Study of Plasma Behavior Based on Particle and Heat Flux Measurements and Numerical Simulation in the GAMMA 10/PDX End-cell

数理物質科学研究科　博士論文の要約

Study of Plasma Behavior Based on Particle and Heat Flux Measurements and Numerical Simulation in the GAMMA 10/PDX End-cell

(GAMMA 10/PDX エンドセルにおける粒子・熱流束計測および数値シミュレーションに基づくプラズマ挙動に関する研究)

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Abstract

1. Background and objectives of the research

The divertor simulation research is a very much important research topic to explore the physical mechanism of plasma detachment for the sustainment of the future fusion devices such as ITER and DEMO. The divertor simulation research has been done in the few tokamak and linear devices. These devices have been performed experiments by seeding a few neutral species into the divertor region. However, the effects of impurity species on the plasma detachment have not yet clarified since the fusion devices have shown plasma detachment results for only a few species so far. The radiation cooling rate of the radiator gases is different. Therefore, it is very much important to explore the detailed comparison of the radiator gases for the formation of detached plasma. The main motivation of the study is to make a detailed comparison of the radiator gases in order to clarify the radiation cooling effect of the gas by using the best use of simple configuration linear fusion device GAMMA 10/PDX. The effects of Ar, Kr and Xe injection into the divertor region of GAMMA 10/PDX have been done in the study. Impurity injection experiments have been done in order to understand the radiation cooling effect of the impurity particles on the plasma detachment and make an extrapolatable database for the future fusion devices.

The objective of the research is to understand the effects of radiator gas seeding on the plasma parameters toward the plasma detachment in the end-cell of GAMMA 10/PDX based on the experimental and numerical simulation study.

2. Experimental studies

GAMMA 10/PDX is the world's largest tandem mirror device which consists of multiple-cells. The divertor simulation research (D-module) has been effectively conducted by using the end-loss flux and the divertor simulation experimental module (D-module) at the GAMMA 10/PDX end-cell. It has been aimed to investigate the physical mechanism of plasma detachment such as radiation cooling, impurity transport, etc. A V-shape target made of tungsten has been installed in the D-module. A set of calorimeters and Langmuir probes has been installed on the upper and lower plate, respectively, of the V-shape target. In addition, a calorimeter and a directional probe have also been installed behind the small gad of the V-shape target. In the research, the effects of radiator gases injection into the D-module have been investigated based on the Langmuir probe and Calorimeter measurements.

2.1 Evaluation of various radiator gases

Gas injection experiments into the D-module using various radiator gases were carried out for evaluation of radiation cooling. Plasma parameters in the D-module have shown a clear dependence on the gas species and gas pressure. The heat flux reduces toward the plasma downstream (Z-axis). Reduction of the heat flux distribution along the Z-axis of the D-module has been observed according to the increment of gas plenum pressure. In the Y-axis, the peak of heat flux distribution has been obtained at 0.0 cm and reduced toward both the Y-directions. The distribution of heat flux along $\pm$Y directions become uniform with the increasing impurity injection. Xe shows good performance on the reduction of the electron temperature, heat and ion fluxes. Particularly, a remarkable reduction in the ion flux has been observed for Xe injection. The electron temperature on the target plate has been reduced to nearly 87%, 90% and 93% by injecting Ar, Kr and Xe, respectively. In the initial stage of the gas injection, the electron density increases due to Ar, Kr and Xe injection. Then, however, it reduces according to the increment of Ar, Kr and Xe injection. These results indicate that detached plasma has been generated. It has also been observed that Xe is the most effective radiator gas than that of Ar and Kr for generating detached plasma.

2.2 Transition of detached to attached plasma using additional plasma heating

The transition of a detached to attached plasma experiment has also been performed by using additional plasma heating. A short pulse (25 ms) of electron cyclotron heating (ECH) was applied in the east plug-cell to examine effects of electron heating on the plasma parameters in the D-module. It has been found that the ion flux at the west end-cell increases significantly during ECH injection. In the ECH injection period, the ion flux increases with the increasing Xe injection which indicates the Xe ion components enhances by ionization in the D-module due to the application of ECH.

3. Numerical simulation studies

3.1 Multi-fluid code "LINDA"

A numerical simulation study by using a multi-fluid code "LINDA" (LINear Divertor Analysis with fluid model) has also been performed in the end-cell of GAMMA 10/PDX to understand the energy loss processes during impurity injection. The LINDA code is a 2D multi-fluid code, which has been developed based on the same fluid model as the B2 code. The B2 code has been developed by B.J. Braams for the numerical simulation of tokamak Scrape-Off Layer (SOL) and divertor plasma. The LINDA code consists of five fluid equations. The fluid equations are discretized and numerically solve in the same way as the B2 code. The standard finite volume method has been applied to solve the fluid equations. The mesh structure of the simulation space has been designed according to the magnetic field configuration of the GAMMA 10/PDX. A tungsten target plate has been designed at the end of the mesh. The atomic processes of hydrogen (CX, ionization, and recombination) are included in the present code. In addition to the hydrogen atomic processes, atomic processes of the radiator gases (radiative power loss, ionization, and recombination) have also been considered in the present code. The recycling hydrogen neutral near the target plate is also considered.

From the simulation results with the LINDA code, it is found that hydrogen (H) seeding into the plasma significantly reduces the ion temperature by enhancing the charge-exchange (CX) loss. The ion temperature also reduces according to the increasing H injection. However, a moderate reduction in the electron temperature has also been observed for H injection. On the contrary, a remarkable reduction in the electron temperature has been observed during simultaneous injection of Ar and H, which indicates the radiation cooling effects of Ar. Under this condition, the energy loss terms for both the electron and ion enhances significantly via the CX, Ionization and radiation loss. It is also found that the CX loss and ionization loss increases with the increasing H injection. On the other hand, the radiation power loss of Ar increases with the increasing Ar injection.

Radiation cooling effect was investigated by using the LINDA code. A comparison among Ar, Kr and Xe shows that Xe is the most effective gas on the reduction of electron and ion temperature. Xe injection leads to a strong reduction in the temperature of electron and ion. The energy loss terms for both the electron and the ion are enhanced significantly during Xe injection. Especially, the radiative power loss increases significantly for Xe injection, which induces a strong reduction in the electron temperature. It is found that the major energy loss channels for ion and electron are charge-exchange loss and radiative power loss of the radiator gas, respectively. These outcomes indicate that Xe injection in the plasma edge region is effective for reducing plasma energy and generating detached plasma in linear device GAMMA 10/PDX.

3.2 Development of kinetic neutral code

Transport of hydrogen neutral particles toward the upstream region has also been studied in the end-cell of GAMMA 10/PDX by developing a kinetic neutral transport code. As a first step, a series of initial test calculations have been performed by injecting hydrogen gas puffing molecules from the target plate with fixed plasma background. The hydrogen neutral particles are introduced into the background plasma with cosine distribution. In the present study, recycling hydrogen neutrals are considered as hydrogen atoms. On the other hand, gas puffing neutrals are considered as hydrogen molecules. It has been shown that neutral particles concentrate near the target plate and reduce toward the upstream region. The hydrogen molecules are dissociated into atoms. As a result, the hydrogen atoms density is increased with the increasing gas puffing molecules. The hydrogen atoms also concentrate near the target plate and reduce toward the upstream region. The kinetic neutral code will be a robust basis in the future to study the effects of molecular processes (especially MAR) on the plasma detachment.

4. Conclusion

In this study, effects of radiator gas seeding into the D-module has been studied based on the calorimeter and Langmuir probe. The radiator gas injection into the D-module reduces both the heat and particle flux. Especially, for the Xe injection, the ion flux reduces drastically. Kr shows intermediate performance between Ar and Kr. The electron density shows a roll-over phenomenon for the Ar, Kr and Xe injection.

From the numerical simulation study by using a multi-fluid code “LINDA”, the following results are clarified: (1) Hydrogen injection reduces the ion temperature significantly by enhancing the CX loss. (2) The electron temperature reduces remarkably during radiator gases (Ar, Kr and Xe) by enhancing the radiation power loss. (3) The radiation power loss for Xe injection is higher than that of Ar and Kr.