Single- and Two-Fluid Tokamak Equilibria with Flow: Review and Progress

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Macroscopic rotation is universally present in tokamaks. High toroidal rotation, spontaneous or driven by eternal sources such as Neutral Beam Injection, is commonly observed and measured in all major tokamaks. Poloidal rotation, also commonly observed in tokamaks, is more difficult to measure. Perhaps for that reason, many numerical codes and theoretical models now include toroidal rotation in their formulation, but much fewer also take into account the poloidal component of the plasma velocity. This is notwithstanding its importance in the L-H transition process and the qualitative modifications to equilibrium that are caused by sufficiently fast poloidal flows. [1-2] Still, a few codes exist that can solve the axisymmetric equilibrium equations with arbitrary toroidal and poloidal rotation. Among them are the MHD code FLOW [3] and the Two-Fluid code FLOW2. [4] Both codes pose no restrictions on geometry or equilibrium parameters and are capable to model configurations different from tokamaks, even though only the older code FLOW has been actively used for the latter purpose. Notably, FLOW2 is to the best of our knowledge the only Two-Fluid equilibrium code currently available to the community. Both codes have been used to model axisymmetric equilibria in a variety of conditions and to verify theoretical predictions. In particular, theoretical works predict the formation of MHD "transonic" tangential discontinuities when the poloidal velocity exceeds a critical value (roughly equal to the poloidal sound speed $C_s B_p/B$) [1] and in the Two-Fluid case the presence of a finite component of the velocity perpendicular to magnetic surfaces, [4] in violation of the *frozen-in* law.

In this work, we first review the problem of axisymmetric equilibrium with flow. We then proceed to highlight the main effects of plasma rotation on tokamak equilibria and illustrate them with numerical results from current and past work. This includes detailed numerical comparisons with the predictions of theory. We continue by discussing the current lines of research and most recent updates to both codes. These include the calculation of transonic Two-Fluid equilibria and the extension of both codes to allow for free-boundary equilibrium calculation via the inclusion of a vacuum region around the plasma. We conclude by highlighting the importance of rotation in current and future experiments (e.g., JET, CFETR). We argue for the necessity of a correct and detailed modeling of rotation in tokamak equilibrium.

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