DENSITY DEPENDENCE OF CONVECTION IN PARALLEL HEAT TRANSPORT IN THE SCRAPE-OFF LAYER OF JT-60U

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The density dependence of the convective parallel heat flux is obtained with reciprocating probes in the Scrape-Off Layer of JT-60U tokamak for the first time. As the line-averaged density increases, the convective contribution increases significantly around the separatrix and exceeds the conductive contribution. As the line-averaged density increases further, the convective contribution exceeds the conductive contribution in the whole radial range. In addition, the power balance among the conductive heat flux, the convective heat flux, and radiated power is discussed. The total power across the probe near the X-point (P_{X}) is calculated by integrating the radial profile of the conductive and the convective parallel heat flux. As the line-averaged density increases, P_{X} decreases due to the X-point radiator and radiation losses in the upstream SOL, while the fraction of convection in P_{X} increases. In contrast, it is found that SONIC modelling does not reproduce the large contribution of the convection in high-density plasmas. These results suggest that another transport model that is not yet implemented in SONIC and that accounts for the large contribution of heat transport by convection is required.

1. INTRODUCTION

Control of heat load onto the divertor target is one of the critical issues in fusion devices. To mitigate the high heat load, a high-density detached divertor operation has been developed, where heat transport characteristics at the Scrape-Off Layer (SOL) are different from those in low-density attached divertor plasmas. The heat flux parallel to the magnetic field in SOL is transported by conduction and convection. Previous studies show in general that the conductive transport is dominant in low-density SOL plasma and that with increasing density, the convective contribution increases [1]. However, the density dependence of the conductive and the convective transport contribution, in particular in high-density detached plasmas, is not yet unveiled experimentally. A systematical database of the transport mechanism in the SOL can be a reference for transport model development for future devices. This paper reports for the first time the density dependence of the convective heat transport contribution in JT-60U SOL plasmas and compare with modelling results.

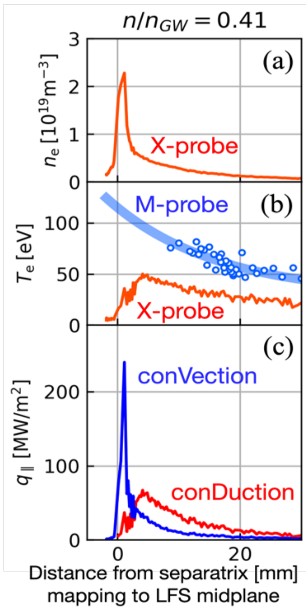

Fig. 1. Radial profile of (a) electron density at X-probe, (b) electron temperature of M-probe(blue) and X-probe(red), (c) conductive(red) and convective(blue) parallel heat flux at X-probe.

2. MEASUREMENTS OF PARALLEL HEAT FLUX USING LANGMUIR PROBES

The conductive and the convective parallel heat flux were measured with high radial resolution by reciprocating Mach probes [2] at the outer midplane (M-probe) and near the X-point (X-probe) in L-mode plasmas in a line-averaged density range between $1.0 \times 10^{19}\ \mathrm{m}^{-3}$ and $3.3 \times 10^{19}\ \mathrm{m}^{-3}$ (Greenwald density fraction n/n_{GW} of 0.18 - 0.60), a plasma current of 1.6 MA, a toroidal magnetic field of 3.2 T, and a neutral beam heating power of 4.0 MW. The conductive and convective heat flux is obtained by $q_\parallel^{\mathrm{conV}} = 5/2\sqrt{\gamma/m_{\mathrm{i}}}M_{\mathrm{X}}n_{\mathrm{e,X}}T_{\mathrm{e,X}}^{3/2}$, $q_\parallel^{\mathrm{conD}} = \kappa_{0\mathrm{e}}T_{\mathrm{e,X}}^{5/2}\left(T_{\mathrm{e,M}} - T_{\mathrm{e,X}}\right)/l_{\parallel,\mathrm{MX}}$ respectively. Here, γ is the heat transmission coefficient, m_{i} is the ion mass, M is the Mach number, n_{e} is the electron density, T_{e} is the electron temperature, κ_{0e} is the parallel electron thermal conductivity, $l_{\parallel,\mathrm{MX}}$ is the connection length between M-probe and X-probe respectively. Fig.1(c) shows the radial profile of the conductive and convective parallel heat flux at

X-probe at a line-average density of $2.2 \times 10^{19}\ \mathrm{m^{-3}}$ $(n/n_{\mathrm{GW}} = 0.41)$. The convective contribution exceeds the conductive contribution around the separatrix. In contrast, in the distance range larger than 3 mm from the separatrix, the conductive contribution is larger than the convective. As the line-averaged density increases further, the radial width of the convective contribution increases and the convective contribution exceeds the conductive contribution in the whole radial range, including the range far from the separatrix.

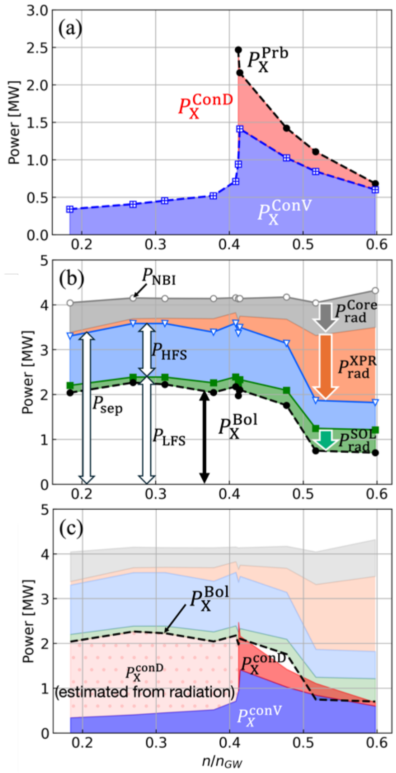

Fig. 2. Electron density dependence of the power across the X-probe obtained by (a) reciprocating Mach probe, (b) NBI injection and radiative power of the bolometer. (c): Comparison of the power across the X-probe obtained in (a) and (b).

3. POWER BALANCE ANALYSIS

The power balance among the conductive heat flux, the convective heat flux, and radiated power is discussed. Fig.2.(a) shows the power across the X-probe obtained by parallel heat flux shown in Fig1. The power across the X-probe with conductive transport ($P_{\mathrm{X}}^{\mathrm{ConD}}$) and convective transport ($P_{\mathrm{X}}^{\mathrm{ConV}}$) is calculated by radial integration of the conductive and convective parallel heat flux. The total power across the X-probe ($P_{\mathrm{X}}^{\mathrm{Prb}}$) is obtained by $P_X^{\mathrm{Prb}} = P_{\mathrm{X}}^{\mathrm{ConD}} + P_{\mathrm{X}}^{\mathrm{ConV}}$ (Fig.2(a)). Note that $P_{\mathrm{X}}^{\mathrm{ConD}}$ is calculated only high-density cases with $n/n_{\mathrm{GW}} > 0.4$ because of the higher T_{e} at the divertor than that at midplane in low density cases. This phenomenon could be caused by transport across the separatrix such as $B \times \nabla B$ drift. As the line-averaged density increases, both of $P_{\mathrm{X}}^{\mathrm{ConD}}$ and $P_{\mathrm{X}}^{\mathrm{ConV}}$ decreases and the fraction of the convection in P_X^{Prb} increases in range $n/n_{\mathrm{GW}} = 0.4 - 0.6$. The power across the X-probe is also evaluated from the radiation power obtained by bolometers ($P_{\mathrm{X}}^{\mathrm{Bol}}$) to validate the P_X^{Prb}, as shown in Fig.2(b). $P_{\mathrm{X}}^{\mathrm{Bol}}$ is given by $P_{\mathrm{X}}^{\mathrm{Bol}} = 2/3\{P_{\mathrm{NBI}} - (P_{\mathrm{rad}}^{\mathrm{Core}} + P_{\mathrm{rad}}^{\mathrm{XPR}})\} - P_{\mathrm{rad}}^{\mathrm{SOL}}$. Here, P_{NBI} is the NBI heating power, $P_{\mathrm{rad}}^{\mathrm{Core}}$ is the radiated power in core plasma, $P_{\mathrm{rad}}^{\mathrm{XPR}}$ is the radiated power from X-point radiator, $P_{\mathrm{rad}}^{\mathrm{SOL}}$ is the radiated power at outer SOL upstream of X-probe. In this analysis, it is assumed that 2/3 of the power flowing across the separatrix to the SOL (P_{sep}) flowed to low-field side. Fig. 2(c) shows the comparison between $P_{\mathrm{X}}^{\mathrm{Prb}}$ and $P_{\mathrm{X}}^{\mathrm{Bol}}$. Both of $P_{\mathrm{X}}^{\mathrm{Prb}}$ and $P_{\mathrm{X}}^{\mathrm{Bol}}$ decrease from about 2 MW to 0.7 MW in range $n/n_{\mathrm{GW}} = 0.4 - 0.6$. The electron density dependence of $P_{\mathrm{X}}^{\mathrm{Bol}}$ supports $P_{\mathrm{X}}^{\mathrm{Prb}}$ under current assumptions.

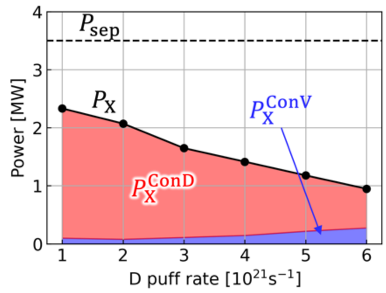

Fig. 3. Electron density dependence of the power across the X-probe obtained by SONIC.

SONIC [3] code, the integrated SOL/divertor code is used to evaluate the electron density dependence of the conductive and convective transport. The electron density scan from attached to detached plasma is simulated by scanning the gas puff rate in range between $1.0 \times 10^{21}\ \mathrm{s^{-1}}$ and $6.0 \times 10^{21}\ \mathrm{s^{-1}}$. The conductive and convective contribution of heat transport at the same position of the X-probe are obtained with the same formulas as in the experiment. In all density cases, including detached plasmas, the contribution from conduction transport exceeds that of convection, and the large contribution of convective transport as shown in the experiment is not reproduced. A lower Mach number by SONIC compared with experimental observation is considered to cause the lower convective heat transport, which is proportional to Mach number. These results suggest that another transport model that is not yet implemented in SONIC and that accounts for the large contribution of heat transport by convection is required.

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