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Thickness of the Layer of Strong Radial Electric Field in JFT-2M H-mode Plasmas

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The poloidal rotation velocity profiles both in L- and H-mode measured in JFT-2M are compared with H-mode models based on ion orbit loss. The profiles of poloidal rotation velocity measured in L- and H-mode is consistent with the calculation which consists of ion orbit loss. The dependence of the thickness of the layer of high shear E_r on poloidal gyro-radius measured is explained by radial diffusion of poloidal rotation velocity due to anomalous perpendicular viscosity.

Keywords: H-mode, Tokamak, Radial electric field, Parallel viscosity, Perpendicular viscosity

Since the transition from low confinement phase (L-mode) to high confinement phase (H-mode) was discovered in 1982 on ASDEX[1], the H-mode plasma has been investigated from both experimental and theoretical aspect. Recently the poloidal rotation velocity and the radial electric field near the plasma periphery have been found to play an important role in the L- to H-mode transition [2-9]. The change of edge poloidal rotation velocity is in the electron diamagnetic direction in the H-mode plasma heated by the NBI, which indicates a increase of the negative radial electric field just inside separatrix, as was observed at L- to H-mode transitions in DIII-D[4-6], JFT-2M[7-9] and ASDEX[10]. A sudden decrease in the edge density fluctuation and magnetic fluctuation levels are observed at the L- to H-mode transition[5,6]. This negative radial electric field may be driven by large outward fluxes of ions, such as ion orbit loss at the plasma edge. Several bias experiments[2,3] demonstrated that the induced radial current can trigger the L- to H-mode transition and support the hypothesis that the outward fluxes causes the L- to H-mode transition[11-21]. Since the discovery of H-mode, various theoretical models for the L- to H-mode transition have been developed. The H-mode models based on ion orbit loss have been proposed to explain fast phenomena at transitions from L- to H-mode predicting the important role of E_r change. The influence of sheared poloidal rotation and/or electric field on edge turbulence have been studied theoretically to understand the improvement of confinement in H-mode[12,14,17,22-24]. The thickness of the layer of high shear radial electric field is a key issue in the H-mode physics, as is understood from the fact that the shear of the rotation velocity, $\partial v_\theta/\partial r$, has the influence on stability and that the pedestal of the H-mode distribution has considerable impact on the improvement of energy confinement time τ_E. Though these important influences have been recognized, the radial structure of the radial electric field has not been analyzed in detail. (The layer of the "source of torque" by orbit loss, i.e. poloidal gyro-radius, ρ_{pi}, and the layer of high shear Er is sometimes confused). The radial structure of electric field or poloidal rotation velocity has been taken into account[15,18,20,21]. In this paper we present the poloidal rotation velocity profiles in the JFT-2M and discuss the poloidal gyro-radius dependence of shear flow region. The comparisons with ion orbit loss H-mode model are also discussed.

The size of radial electric field is determined through poloidal momentum balance. The plasma flow velocity **V** is governed by the momentum equation [12,16]

$$m_i n_i \frac{\partial \mathbf{V}}{\partial t} + m_i n_i \mathbf{V}\cdot\nabla\mathbf{V} = -\nabla p - \nabla\Pi + \rho\mathbf{E} + \mathbf{j}\times\mathbf{B} + \mathbf{F} \qquad (1)$$

Where m_i is ion mass, n_i is ion density, p is plasma pressure, $\nabla\Pi$ is viscosity, ρ is charge density, and **F** is force to provide plasma flow. Assuming the poloidal symmetry of flow and pressure, $\mathbf{V}\cdot\nabla\mathbf{V}$ and ∇p term in poloidal component can be neglected. The poloidal momentum balance equation is

$$m_i n_i \frac{\partial V_\theta}{\partial t} = j_r \times B_\phi + \rho E_\theta + F_\theta - \nabla_\parallel \Pi - \nabla_\perp \Pi \qquad (2)$$

and

$$-j_r \times B_\phi = \varepsilon_0 \frac{\partial E_r}{\partial t} B_\phi \approx \varepsilon_0 B_\phi^2 \frac{\partial V_\theta}{\partial t} \qquad (3)$$

$$\rho E_\theta \le \left| \tilde{j}_r \tilde{B}_\phi \right| \le \left| \frac{k}{\mu_0} \tilde{B}^2 \right| \qquad (4)$$

The $j_r \times B_\phi$ term is a factor of $\varepsilon_0 B_\phi^2/(n_i m_i)$ smaller than the $m_i n_i \partial v_\theta/\partial t$ term and can be neglected. The time averaged ρE_θ becomes finite when magnetic fluctuation exist in the plasma. However this term is also negligible, because the fluctuation level of $\Delta B/B$ is of the order $10^{-3} \sim 10^{-4}$, wave number k [$=(m/2\pi r)$, where m is mode number and r is plasma minor radius] of magnetic fluctuation is ~ 0.5. The third term F_θ is a poloidal force due to non-ambipolar flux of ions and electrons in the plasma and $\nabla_\parallel \Pi$ and $\nabla_\perp \Pi$ is parallel and perpendicular viscosity, respectively. At the transition of L- to H-mode, when poloidal rotation velocity changes rapidly, $m_i n_i \partial v_\theta/\partial t$ gives the lower limit of the poloidal force at the peak of poloidal rotation velocity profile. However, the time resolution of poloidal rotation velocity measurements is too slow to evaluate the magnitude of $\partial v_\theta/\partial t$ at the L- to H-mode transition. In this equation (2), the shear viscosity governs the radial derivative of v_θ [12,15].

In the steady-state phase of H-mode, the poloidal force, F_θ, should be balanced with viscosity;

$$F_\theta=\nabla_{\parallel}\Pi+\nabla_{\perp}\Pi \tag{5}$$

Since it has been experimentally found that the perpendicular viscosity is anomalous[25,26] and the parallel viscosity, is neoclassical[27], we estimate $\nabla_{\parallel}\Pi$ using neoclassical theory, and $\nabla_{\perp}\Pi$ with anomalous momentum diffusivity μ_θ (shear viscosity):

$$\nabla_{\parallel}\Pi=(\sqrt{\pi}/4)(r/R^2)n_i m_i v_{th}\frac{B}{B_\theta}(I_p V_\theta+I_T V_{p0}) \tag{6}$$

$$\nabla_{\perp}\Pi=n_i m_i \mu_\theta \nabla_{\perp}^2 V_\theta \tag{7}$$

$$F_\theta=F_\theta(0)\exp\left(-c^2x^2/\rho_{\theta i}^2\right) \tag{8}$$

where I_p and I_T are coefficients for energy integral and Vp0 is defined as $-\rho_i v_{th}(\partial T/\partial r)/2T$ in Ref[16]. The parallel viscosity is almost proportional to the magnitude of poloidal rotation, velocity since V_{p0} term is much smaller than v_θ and energy integrals I_p and I_T are of the order unity. The perpendicular viscosity term is determined by the velocity shear in the different magnetic surface. The shear viscosity is known to be of the order of the anomalous energy transport coefficient experimentally[25] and theoretically[26]. The coefficient μ_θ is given as a parameter in this analysis. The poloidal force F_θ is a jxB force due to ion orbit loss and is considered to increase as exponential form toward the separatrix. The x in eq.(8) is a distance from the location of poloidal rotation peak, r_{peak} , which is considered to be a distance from the separatrix. The coefficient c is a shape factor of poloidal force and is of order unity. Using equations (5) - (8), the poloidal rotation velocity profile is simulated. The boundary condition in this simulation are $\partial v_\theta(0)/\partial r=0$ and $v_\theta(\infty)=0$. The poloidal force $F_\theta(0)$ is chosen to match the peak poloidal rotation velocity $v_\theta(0)$ to the measured values.

The poloidal rotation velocities are measured with multi-chord spectroscopy[28] for the deuterium plasma in the JFT-2M tokamak with a major radius R of 1.3m, a minor radius a of 0.3m, a toroidal field B_ϕ of 1.26T, a plasma current of 280kA, a safety factor q = 2.8 in a upper single-null-divertor configuration. The neutral beam (NB) is injected at t = 700ms with the power of 1.2MW in balanced NB injection. The power of NB decreases below H-mode threshold power (0.7MW) at t = 825ms. The plasma shows L- to H-mode transition at t = 730ms and H- to L-mode transition at t = 835ms. Figure 1 shows the radial profiles of poloidal rotation velocity, perpendicular, parallel viscosities and coefficient Ip for L-mode phase (t = 875ms) and H-mode phase (t = 742ms), respectively. The edge electron density and ion temperature at the peak of poloidal rotation velocity are 3.7 x 10^{19} m^{-3} and 82 eV (in L-mode after H/L transition) and 2.8 x 10^{19} m^{-3} and 96 eV (in H-mode), respectively. Here we take numerical coefficient c = 1, μ_θ = $5m^2s^{-1}$, and $F_\theta(0)$ = 38 Nm^{-3} (L-mode) and 42 Nm^{-3} (H-mode) to get best fit of the solution of Eq.(5) to the experimental data of $v\theta(r)$. In L-mode, the poloidal rotation velocity is below critical velocity for $\nabla_\parallel \Pi$ change[29], and the coefficient of Ip is around unity in all region of the plasma. Neoclassical parallel viscosity is more dominant than perpendicular viscosity in L-mode as is shown by the dashed lines. Simulated poloidal rotation velocity profile is mainly determined by the balance of poloidal force and neoclassical parallel viscosity and is less sensitive to the magnitude of μ_θ in L-mode. However, in H-mode, the peak poloidal rotation velocity exceed the critical velocity and the coefficient Ip starts to decrease below unity (~ 0.4) toward the peak of poloidal rotation velocity. This indicates that the neoclassical parallel viscosity becomes less important. On the other hand, the perpendicular viscosity becomes large enough to limit the peak poloidal rotation velocity, due to the sharp gradient of poloidal rotation velocity. It is noted that H-region (Ip <1) is located only near the peak of poloidal rotation velocity and the rest remains in L-mode (Ip>1). This result confirms analytical H-mode model[15].

Simulation of the poloidal rotation velocity profiles in H-mode (t = 742ms) for a plasma current of 280kA (q = 2.8, n_e =

2.8×10^{19} m^{-3}, T_i = 96 eV) and 170kA (q = 4.2, $n_e = 3 \times 10^{19}$ m^{-3}, T_i = 70 eV) are compared with the measurements to study the dependence on the poloidal gyro-radius dependence. Figure 2 shows measured poloidal rotation velocity profiles and simulated ones with various magnitude of perpendicular viscosity, μ_θ. Since the influence of the perpendicular viscosity can be significant only in H-mode, the simulation with various μ_θ was done only in H-mode. The shape factor of poloidal force F_θ is fixed (c = 1) and the magnitude of poloidal force $F_\theta(0)$ is chosen to agree with the measured peak poloidal rotation velocity. When the perpendicular viscosity is small, μ_θ =0.5 m^2s^{-1}, the simulated poloidal rotation velocity profiles are sensitive to the profile of poloidal force i.e. poloidal gyro-radius. However, it becomes insensitive to the profile of poloidal force as the magnitude of radial diffusion is increased. The best fit of simulated poloidal rotation velocity profile to measured ones are obtained for $\mu_\theta = 5m^2s^{-1}$. This perpendicular viscosity is comparable to the anomalous momentum diffusivity of toroidal rotation velocity or ion thermal diffusivity that are determined with transport analysis of the core plasma. The linear dependence of the size of poloidal rotation velocity profiles on poloidal gyro-radius is not observed with the existence of radial diffusion.

Figure 3 shows the width of the layer of the poloidal rotation velocity shear for various poloidal gyro-radius ρ_{pi} with plasma current of 170 kA to 280 kA and with hydrogen and deuterium working gas. The widths of poloidal rotation velocity shear, $L(v_\theta)$, is defined as twice of the half width at half maximum (2HWHM) of the poloidal rotation velocity profile estimated only inside the separatrix in the H-mode plasmas. (The widths of poloidal rotation velocity shear were estimated with profiles both inside and outside the separatrix in the previous analysis[8].) The bold lines are simulated values for the width of poloidal rotation velocity profile with the constant density, n_e of 3 x 10^{19} m^{-3}, ion temperature, T_i of 100eV, poloidal mach number, $B_\phi v_\theta/(B_\theta v_{th})$ of 2, poloidal force profile parameter, c of 1, and various momentum diuffusivity, μ_θ. The simulation demonstrates that the size of poloidal rotation velocity has offset linear like dependence on poloidal gyro-radius in the large ρ_{pi} limit, and that the absolute value of the size agree with the measured ones. When the poloidal gyro-radius is small, the poloidal rotation velocity profile is narrow and the radial diffusion becomes dominant, i.e. perpendicular viscosity is large than parallel viscosity. In this limited, the size of poloidal rotation velocity shear are roughly proportional to $\mu_\theta^{1/2}$ and insensitive to the poloidal gyro-radius. On the other hand, when the poloidal gyro-radius becomes large, the layer thickness increases and perpendicular viscosity becomes less important, so that linear relation between the size of poloidal rotation velocity profile and poloidal gyro-radius becomes clear (in the case that μ_θ is constant). In the condition of the H-mode experiment on JFT-2M tokamak discussed here, perpendicular viscosity at the peak may be comparable to parallel viscosity.

Recently the effects of orbit squeezing[30] has been studied by K.C.Shaing[18], and it was proposed theoretically that the width of the edge radial electric field layer in the H-mode, as estimated from the ion orbit loss model, does not depend explicitly on the poloidal gyro-radius. However the expression of the layer thickness in Ref[18] contains $\partial E_r/\partial r$ (which is a function of the layer thickness), so that the explicit form of the gradient layer width is not completed. In other words, the determination of the layer width would be given waiting the solution of the radial structure. The experimental data in larger poloidal gyro-radius is required to complete more definite test of the ion orbit loss H-mode model. However, the scanning range of poloidal gyro-radius is relatively narrow in tokamaks, since the ion temperature tends to increase as the poloidal magnetic field is increased.

In this analysis, the magnitude of poloidal force is chosen to match the measured peaked poloidal rotation velocity. The steady state analyses cannot determine the magnitude of the magnitude of $F_\theta(0)$. The value $F_\theta(0)$ remains a fitting parameter. A direct measurements of poloidal force requires studies on the dynamic time scale of the transition. The measurements of poloidal rotation velocity at the transit phase, such as L-H transition can give lower limit of poloidal force F_θ. Theories based on the ion orbit loss has predicted a typical transition time of ~ 30μs [12], which is far beyond the presently available time resolution. Since the time resolution of the measurements is planed to be improved to 8 kHz, the complete test is left for future study. In conclusion, the size of poloidal rotation velocity and the dependence of the size on poloidal gyro-radius measured in JFT-2M are consistent with ion orbit loss model when the perpendicular viscosities are anomalous.

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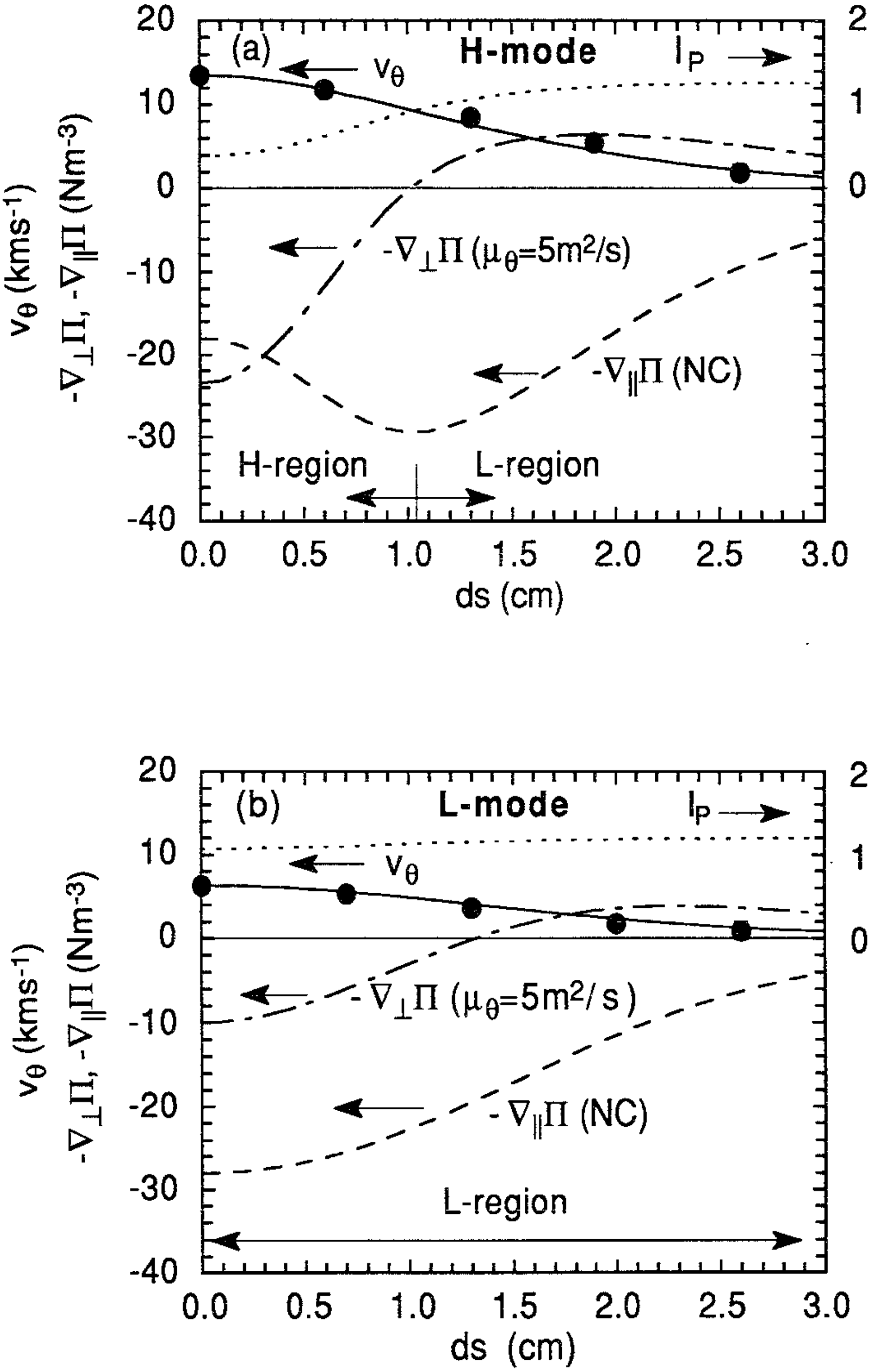
Figure captions.

Fig.1.Radial profile of poloidal rotation velocity, parallel viscosity, perpendicular viscosity, and Ip for (a) H- and (b) L-mode plasmas. The x stands for the distance from the peak of poloidal rotation velocity; $x = r_{peak} - r$.

Fig.2. Radial profile of poloidal rotation velocity for H-mode plasmas with a plasma current of (a) 280kA and (b) 170kA. Three lines are simulated poloidal rotation velocity profile with various magnitude of perpendicular viscosity coefficient.

Fig.3. The width of the poloidal rotation velocity shear, $L(v_\theta)$, as a function of poloidal gyro-radius. Open circles are for hydrogen plasma and closed circles are deuterium plasma. Three lines are width of poloidal rotation velocity simulated with neoclassical parallel viscosity and anomalous perpendicular viscosity with three different magnitude.



(a)
H-mode
v_θ
I_P
$-\nabla_\perp \Pi$ (μ_θ=5m^2/s)
$-\nabla_\| \Pi$ (NC)
H-region
L-region
v_θ (kms^{-1})
$-\nabla_\perp \Pi$, $-\nabla_\| \Pi$ (Nm^{-3})
ds (cm)
(b)
L-mode
v_θ
I_P
$-\nabla_\perp \Pi$ (μ_θ=5m^2/s)
$-\nabla_\| \Pi$ (NC)
L-region
v_θ (kms^{-1})
$-\nabla_\perp \Pi$, $-\nabla_\| \Pi$ (Nm^{-3})
ds (cm)

Figure 1

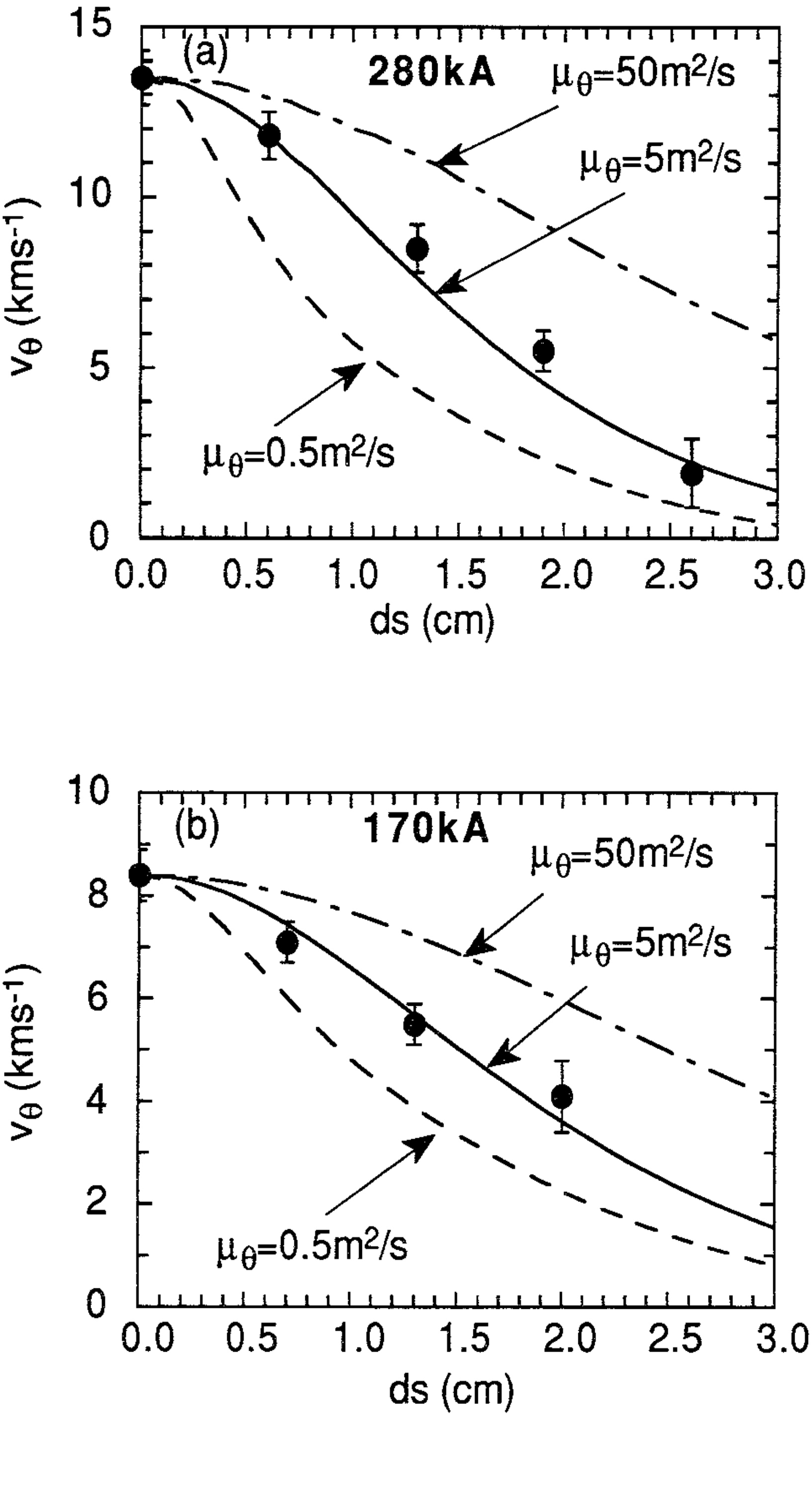

(a)
280kA
μ_θ=50m²/s
μ_θ=5m²/s
μ_θ=0.5m²/s
v_θ (kms⁻¹)
ds (cm)
(b)
170kA
μ_θ=50m²/s
μ_θ=5m²/s
μ_θ=0.5m²/s
v_θ (kms⁻¹)
ds (cm)

Figure 2

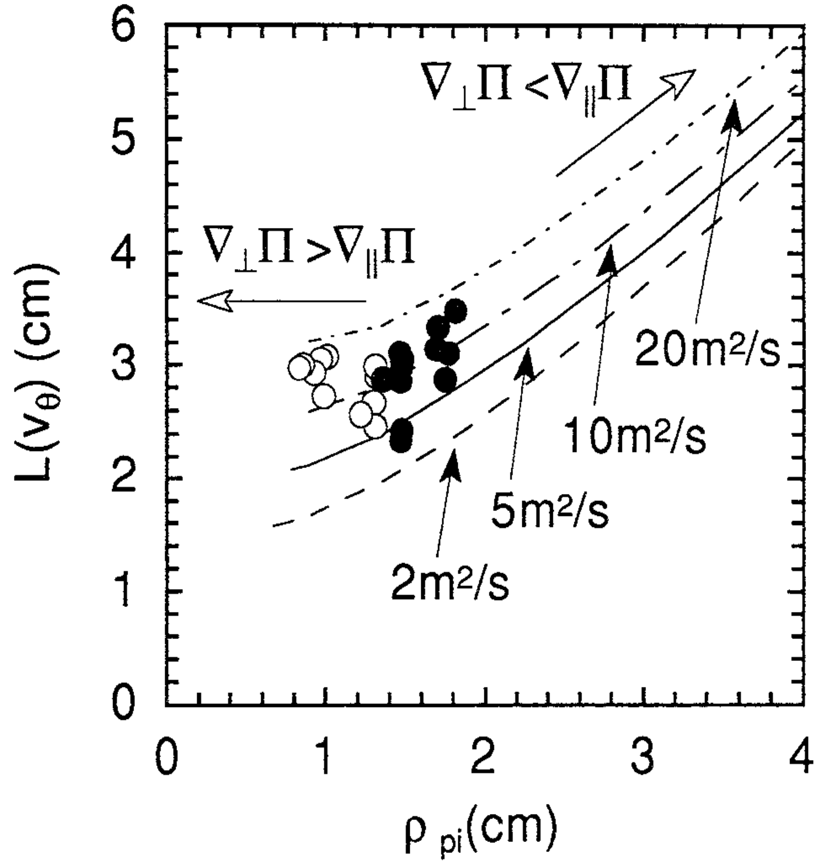


Figure 3

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