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On Relation between Local Transport Coefficient and Global Confinement Scaling Law

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Abstract

The relation between the local thermal transport coefficient and the scaling law of the global energy confinement time is discussed. It is found that the parameter dependence of the scaling law is modified strongly by the density profile and is often dictated by the transport coefficient near the plasma boundary. When the plasma has the steep gradient near edge, the effect is enhanced. The representation of the empirical scaling law by the averaged quantities of the plasma (such as the beta value, effective collision frequency etc.) could be misleading in this respect.

Keywords: Tokamaks, Scaling law, Energy confinement time,
Local Thermal Conductivity, Density profile

Recently much effort has been paid for the establishment of the empirical scaling law of the energy confinement time, especially for cases of additional heating plasma in toroidal devices[1-7]. The data base has become abundant and the detailed parameter dependences have been discussed. One way to represent an empirical scaling law, such as of the energy confinement time, is to express it in terms of the global parameters. The size of the device, magnetic field, total plasma current, heating power, average density and so on are often used as parameters.

Associated with the appearance of abundant scaling laws, attempts have also been made to explain the scaling law from a fundamental basis. The design of the future devices deserves the physics basis of the scaling law, in order to obtain the better predictability of the scaling law.

One way is to compare the experimental result with the one- (or more) dimensional transport code. This approach has been performed enthusiastically; nevertheless the comparison study with the empirical data has been far from complete. Much simplified picture is often employed. This method is to discuss the dimensional dependence of the scaling law and compare it with the dimensional dependence of the local transport coefficient. For instance, if one writes the effective thermal transport coefficient as χ_{eff}, i.e., the heat flux $\mathbf{q}$ satisfies

$$\mathbf{q} = -n\chi_{eff}\nabla T, \tag{1}$$

where n and T being the density and temperature, respectively, then the energy confinement time is estimated as

$$\tau_E \sim a^2/\chi_{eff}, \tag{2}$$

where a is the minor radius of the torus. From this relation, the parameter dependence of χ_{eff} is often interpreted and discussed.

Equation (2) has an ambiguity in the evaluation of the averaged value of $1/\chi_{eff}$. A simple way is to estimate χ_{eff} by $\bar{\chi}_{eff}$ which is evaluated by the averaged plasma parameters (such as ⟨T⟩,..., and the symbol ⟨ ⟩ indicates the volume averaged value). If one substitutes them into Eq.(2), then one has a set of equations

$$\tau_E = a^2/\bar{\chi}_{eff} \tag{3-1}$$

$$\bar{\chi}_{eff} = \chi_{eff}[\langle T\rangle, \langle n\rangle, \cdots] \tag{3-2}$$

$$\langle T\rangle = P\ \tau_E\ /3\langle n\rangle V_p, \tag{3-3}$$

where P is the total heating power. If the plasma transport is well described by only the averaged quantities, then $\bar{\chi}_{eff}$ may reflect the true characteristics of the transport. However, if the plasma profiles are taken into account, the situation becomes different. The value of $\bar{\chi}_{eff}$ does not necessarily correspond to

χ_{eff} in the core plasma but is modified by the weighting function due to the density profile.

In this article we re-examine the relation between the global energy confinement time and the local thermal conductivity in the zero-dimensional analysis. The appropriate averaging of χ_{eff} is discussed, where the role of the density profile is emphasized. In the case where only one scale length of the gradient exists, the total plasma energy W_p has one relation to the heating power, P. However, if there are two or more scale lengths, two ore more terms, which have different P-dependences, are expected. Offset term[5] can appear in the relation of W_p and P. In this case, simplified argument based on Eq.(3) can become inappropriate.

The plasma stored energy W_p is given as

$$W_p = 12\pi^2 R \int_0^{a_s} rdr\ nT. \tag{4}$$

For simplicity we assume that $T_i = T_e = T$ and $n_i = n_e = n$ (i.e., the plasma is pure), and the suffix denoting the species is suppressed. The upper bound of the integral includes the scrape-off layer (SoL) plasma, the edge is given by $r = a_s$. Performing the partial integral once, Eq.(4) is reduced to

$$W_p = -6\pi R \int_0^{a_s} N(r) T'(r)\ dr, \tag{5}$$

where N(r) is the particle number per unit length (in the axial direction) within the minor radius r, i.e.,

$$N(r) = 2\pi \int_0^r r dr\ n(r) \tag{6}$$

and $N(a_s)=N_p$ (N_p is the total particle number per unit length). Introducing the normalized heat flux $q_n = 2\pi a R q_r(r)/P$, we have

$$W_p = a^2 P \int_0^1 G(x) \frac{1}{\chi_{eff}(x)} dx \tag{7}$$

with

$$G(r/a) = \frac{3N(r)}{a^2 n(r)} q_n(r) \tag{8}$$

where x=r/a, the weighting function G(r) is a dimensionless number, and q_n is normalized to $q_n(a) = 1$.

In the zero-dimensional argument on the confinement, the energy confinement time is defined as $W_p = P\tau_E$. Noting the relation (8), where the profile effects are taken into account, we have

$$\tau_E = a^2 < \frac{1}{\chi_{eff}} > \tag{9}$$

and

$$< \frac{1}{\chi_{eff}} > \equiv \int_0^1 G(x) \frac{1}{\chi_{eff}(x)} dx \tag{10}$$

where the 'average' of the inverse of the thermal transport coefficient is introduced.

Let us discuss the difference between the true local heat conductivity, χ_{eff}, and the one discussed from the empirical τ_E scaling, Eq.(3).

For instance, the simple L-mode scaling law is given as[2)]

$$\tau_E = C\, I_p\, P^{-0.5} R^{1.75}\, a^{-0.37}\, \kappa^{0.5} (A_i/1.5)^{0.5}\ , \quad C=0.037 \qquad (11)$$

in which I_p (plasma current), P, R (major radius), and a are measured in the units of MA, MW, m and m, and the coefficient C adjusts the dimension of the right hand side.

Attempts have been done by using the point model approach (Eq.(3)) in order to correlate the L-mode scaling[2)] (Eq.(11)) with drift-wave-driven diffusion coefficient[8)],

$$\chi_d \sim (\rho/a)\cdot(T/16eB), \qquad (12)$$

which is often called as Gyro-reduced Bohm diffusion coefficient. If the temperature is replaced by the averaged value and rewritten by the input power as $nT \propto P^{\alpha}$, Eqs.(3) and (12) give a relation which is similar to the L-mode scaling, Eq.(11). The other attempt is to express $\bar{\chi}_{eff}$ in a more general form as

$$\bar{\chi}_{eff} = \chi_d\, F[\beta,\ \nu_*,\ q,\ \cdots] \qquad (13)$$

and find out the form factor F from the experimental data. In Eq.(13), β, ν_* and q correspond to the beta-value, effective collision frequency and the q-value, respectively. A theory has shown that the thermal diffusion coefficient can be given in the form of Eq.(13), where the minimum number of assumptions on the processes causing the anomalous transport are taken into account[9]. Equations.(3) and (13) can give a scaling law of τ_E as a functional of F. Comparing the result to the empirical scaling, the form of F can be fitted.

These two attempts to correrate Eqs.(12) and (13) to the L-mode scaling are nothing but the replacement of τ_E scaling by $\bar{\chi}_{eff}$ from the view point of the point model. They hardly represent the nature of χ_{eff} inside the plasma. Although the similarity between τ_E which is obtained from Eqs.(3) and (12) (or (3) and (13)) and the empirical law of τ_E, the local thermal transport coefficient is not governed by the expression $\bar{\chi}_{eff}$. [The dimensional approach gives that the χ_{eff} is an increasing function of the temperature T. In other words, the thermal transport coefficient is predicted to be large inside. On the contrary, the transport analysis on the experimental data usually shows a larger value of χ_{eff} near the periphery.]

On the contrary, the result Eqs.(9) and (10) shows the method to obtain the averaged thermal conductivity, which is directly compared to the scaling laws on the global confinement time. The weighting function G(x) has an important role on the average of the transport coefficient. It is also shown that the parameter dependence near the periphery has the large influence. In the vicinity of the magnetic axis, the lowest order of the radial dependences of $N(r)$ and $q_n(r)$ are proportional to $(r/a)^2$ and (r/a), respectively. This gives the relation $G(r) \propto (r/a)^3$ near the plasma center. Near the edge of the plasma, the density decreases, so that the value of N/n becomes large.

Figure 1 shows an example of the radial dependences of $n(r)$ and $G(r)$. This example is taken from the low density discharge in JET[10). The weighting function $G(r)$ is very small in the plasma core, and the integral (9) comes from the contribution near the edge. This is more clearly seen in the cases with the sharp edge such as the H-mode. Figure 2 shows an example for the H-mode discharge, in which the density pedestal is formed. In this case, the form of $G(r)$ shows a steep increase near the plasma boundary.

From Eq.(9), we see that the average of χ_{eff} should be evaluated by taking the structure of the weighting function $G(x)$. The weighting function has a large contribution from the peripheral region. The evaluation of $\bar{\chi}_{eff}$ by use of the average plasma parameter (such as the temperature and density) does not necessarily give the proper relation with the global energy confinement time. The averaged values of the temperature and density usually show the values around the half radius of the plasma. The average thermal conductivity is dominantly determined by the peripheral value of χ_{eff}, because of the shape of $G(r)$.

Next we examine the case where two or more characteristic gradient lengths exist in the plasma. In this case, χ_{eff} in the core and that near the periphery have different nature. The H-mode, for instance, has the gradient length of T in the core which is of the order of the minor radius. This mode has the different gradient length near the edge which is steeper and may not scale with the plasma size. The plasma internal energy integral, Eq.(9), is divided into multiple terms as

$$W_p = a^2 P \int_0^{1-\Delta/a} G(x) \frac{1}{\chi_{eff}} dx + a^2 P \int_{1-\Delta/a}^{1} G(x) \frac{1}{\chi_{eff}} dx + a^2 P \int_1^{a_s/a} G(x) \frac{1}{\chi_{eff}} dx \qquad (14)$$

where the first term is the core contribution, the second is that near the edge and the last one corresponds to that of the SoL plasma. (The third term usually remains small.) The thickness Δ in Eq.(14) is considered to be the width of the transport barrier in H-mode[11] and is very thin compared to the scale lengths of the core plasma. In the presence of ELMs, the edge gradient is often limited to a certain threshold value. Let us consider such a case. The second term is estimated as

$$a P \Delta G(1)/\chi_{eff}(1) \simeq 6\pi^2 R a^2 \Delta p_c' \qquad (15)$$

where p_c' is the attainable limit of the pressure gradient. The critical gradient has been reported to be seemingly dictated by the ballooning mode[11]. If one estimates p_c' according to the ballooning mode stability, then the critical pressure gradient is predicted as[12]

$$-p' \le f(s) \frac{B^2}{2\mu_0 R q^2} \qquad (16)$$

$$s = rq'/q. \qquad (17)$$

where s is the magnetic shear parameter, and f is an increasing function of s. The critical value, p_c', is estimated by $f(s)B^2/2\mu_0 q^2 R$. This estimation yields the second term in Eq.(14) as

$$6\pi^2 \frac{a^2\Delta}{q^2} f(s) \frac{B^2}{2\mu_0} \qquad (18)$$

The second term and the first term in Eq.(14) have different dependences on the total heating power. In the limit of the high heating power, Eq.(18) predicts that the contribution of the pedestal is only weakly dependent of the power. For instance, Ref.[13] predicts that the thickness of the transport barrier, Δ, scales with the poloidal gyroradius, i.e, depends on $\sqrt{T}$ near the edge. The transport analysis on the SoL region has shown that the edge temperature has a weak dependence on the heating power[14]. These give the weak dependence of Eq.(18) on the heating power ($\propto P^{0.2}$). This would be interpreted to be the occurrence of the offset term in the relation of W_p and P. Some data analysis on the experiment has shown that the contribution of the pedestal distribution (defining Δ as a/20) to the total stored energy in the case of the H-mode has a slower dependence on the power than that of the total stored energy[15,16].

In summary we studied the relation of the total energy confinement time and the local transport coefficient in the zero-dimensional analysis. An appropriate method to evaluate the averaged value of the thermal conductivity is presented. The importance of the weighting function G(r) is discussed. The spatial form of G(r) shows that the global energy confinement time is strongly influenced by the values of χ_{eff} in the vicinity of the plasma periphery. The interpretation of the empirical τ_E scaling only from the transport coefficient of the core part of the plasma can be misleading.

In an weighting function G(r), the density profile plays an important role. The importance of the density profile in averaging $1/\chi_{eff}$ has also been pointed out in Ref.[17]. The density profile is determined by the particle diffusion and inward pinch, and also by the ionization processes. The ionization deposition profile is influenced by the recycling of neutrals and atomic processes especially near the edge. The simple interpretation in terms of β, ν_* in the core would then be difficult. It is also concluded that the inward pinch of particles, which causes the peaking of the density, has an effect on the energy confinement time[18]. The peaked density profile makes the width of G(r) broader. If the thermal transport coefficient χ_{eff} is larger near edge compared to the core plasma, this broadening of G(r) leads to the reduction of the average of χ_{eff}.

The integral Eq.(9) and (10) indicates the difficulty in the interpretation of τ_E in terms of a simple parameter dependence of χ_{eff}. The parameter dependence of τ_E may come either from the parameter dependence of the local χ_{eff} value (at $r \simeq a-\delta$) or from that of δ (δ being the half width of G(r) function at half maximum). The power dependence of τ_E can come from the temperature dependence of χ_{eff}, but is also influenced by the power dependence of the density profile.

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Figure Captions

Fig.1 Density and the weighting function profiles for the low density discharges. Power deposition profile is chosen to be moderately broad, i.e., $q_r \propto x(1-0.3x^2)$.

Fig.2 Density and the weighting function profiles for the case of the H-mode. n(r) profile is chosen according to Fig.3 of Ref.[10]. q_r profile is same as in Fig.1.

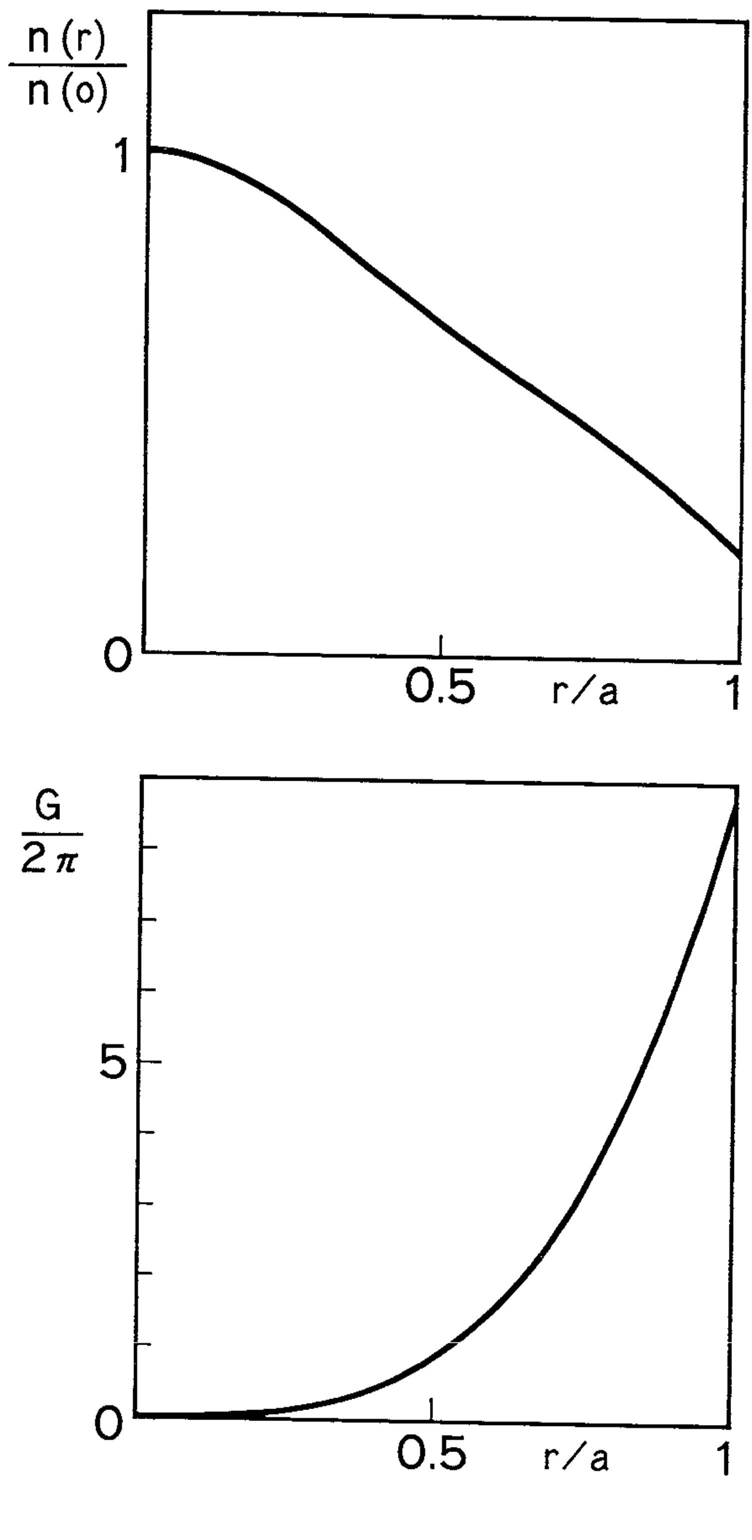
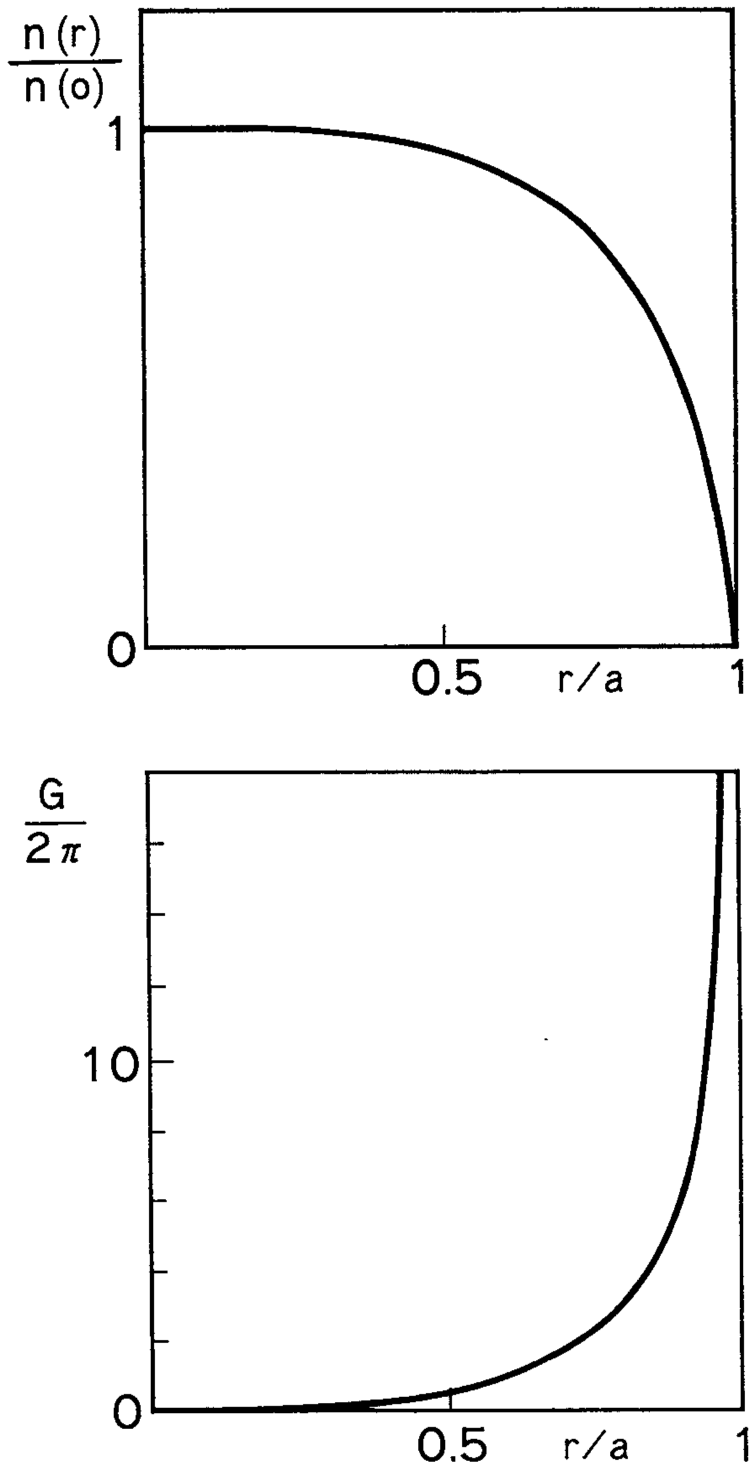

n(r)/n(o)
1
0
0.5
r/a
1
G/2π
5
0
0.5
r/a
1

Fig. 2



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