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Numerical analysis of two-fluid and finite Larmor radius effects on reduced MHD equilibrium with flow

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Effects of two-fluid and ion finite Larmor radius (FLR) effects on equilibrium with flow in reduced MHD equations for high-beta toroidal plasmas are investigated numerically. Equilibrium flow plays an important role in the suppression of instability and turbulence in fusion plasmas. In the region of steep gradient in the improved confinement mode achieved by the flow shear, small scale effects such as two-fluid effects and ion FLR effects are not negligible. Plasma flows induced by the neutral beam injection has strong pressure anisotropy. Since fusion plasmas become high temperature and low collisionality, non-Maxwellian component is important. The macroscopic behaviors of fusion plasmas including above-mentioned multiscale effects are described by extended MHD equations. Equilibrium solution in the presence of flow for the extended MHD equations is needed to study stability and for initial conditions of nonlinear multiscale simulations. The equilibrium equations for extended MHD are expanded with respect to the inverse aspect ratio of a torus for high-beta tokamaks to obtain the Grad-Shafranov (GS) type equations [A. Ito and N. Nakajima, Nucl. Fusion **51** (2011) 123006]. The toroidal and poloidal flows are assumed to be comparable to the poloidal sound velocity. This order of flow is included by taking higher order terms of expansions. The coupling of the equations for the parallel flow and pressure, the characteristic of the slow magnetosonic wave appears. The interaction between the poloidal flow and slow magnetosonic wave causes singularity. By including two-fluid and ion FLR, the effects of diamagnetic drift is induced. The ion FLR effect is included as gyroviscosity in the fluid moment equations. Since, in low-collisionality plasmas, non-Maxwellian component is not negligible, pressure anisotropy and parallel heat flux are also taken into account with a closure model. The expanded GS equations include complicated effects, but can be solved easily. We solve the GS equations numerically by using the finite element method. We obtain equilibrium structures such as the magnetic flux surfaces and isosurfaces of anisotropic pressures and stream functions for ions and electrons. The numerical solutions show the key features of such multiscale equilibrium that the pressures and stream functions are not constant. Since the poloidal flow consists of $E \times B$ and diamagnetic drifts, the equilibrium depends on the direction of $E \times B$ flow. Application to the stability analysis is also discussed. Since this equilibrium includes toroidicity and compressibility, it is applicable to study the effect of flow and the small scale effects on the ballooning and geodesic acoustic modes (GAM).

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Japan

Author: ITO, Atsushi (National Institute for Fusion Science)

Co-author: NAKAJIMA, Noriyoshi (National Institute for Fusion Science)

Presenter: ITO, Atsushi (National Institute for Fusion Science)

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