Need for Simulating Plasma-Neutral Dynamics

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Simulating the effect of neutral interactions with plasma is important for several topics identified by the Integrated Simulations panel. Plasma-material interactions (PMI) at surfaces can produce neutrals that enter the plasma volume and affect plasma performance. Neutrals are generated from material surfaces through plasma-material interactions (PMI), which can produce neutrals that enter the plasma volume and affect performance. Plasma-neutral interactions are fundamental to pellet fueling and massive gas injection (MGI) for disruption mitigation. This whitepaper suggests a path for simulating the dynamics and interactions of neutral and plasma species which could lead to a deeper understanding of plasma dynamics.

Several on-going efforts to simulate plasma-neutral environments for magnetic fusion energy applications have made valuable contributions. Considerable work is being conducted concerning plasma-neutral dynamics in the vicinity of divertors and the scape off layer (SOL) of tokamak plasmas. Large neutral pressures are present in the divertor region while operating in an intended detached state. A widely used code for modeling the tokamak SOL is SOLPS (Scape-off Layer Plasma Simulation), which was formerly called B2-Eirene [1]. SOLPS is a hybrid 2-D code, featuring a multi-fluid model for ions and electrons in the edge region and a 3D, kinetic, Monte-Carlo model for neutrals (Eirene). SOLPS has been used to finalize the ITER divertor design, and is now being used to prepare for machine operation. B2-Eirene has been used to simulate edge and core fueling with the presence of a pedestal in H-mode operation.

Significant research is being conducted to investigate PMI [2–4]. The widely used UEDGE code provides a self-consistent model of boundary plasma based on a set of multi-fluid, multi-species transport equations for the plasma species coupled with a reduced set of Navier-Stokes transport equations for hydrogen isotope atoms [3]. UEDGE simulates transport in realistic 2-D geometries assuming the toroidal symmetry of the tokamak plasma, and has had some success in simulating the edge plasma in type-I ELMy H-mode plasmas on DIII-D [3]. B2-Eirene has also been used to simulate erosion and tungsten transport while coupled with the DIVIMP (divertor impurity) code that will be important for determining divertor longevity [2].

Another active area for plasma-neutral modeling is MGI to mitigate disruptions in tokamaks, which is of particular importance on ITER and other future high-performance fusion experiments. Unmitigated disruptions pose a threat to ITER due to the large thermal loading of divertor targets, large structural stresses driven by halo currents, and possible generation of damaging runaway electron beams [5, 6]. MGI has been an effective means of reducing the severity of these issues on disruptions in C-Mod and DIII-D. However, the efficacy of MGI on larger machines remains uncertain [6] without detailed simulations of the plasma-neutral interactions. A modified NIMROD code (NIMRAD), which couples the NIMROD MHD code and the KPRAD atomic physics code, has been developed to better model the penetration of injected noble gases into the core via MHD turbulence, which may better arrest runaway electron beam generation in addition to reducing the other deleterious effects of disruptions [6]. This code is being benchmarked against other tokamak experiments and is being developed to provide a predictive tool for evaluating MGI effectiveness for mitigating disruptions on ITER. Such predictive capability is a critical part of the US contribution to the ITER project.

Neutrals interact with plasma through scattering collisions and atomic reactions. For magnetic fusion plasmas, the atomic reactions can be limited to electron-impact excitation, radiative recombination, and resonant charge exchange, since other reactions have lower probabilities and smaller effects on the plasma dynamics. A complete description of plasma-neutral interactions requires a kinetic model based on a Boltzmann equation for each species, where each ionization state represents a different species. Such a kinetic model is generally not computationally tractable for magnetic fusion devices. However, simpler plasma-neutral models can be derived based on fluid equations if the mean free paths are sufficiently short. [7–11]

Recently, a general nonlinear fluid model [11] has been published that captures the primary effects of neutral species in plasmas, by limiting the reactions to electron-impact ionization, radiative recombination, and resonant charge exchange,

$$\begin{aligned} e^- + n &\to i^+ + 2e^- - \phi_{ion} \\ e^- + i^+ &\to n + h\nu \\ i^+ + n &\to n + i^+, \end{aligned}$$

in addition to non-reacting elastic scattering interactions. The model derivation follows the approach presented by Braginskii [12], with the addition of atomic reactions. The model derives closed-form expressions for the reaction terms by considering only the Maxwellian component of the reacting species, which is consistent with the multi-fluid formulation of the model – a three-component electron-ion-neutral mixture. The multi-fluid model contains evolution equations for the density, momentum, and energy for each species. Therefore, complete and self-consistent dynamics are computed for all species.

The multi-fluid model can be simplified and placed into the context of single-fluid MHD by combining the ion and electron species into a single plasma fluid and leaving the neutral species as a separate fluid. This formulation more easily fits into the framework of existing MHD codes. An alternative formulation would use a center-of-mass single fluid for all species and relative drift velocities for two of the individual species.

The interactions of neutrals with plasma are known to be important for several issues relevant to understanding plasma dynamics and overall plasma performance. Simulating the plasma-neutral effects in a complete and self-consistent manner will lead to greater understanding and better predictability of plasma devices.

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