§4. Equilibria of Toroidal Plasmas with Flow in High-beta Reduced MHD Models

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Effects of toroidal and poloidal flow comparable to the poloidal sound velocity, two-fluid, ion finite Larmor radius, pressure anisotropy and parallel heat fluxes on high-beta toroidal equilibrium were studied based on reduced magnetohydrodynamic (MHD) models. A reduced set of Grad-Shafranov (GS) type equilibrium equations for high-beta tokamaks was derived from the fluid moment equations for collisionless, magnetized plasmas$^{1)}$. We have introduced pressure anisotropy and the parallel heat fluxes that were not taken into account in the previous models$^{2,3)}$. The gyrovisosity and other FLR effects cause the so-called gyroviscous cancellation of the convection due to the ion diamagnetic flow induced by the two-fluid effects in the equilibrium equations of momentum balance, pressure and heat fluxes. The reduced GS equations were solved numerically by means of the finite element method. The circular cross-section and the fixed boundary condition at the normalized minor radius r=1 are assumed. Figure 1 shows the radial profiles at the midplane of (a) the magnetic flux ψ, (b) the total pressure p, (c) the ion stream function Ψ and (d) the parallel and perpendicular pressures for ions and electrons. The two-fluid effects induce the diamagnetic flows, which result in asymmetry of the equilibria with respect to the sign of the $E\times B$ flow. Higher order terms of quantities like the pressures and the stream functions show the shift of their isosurfaces from the magnetic surfaces due to effects of flow, two-fluid and pressure anisotropy. The parallel and perpendicular components of the pressures for ions and electrons [Fig. 1 (d)] are self-consistently determined and show their peaks in different positions from those of the magnetic flux and each other. The shift of the isosurfaces of the ion stream function from the magnetic flux is caused by the breaking of the frozen-in condition due to the two-fluid effect. However, we have found that it also depends on the FLR effect. Fig. 2 shows that these shifts in the FLR two-fluid and the Hall MHD models are in opposite radial directions.

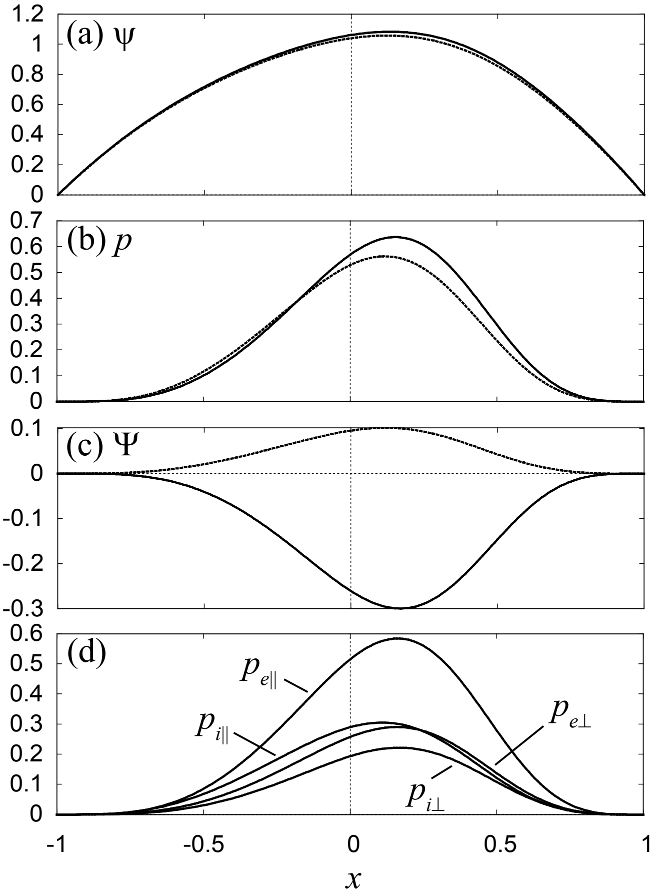

Fig. 1. Radial profiles in the midplane obtained from numerical solutions for the FLR two-fluid model. The solid (dashed) lines show the case where the poloidal directions of the $E\times B$ and the ion diamagnetic flows are the same (opposite).

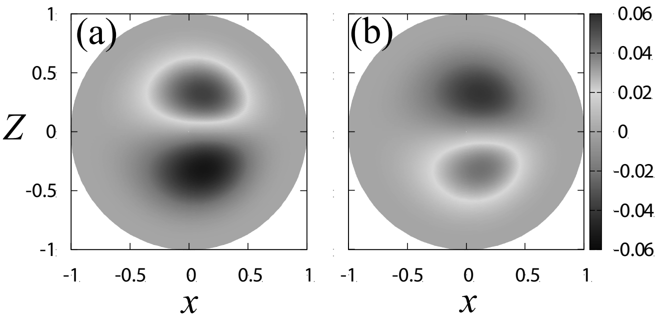

Fig. 2. Profiles of $(\nabla\psi \times\nabla\Psi)\cdot(R\nabla\varphi)$ in the poloidal cross-section for (a) the FLR two-fluid and (b) the Hall MHD models. This quantity is always zero in the single-fluid MHD model since $\Psi=\Psi(\psi)$.

1) Ito, A. and Nakajima, N.: submitted to Nucl. Fusion.

2) Ito, A. and Nakajima, N.: AIP Conf. Proc. **1069**, 121 (2008).

3) Raburn, D. and Fukuyama, A.: Phys. Plasmas **17**, 122504 (2010).