plasma behaviours during the performance-mode operational regime. The pedestal is modeled based on the experimental observation that the strong gradient is formed during the transition from *L*-mode to *H*-mode. When the transport barrier appears, the temperature and density over the whole plasma increase, and, consequently, the energy confinement improves. The pellet injection which is one of refuelling techniques can be introduced to induce the formation of *H*-mode. Pellet size and velocity have significant impact on the *H*-mode formation, and they will be the focus of this study.

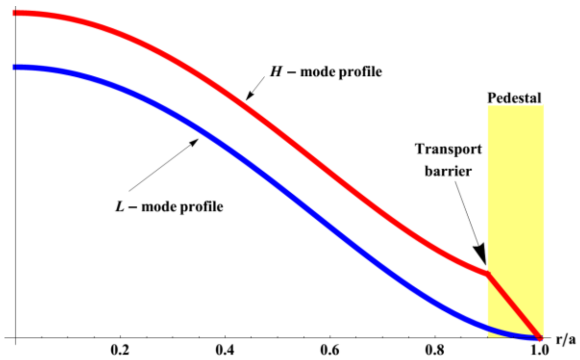

Figure 1: *L*-mode and *H*-mode profile in tokamak

Description of model

For simplicity, axisymmetric plasma is assumed so only one dimension of the radial plane is considered. The plasma pressure profile in tokamak is represented by the height profile of a sandpile. The height difference of adjacent position is defined as the local gradient of the sand pile which can be stable in two difference regimes, low gradient at the centre and steep gradient at the edge. The simulations start from a flat profile. In every cycle, one grain of sand is dropped randomly for n times, defined as deposition rate. Then, the local gradient is calculated to check the stability (see Figure 2) of each position (total of 100). If any position is unstable, some grains of sand can diffuse according to the relaxation rules. The diffusion rate is the number of sand grains D which diffuse out when local slope satisfy first unstable regime. The ratio of deposition rate to diffusion rate is defined as $n/D = f$.

To study the effects of pellet injection, the particles are randomly dropped in a Gaussian function shape with the standard deviation of two FWHM = $4\sqrt{2\ln 2}$ to represent the peaked density profile of the pellet in the model. The pellets started to be injected from the 8,000th time step, at which time steep pedestal profile does not appear in the profiles.

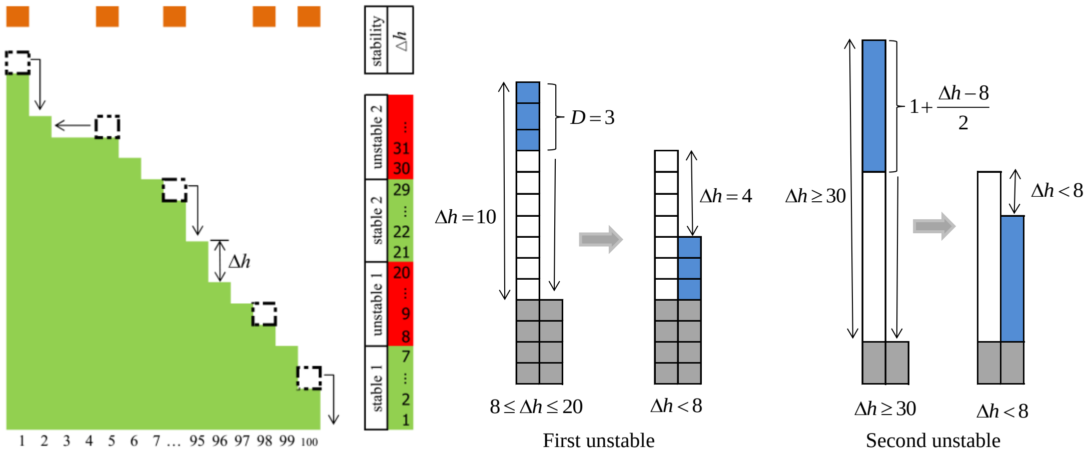

Figure 2: (left) The schematic diagram of the sandpile model and (right) its relaxation rules. For first unstable local slope, a fixed *D* grains can diffuse to the outer adjacent position. For second unstable slope, the least number of grains must diffuse to the next outer position to satisfy the first stable regime.

Simulation results

The simulation results of saturated profile without pellet injection show the steep gradient region when the ratio $n/D>1$, which correspond with the results of I. Gruzinov *et al.* [2]. This sharp gradient region starts to form at the edge and then expands to the centre as time progresses. The width of this region can grow until a saturation value which depends on the ratio n/D. For $n/D \leq 1$, the steep edge region cannot be observed at any time of simulation even for a very long time.

The pellet injection, which is a technique for refuelling the tokamak plasma, is used to induce the formation of steep gradient region in the case of $n/D \leq 1$. The pellets are injected at position 20 from the edge with a constant frequency of 1/50. Note that the injection start from time step 8,000. The pellet size of 100 and 1,000 particles are compared. For the pellet size of 100 particles, the pedestal can be first observed after about 10 injections. But for the pellet size of 1,000 particles, the pedestal appears after only 2 injections. This high gradient profile starts to form at the centre of the injection then expands to the outer edge as time progresses. When the injection frequency is decreased to 1/100, the steep region can be observed after the same pulse is injected. The width of this region, however, expands more widely than the previous frequency because it takes more time during the injection so the width can expand more.

Then, only one pellet is used to induce the formation of high gradient profile. In this case the pellet size of 10,000 particles is assumed to be injected at the position 20 from the edge in order to induce a steep gradient profile for the case of $f = 1$ which previously cannot be observed in the pedestal region. Note that a pellet is injected after a long time of operation and only one regime of slope can be observed in this first stage. As the pellet is injected, the profile near the edge can take effect of the pellet ablation and the gradient at this region rapidly changes from the stable shallow gradient region to stable steep gradient region. Then, the profile height gradually increases from the edge to the centre and can become stable without any additional injections as shown in Figure 3. However, this profile can transit back to former stage if the deposition rate is decreased and hence $f < 1$.

For $f < 1$, the injection of a 10,000-particle pellet can also induce the formation of steep gradient at the edge which results in enhancement of the profile at the central region but this profile becomes unstable so it quickly transits back to the original state, leading to a disappearance of the steep region. However, if the deposition rate is immediately increased in order to get $f \geq 1$. The pedestal region in this simulation remains alive and a new steady state profile is formed.

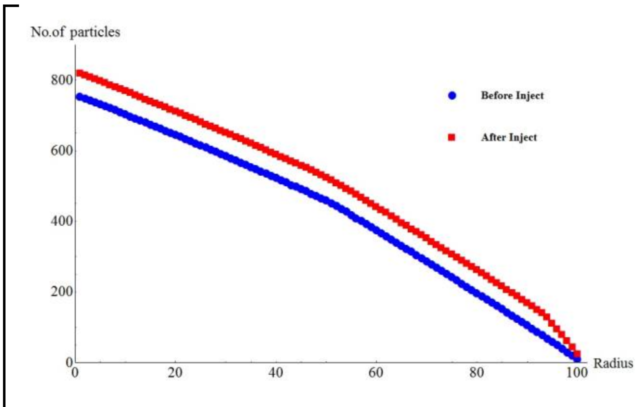

Figure 3: The comparison of steady-state profiles for f = 3/3 before and after pellet injection.

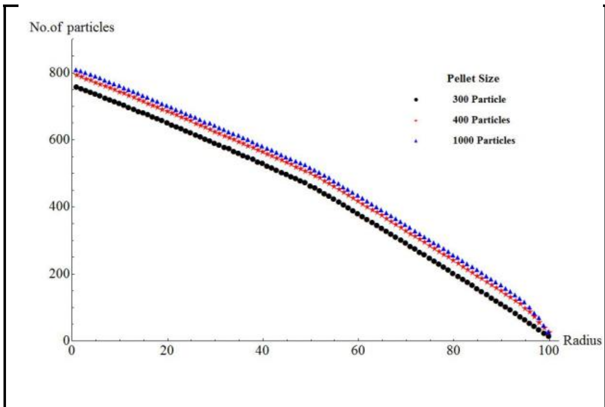

Figure 4: The steady state profiles when *H*-mode is triggered at position 20 from the edge with different pellet sizes from 300 particles to 1,000 particles.

Effect of pellet size is investigated by repeating the condition of $f = 1$ but the size of pellet is varied from 100 to 1,000 particles then its steady state profile is observed. Note that the position of pellet centre in this simulation is 20 units from the edge. The results of the steady state profile in these simulations do not take the effect of injection when its size is less than about 300 particles. For pellet size larger than 300, however, the steady state profile starts to grow as the pellet size is increased and the pedestal starts to form and expand wider to the centre of the profile. This profile, then, grows to a new steady state when the pellet size is about 500 particles as shown in Figure 4. These results show that the pellet size must exceed some critical value in order to induce pedestal formation efficiently. The reason is that as soon as the pellet is injected, the plasma particles will be relaxed from the injection position by transports to nearby positions according to the relaxation processes. If the pellet size is too small, the number of particles which can diffuse to the edge is insufficient to perturb the gradient in the edge region and induce a local gradient reach the steep stable regime so the pedestal cannot form. But if the size of pellet is sufficiently large, the number of particles which diffuse to the edge can take effect to the local gradient and the steep profile can be induced.

The velocity of pellet is also studied in this model by changing the position of pellet centre from the edge, from 20 (of the previous result) to 50. The result in this case resembles the previous one but the steady state profile gradually shifts up when the pellet size is about 350 particles then begins to approach a new steady state when the pellet size is about 650 particles. These results indicate that if the position of injection is farther from the edge the size of the pellet has to be larger in order to trigger the pedestal formation. The reason is when the perturbation occurs far from the edge it has a smaller effect so the amplitude of perturbation has to increase in order to perturb the edge gradient efficiently.

Conclusions

The formation of transport barriers in tokamak plasmas can be modelled by using a sandpile model with two stable and two unstable ranges of slopes. The pellet injection is introduced into the model in order to study the behaviour of the plasma density profile during the *L-H* transition. Pellet injection in this model can be used to induce *H*-mode formation which agrees with the results from Gohil *et al* [4]. To induce the formation of a transport barrier, the pellet size has to be sufficiently large to achieve large perturbation amplitude to access the high gradient stable regime. A new profile of particle number requires the rate of incoming particles to be at least equal to the rate of particle diffusion to maintain this new stable profile. The minimum requirement of the pellet size also depends on the radial position of the injection; the nearer to the edge, the smaller pellet size is required to induce a steep profile.

References

[1] F. Wagner *et al*., *Phys. Rev. Lett*. **49**, 1408 (1982)

[2] P. Bak, C. Tang, and K.Wiesenfeld, *Phys. Rev. Lett*. **59**, 381 (1987)

[3] I. Gruzinov, P.H. Diamond, and M.N. Rosenbluth, *Phys. Rev. Lett*. **89**, 255001 (2002)

[4] P. Gohil *et al*., *Phys. Rev. Lett*. **86**, 644 (2001)