Modeling Heat Transport in Magnetized Plasmas

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I. Introduction

Controlled thermonuclear fusion will likely be possible using a plasma that is magnetically confined in a tokamak such as ITER [1]. In order to achieve fusion the temperature of the plasma must be extremely high in the core of the tokamak. This necessitates studies of heat transport mechanisms by which the plasma loses energy. Numerical methods used to model this heat transport are varied and complicated. This research is an investigation of the accuracy and efficiency of three algorithms implemented in the plasma code NIMROD[2], and serves as a precursor to the exploration of kinetic effects on heat transport in tokamaks.

ITER will be the world’s largest tokamak fusion device and will be the first to produce net energy, expecting an output energy of 10 times the input energy.

II. Theory

In the steady state equilibrium and ignoring the pressure and flow velocity terms, the plasma temperature equation is often simplified to

$$\nabla \cdot \mathbf{q} = Q$$

where \(\mathbf{q}\) is the conductive heat flow and \(Q\) is a volumetric heat source.

These simplifications allow one to focus solely on the anisotropic nature of heat transport in magnetized plasmas. The physically correct model for \(\mathbf{q}\) is a kinetic closure. A simplified model appropriate for collisional plasmas is the conduction model of Braginskii [3],

$$q = -[\kappa_\parallel \hat{b} \cdot \nabla T + \kappa_\perp (I - \hat{b} \hat{b})] \cdot \nabla T$$

where \(\kappa_\parallel\) and \(\kappa_\perp\) are the parallel and perpendicular thermal conductivities, and \(\hat{b}\) is the direction of the magnetic field.

III. Case & Algorithms

Our test case uses a square domain with a fixed heating source, \(Q\), and magnetic field, \(B\). Three separate algorithms are used to compute \(\mathbf{q}\) and evolve the steady state temperature.

The first algorithm (standard) implements the Braginskii closure explicitly, while the second (mixed) uses a mixed auxiliary scalar in the finite element representation for the parallel component of heat conduction. The kinetic algorithm computes the parallel component of \(\mathbf{q}\) from a solution to the drift kinetic equation.

To test the algorithms we computed solutions using five different spatial resolutions for the 2-D finite element representation.

IV. Results & Conclusions

As the effective grid size \(h\) is decreased, the mixed and kinetic methods are seen to be the most accurate in terms of achieving the correct \(T\) in the center of the domain.

This plot shows the improved spatial convergence properties of the mixed (Braginskii) and kinetic closures for \(q_\parallel\).

Magnetic field geometry of 2/1 magnetic island in toroidal geometry. Similar geometry may be present in ITER.

V. Further Work

Using the verified mixed and kinetic algorithms, we will next study the free streaming and trapped particle effects found in magnetic island perturbations in toroidal magnetic geometry to better understand heat transport in modern tokamak fusion experiments.

Study conducted using computational resources provided by the USU Department of Physics.