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Particle and Heat Transports in the Scrape-Off Layer of JFT-2M Tokamak

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Abstract
In the scrape-off layer of the JFT-2M tokamak, ion temperature was measured by means of two types of double probes. Plasma density and electron temperature were measured by means of Langmuire probes. The results show that they decayed exponentially with radius having different decay lengths. Using these values, particle and thermal diffusivities for ion and electron are obtained from a model averaged along a magnetic field.

Keywords:
scrape-off layer, tokamak, transport, diffusivity, thermal diffusivity, ion temperature, probe measurement

1. Introduction
The importance of the scrape-off layer of tokamak plasma has been recognized in relation to improved confinement modes [1]. The probe method has been widely used to measure the plasma in the scrape-off layer, although the probe measurement has some difficulties to be adapted under strong magnetic field [2].

In the JFT-2M tokamak, a rotating double probe [3] and an asymmetric cylindrical double probe [4] have been used to measure ion temperature. For plasma density and electron temperature, Langmuire probes have been used [5]. Since only a few profiles of ion temperature of the scrape-off layer have been measured, reliable ion thermal diffusivity in the scrape-off layer has not been obtained yet. Here, we present particle and thermal diffusivities for ion and electron on the basis of the probe measurements using a model, which is extended from our previous model [6].

2. Probe Measurements
To obtain the profile of the ion temperature, two types of double probes were used. One was a rotating cylindrical probe. This double probe uses the shadowing effect of one electrode on the other electrode, where the ion temperature is evaluated on the basis of a Monte Carlo calculation of ion orbits to the two electrodes [3]. The other was an asymmetric cylindrical double probe consisting of two electrodes with different cylindrical lengths whose axes are made parallel to the magnetic field. In the latter double probe, the probe current is evaluated from an analytical form, which depends on the ion temperature, the magnetic field and the length of the cylinder [4].

The profiles of the plasma density and the electron temperature were obtained by use of Lagmuire probes. The plasma density was evaluated from the ion saturation current and the electron temperature was evaluated from the probe characteristics with bias around a floating potential.

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Figure 1 shows the result of these measurements of the scrape-off layer of the ohmic discharge of the JFT-2M tokamak with an upper single null divertor, where the major radius is R = 1.3m, the separatrx radius on the equatorial plane is $r \simeq 0.29$m (the ellipticity is $\kappa \simeq 1.3$ and the triangularity is $\delta \simeq 0.41$), the toroidal magnetic field is B_T = 1.25T, the toroidal current is $I_T \simeq$ 190kA and the safety factor at the scrape-off layer is $q \simeq 4.0$.

3. Transport Model

The ion and electron diffusivities are derived from the particle continuity equation averaged along a magnetic field line with a length of $L = 2\pi qR\sqrt{1 + [a/(qR)]^2}$

$$\frac{\mathrm{d}\Gamma_\perp^{(j)}}{\mathrm{d}x} + \frac{nc_s}{L} = n\alpha \tag{1}$$

with the perpendicular particle flux

$$\Gamma_\perp{}^{(j)} = D_\perp^{(j)}\left(-\frac{\mathrm{d}n}{\mathrm{d}x} \pm n\frac{eE_\perp}{T_j}\right), \tag{2}$$

where the plus sign for ion (j = i) and the minus sign for electron (j = e). If the ion sound velocity is written as $c_s = c_s(0)\exp(-x/\lambda_s)$, then $c_s(0) = \sqrt{[T_e(0) + T_i(0)]/m_i}$ and

$$\frac{1}{\lambda_s} \simeq \frac{1}{2[T_e(0)+T_i(0)]}\left(\frac{T_e(0)}{\lambda_{T_e}} + \frac{T_i(0)}{\lambda_{T_i}}\right),$$

since all the measured plasma quantities decay exponentially, such as $n = n(0)\exp(-x/\lambda_n)$, $T_j = T_j(0)\exp(-x/\lambda_{T_j})$. The coefficient α of the right-hand-side of eq. (1) is due to the existence of neutral particles (ionization) and we put $\alpha = \alpha(0)\exp(-x/\lambda_\alpha)$, with $\alpha(0) = n_0(0)S_i(0)$ and $1/\lambda_\alpha = 1/\lambda_0 + 1/\lambda_{T_e}$. The neutral density at the limiter edge (x = 0)

$$n_0(0) = n(0)\frac{c_s(0)}{v_n(0)}\frac{1}{2\pi R(1/\lambda_n{}^{\mathrm{OUT}} + 1/\lambda_s{}^{\mathrm{OUT}})},$$

is deduced by assuming that all the neutrals recombined on the limiter flow back into the scrape-off layer. Here, $\lambda_n{}^{\mathrm{OUT}}$ and $\lambda_s{}^{\mathrm{OUT}}$ mean the decay lengths of the plasma density and the ion sound velocity out of the limiter edge ($x > 0$). The decay length of neutral particle is $\lambda_0 = -v_n(0)/[n(0)S_i(0)]$ with $v_n(0) = \sqrt{8T_n/(\pi m_i)}$, where T_n is the neutral temperature being equal to the limiter temperature ($\simeq$ 0.3eV). Note that $\lambda_0 < 0$ because the neutral density increases with x. The ionization rate in m^3/s is approximated by

$$S_i = \exp\left(-\frac{I}{T_e}\right)\sqrt{\frac{T_e}{I}}\left\{2.16\times10^{-14} - 1.14\times10^{-14}\left[\log_{10}\left(\frac{T_e}{I}\right)\right]^2\right\},$$

for a hydrogen plasma in the case of $T_e/I \lesssim 8$ with an ionization energy I in eV (I = 13.60) [7].

Now, if we put $D_\perp{}^j = D_\perp{}^{(j)}(0)\exp(-x/\lambda_{D_\perp^{(j)}})$ and assume that T_i is very high, we have the approximation

$$\Gamma_\perp^{(i)} \simeq -D_\perp^{(i)}\frac{\mathrm{d}n}{\mathrm{d}x} = \frac{nD_\perp^{(i)}}{\lambda_n}.$$

Further, assuming that $E_\perp = C[T_e(0)/(e\lambda_n)]\exp(-x/\lambda_{T_e})$, we have

$$\Gamma_\perp{}^{(e)} = \frac{nD_\perp{}^{(e)}}{\lambda_n}(1 - C).$$

The ion and electron thermal diffusivities are thus obtained as follows:

$$D_\perp^{(i)}(0) = \frac{c_s(0)/L - \alpha_0}{(1/\lambda_n)(1/\lambda_n + 1/\lambda_{D_\perp^{(i)}})}, \tag{3}$$

$$D_\perp{}^{(e)}(0) = \frac{D_\perp{}^{(i)}(0)}{1 - C} \tag{4}$$

and

$$\lambda_{D_\perp^{(i)}} = \lambda_{D_\perp^{(e)}} = \frac{c_s(0)/L - \alpha_0}{c_s(0)/(L\lambda_s) - \alpha_0/\lambda_\alpha}. \tag{5}$$

The ion and electron thermal diffusivities are derived from the conservation equation of heat averaged along a magnetic field

$$\frac{\mathrm{d}Q_\perp^{(j)}}{\mathrm{d}x} + \frac{Q_\parallel^{(j)}}{L} = \pm\left[enE_\perp v_\perp^{(j)} - \frac{3}{2}n(T_i - T_e)\nu_T{}^{ei}\right] - nT_j\beta_j \tag{6}$$

with the perpendicular heat flux

$$Q_\perp^{(j)} = -n\chi_\perp{}^{(j)}\frac{\mathrm{d}T_j}{\mathrm{d}x} + \frac{3}{2}nT_j v_\perp^{(j)}, \tag{7}$$

and the parallel heat flux

$$Q_\parallel^{(j)} = A_j nT_j c_s, \tag{8}$$

where

$$A_i = 2, \text{ and } A_e = 2 + \frac{1}{2}\ln\left[\frac{m_i}{2\pi m_e}\frac{T_e(0)}{T_e(0)+T_i(0)}\right]$$

are used. The second term of the right-hand-side of eq. (6) is due to heat exchange between ion and electron and

$$\nu_T^{ei} = 4.11 \times 10^{-14} \frac{Z}{A_{mass}} \frac{n}{T_e^{3/2}}$$

with the charge state Z and the mass number A_{mass} of an ion (ν_T^{ei} in s^{-1}, n in m^{-3} and T_e in eV). The third term of the right-hand-side of eq. (6) is due to the existence of neutral particles and we put $\beta_j = \beta_j(0)\exp(-x/\lambda_{\beta_j})$ with $\beta_i = n_0(S_i + S_{CX})$ and $\beta_e = n_0 S_i\,[3/2 + I/T_e(0)]$. Since the cross-section in m^2 for charge exchange by protons in atomic hydrogen is approximated by

$$\sigma_{CX} \simeq 3.95 \times 10^{-19} - 5.90 \times 10^{-22} E_i$$

for an ion energy of $50 \lesssim E_i \lesssim 200$eV [8], the rate of the charge exchange in m^3/s is approximated by

$$S_{CX} \simeq (6.18 \times 10^{-15} - 1.84 \times 10^{-17} T_i)\sqrt{T_i}$$

for $T_i \sim 100$eV. Then, we have $\beta_i(0) = n_0(0)\,[S_i(0) + S_{CX}(0)]$, $\beta_e(0) = n_0(0) S_i(0)$, $1/\lambda_{\beta_e} = 1/\lambda_0 + 1/\lambda_{Te}$ and

$$\frac{1}{\lambda_{\beta_i}} = \frac{1}{\lambda_0} + \frac{T_e(0)}{T_e(0) + 0.78\sqrt{T_i(0)}} \frac{1}{\lambda_{T_e}} + \frac{0.78\sqrt{T_i(0)}}{T_e(0) + 0.78\sqrt{T_i(0)}} \frac{1}{2\lambda_{T_i}}.$$

Assuming $\chi_\perp^{(j)} = \chi_\perp^{(j)}(0)\exp(-x/\lambda_{\chi_\perp^{(j)}})$, we finally obtain the ion and electron thermal diffusivities as follows:

$$\chi_\perp^{(j)}(0) = \frac{F_N^{(j)}}{F_{D1}^{(j)}} \tag{9}$$

and

$$\lambda_{\chi_\perp^{(j)}} = \frac{F_N^{(j)}}{F_{D2}^{(j)}}, \tag{10}$$

where

$$F_N^{(i)} = \frac{A_i c_s(0)}{L} - \frac{eE_\perp(0)\, v_\perp(0)}{T_i(0)} + \left[1 - \frac{T_e(0)}{T_i(0)}\right] \nu_T^{ei}(0) + \beta_i(0) - B_i \frac{D_\perp^{(i)}(0)}{\lambda_n}\left(\frac{1}{\lambda_n} + \frac{1}{\lambda_{T_i}} + \frac{1}{\lambda_{D_\perp^{(i)}}}\right), \tag{11}$$

$$F_N^{(e)} = \frac{A_e c_s(0)}{L} + \frac{eE_\perp(0)\, v_\perp(0)}{T_e(0)} + \left[1 - \frac{T_i(0)}{T_e(0)}\right] \nu_T^{ei}(0) + \beta_e(0) - B_e \frac{D_\perp^{(e)}(0)}{\lambda_n}\left(\frac{1}{\lambda_n} + \frac{1}{\lambda_{T_e}} + \frac{1}{\lambda_{D_\perp^{(e)}}}\right), \tag{12}$$

$$F_{D1}^{(i)} = \frac{A_i c_s(0)}{L} - \frac{C}{\lambda_n} \frac{T_e(0)}{T_i(0)} \frac{D_\perp^{(i)}(0)}{\lambda_n} + \left[1 - \frac{T_e(0)}{T_i(0)}\right] \nu_T^{ei}(0) + \beta_i(0) - B_i \frac{D_\perp^{(i)}(0)}{\lambda_n}\left(\frac{1}{\lambda_n} + \frac{1}{\lambda_{T_i}} + \frac{1}{\lambda_{D_\perp^{(i)}}}\right), \tag{13}$$

$$F_{D2}^{(e)} = \frac{A_e c_s(0)}{L} + \frac{C}{\lambda_n} \frac{D_\perp^{(i)}(0)}{\lambda_n} + \left[1 - \frac{T_i(0)}{T_e(0)}\right] \nu_T^{ei}(0) + \beta_e(0) - B_e \frac{D_\perp^{(e)}(0)}{\lambda_n}\left(\frac{1}{\lambda_n} + \frac{1}{\lambda_{T_e}} + \frac{1}{\lambda_{D_\perp^{(i)}}}\right), \tag{14}$$

$$F_{D2}^{(i)} = \frac{A_i c_s(0)}{L} \frac{1}{\lambda_s} - \frac{C}{\lambda_n} \frac{T_e(0)}{T_i(0)} \frac{D_\perp^{(i)}(0)}{\lambda_n} \left(\frac{1}{\lambda_{T_e}} - \frac{1}{\lambda_{T_i}} + \frac{1}{\lambda_{D_\perp^{(i)}}}\right) + \left[\left(\frac{1}{\lambda_n} - \frac{3}{2}\frac{1}{\lambda_{T_e}}\right) - \frac{T_e(0)}{T_i(0)}\left(\frac{1}{\lambda_n} - \frac{1}{2}\frac{1}{\lambda_{T_e}} - \frac{1}{\lambda_{T_i}}\right)\right] \nu_T^{ei}(0) + \beta_i(0)\frac{1}{\lambda_{\beta_i}} - B_i \frac{D_\perp^{(i)}(0)}{\lambda_n \lambda_{D_\perp^{(i)}}}\left(\frac{1}{\lambda_n} + \frac{1}{\lambda_{T_i}} + \frac{1}{\lambda_{D_\perp^{(i)}}}\right), \tag{15}$$

and

$$
\begin{aligned}
F_{D2}^{(e)} = & \frac{A_e c_s(0)}{L}\frac{1}{\lambda_s} + \frac{C}{\lambda_n}\frac{D_\perp^{(i)}(0)}{\lambda_n}\frac{1}{\lambda_{D_\perp^{(i)}}} \\
& + \left[\left(\frac{1}{\lambda_n} - \frac{3}{2}\frac{1}{\lambda_{T_e}}\right)\right. \\
& \left. - \frac{T_i(0)}{T_e(0)}\left(\frac{1}{\lambda_n} - \frac{5}{2}\frac{1}{\lambda_{T_e}} + \frac{1}{\lambda_{T_i}}\right)\right] v_T^{ei}(0) \\
& + \beta_e(0)\frac{1}{\lambda_{\beta_e}} \\
& - B_i \frac{D_\perp^{(e)}(0)}{\lambda_n \lambda_{D_\perp^{(e)}}}\left(\frac{1}{\lambda_n} + \frac{1}{\lambda_{T_e}} + \frac{1}{\lambda_{D_\perp^{(e)}}}\right), \qquad (16)
\end{aligned}
$$

It is worth noting that C is a value, with which all the transport coefficients are positive.

4. Conclusion

Using the model in the previous section with the plasma density $n \simeq 6.0 \times 10^{16}\mathrm{m}^{-3}$, the ion temperature $T_i \simeq 80\mathrm{eV}$, the electron temperature $T_e \simeq 6\mathrm{eV}$ at the limiter edge ($x = 0$) and their decay lengths $\lambda_n \simeq 0.014\mathrm{m}$, $\lambda_{T_i} \simeq 0.13\mathrm{m}$, $\lambda_{T_e} \simeq 0.053\mathrm{m}$ between the separatrix and the limiter edge ($x < 0$) from Fig. 1, we obtain the ion diffusivity $D_\perp^{(i)} \simeq 0.7\mathrm{m}^2/\mathrm{s}$, the electron diffusivity $D_\perp^{(e)} \simeq 0.6$–$0.7\mathrm{m}^2/\mathrm{s}$, the ion thermal diffusivity $\chi_\perp^{(i)} \simeq 2.3$–$2.5\mathrm{m}^2/\mathrm{s}$ and the electron thermal diffusivity $\chi_\perp^{(e)} \simeq 2.0$–$2.7\mathrm{m}^2/\mathrm{s}$, for $|C| \lesssim 0.2$ or $|E_r| \lesssim 90\mathrm{V/m}$.

In summary, the estimated ion and electron diffusivities are about twice the Bohm diffusivity $D_B = eT_e/(16B) \simeq 0.29\mathrm{m}^2/\mathrm{s}$ and the estimated ion and electron thermal diffusivities are about eight times larger than D_B.

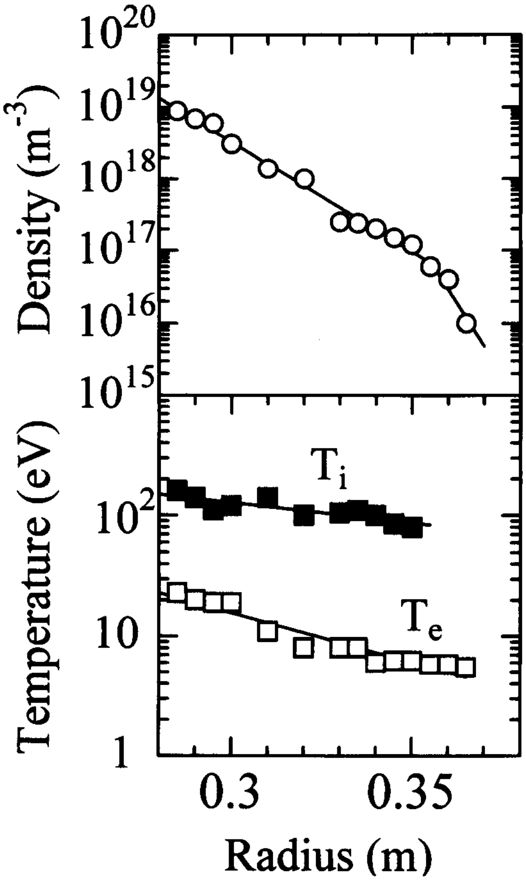

Fig. 1 The profiles of the plasma density, the ion temperature and the electron temperature measured at the scrape-off layer of the ohmic discharge plasma of the JFT-2M tokamak with an upper single null divertor, where major radius is R = 1.3m, the toroidal magnetic field is B_T = 1.25T, the toroidal current is $I_T \simeq$ 190kA and the safety factor at the scrape-off layer is $q \simeq$ 4.0. The separatrix is located at the radius r $\simeq$ 0.29m and the limiter edge is located at the radius r $\simeq$0.35m.

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