Journal of Computational Physics 274 (2014) 283–298

Contents lists available at ScienceDirect

Journal of Computational Physics

www.elsevier.com/locate/jcp

A penalization technique to model plasma facing components in a tokamak with temperature variations

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ARTICLE INFO

Article history:
Received 13 January 2014
Received in revised form 17 April 2014
Accepted 16 May 2014
Available online 2 June 2014

Keywords:
Immersed boundary method
Penalization
Scrape-off layer
Tokamak
Plasma–wall interaction

ABSTRACT

To properly address turbulent transport in the edge plasma region of a tokamak, it is mandatory to describe the particle and heat outflow on wall components, using an accurate representation of the wall geometry. This is challenging for many plasma transport codes, which use a structured mesh with one coordinate aligned with magnetic surfaces. We propose here a penalization technique that allows modeling of particle and heat transport using such structured mesh, while also accounting for geometrically complex plasma-facing components. Solid obstacles are considered as particle and momentum sinks whereas ionic and electronic temperature gradients are imposed on both sides of the obstacles along the magnetic field direction using delta functions (Dirac). Solutions exhibit plasma velocities ($M = 1$) and temperatures fluxes at the plasma–wall boundaries that match with boundary conditions usually implemented in fluid codes. Grid convergence and error estimates are found to be in agreement with theoretical results obtained for neutral fluid conservation equations. The capability of the penalization technique is illustrated by introducing the non-collisional plasma region expected by the kinetic theory in the immediate vicinity of the interface, that is impossible when considering fluid boundary conditions. Axisymmetric numerical simulations show the efficiency of the method to investigate the large-scale transport at the plasma edge including the separatrix and in realistic complex geometries while keeping a simple structured grid.

1. Introduction

Magnetic confinement fusion aims at producing power in devices where magnetic fields are used to confine the hot fusion fuel in the form of a plasma. The use of magnetic confinement fusion as an energy source requires the accelerated development of computational tools and techniques to address the physics of the plasma, in particular near the boundary layers, i.e. in the edge plasma of a tokamak. In this region, the plasma is governed by multi-physics processes leading to a large number of dimensionless parameters related to atomic processes or to the geometrical features of the plasma-facing components. This complexity might lead to uncertainties in the empirical scaling laws implemented in most theoretical and numerical models.

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http://dx.doi.org/10.1016/j.jcp.2014.05.025
0021-9991/

The plasma–wall interaction is of great concern for tokamak operations, as it determines plasma conditions in the scrape-off layer (SOL). As a result of complex atomic physics, it fixes the level of impurity recycling which is involved in the global fuel cycle in the machine. It also determines the main exhaust channel for heat (typically conduction to the wall or radiation) and is therefore critical in determining the heat load on the first wall, seen as a limiting factor for fusion performance because of its role in wall erosion [1]. From the point of view of transport, the plasma–wall interaction is responsible for the establishment of large-scale flows and must be taken into account for the design of exhaust systems capable of handling power levels expected in fusion reactors [2]. Finally, it contributes to determining plasma profiles in the SOL which, through intricate feedback mechanisms involving SOL flows, could possibly lead to core/SOL specific instabilities [3], influence plasma transport from the core to the SOL and be a factor in the H-mode threshold and pedestal height.

Fusion plasmas are weakly collisional, and a fluid approach is not warranted. However, computing the plasma distribution function through either the Vlasov equation or gyrokinetic equations is still too expensive computationally to allow long-time simulations owing to the high dimensionality of both approaches (6 dimensions and 5 dimensions respectively). Fluid models, based on the Braginskii equations [4] applied to the mixture of electrons and ion gases constituting the plasma, are more tractable and provide a valuable tool for global simulations of the plasma edge, despite their incomplete description of the physics involved. In this approach, fluid-like equations are obtained directly by advancing velocity moments of the kinetic equation in time with closures assuming high collisionality, strong fields and long times. Usually, solid obstacles like limiters or divertors are taken into account in numerical codes by implementing the Bohm boundary conditions [5] on the obstacle surface. One challenging aspect of magnetized plasma modeling, and which is not usually encountered in other fields, is related to the very strong anisotropy between parallel and transverse transport with respect to the magnetic field. In tokamak, the particle dynamics is that of nonlinear acoustic waves in the parallel direction and close to a slower diffusive process by background turbulence in the perpendicular one. The electron heat thermal conductivity in the direction parallel to the magnetic field is also typically much larger than that in the perpendicular direction. These features favour the use of meshes aligned with the magnetic surfaces (Fig. 1(a)), in the parallel direction along which transport is the strongest. Otherwise, the mesh would lead to unphysical transport in the perpendicular direction associated to unacceptable numerical diffusion and in addition would strongly couple both directions in the differential operators, which typically renders the inversion of these operators more difficult when it is needed. However, work was done in the development of specific algorithms that do not use field-aligned coordinates to reduce this pollution of perpendicular transport by numerical diffusion [6]. On the other hand, the irregular boundaries of the various plasma wall-facing components would require body-fitted unstructured meshes or remeshing strategies, which can be time- and memory-consuming, to satisfy the required boundary conditions on the solid surfaces. In this context, immersed boundary techniques as the penalization technique are an efficient way of introducing obstacles while keeping the advantages of structured grids. Immersed boundary techniques are currently used in the Computational Fluid Dynamics community in the framework of Navier–Stokes equations. The obstacle is embedded in the computational domain and fluid equations are modified by adding penalization terms characterized by a mask function χ defining the geometry. This class of methods was initially proposed in [7] to model the flows interaction with porous materials by adding a Darcy drag term to the Navier–Stokes equations. It has been subsequently applied to problems with different boundary conditions. Non-isothermal incompressible flows with homogeneous Neumann boundary condition at solid wall were only recently considered in [8]. Solid mathematical background has been developed in [9] to prove the convergence of the method. More detailed mathematical works can be found in [10] with an extension of the method known as H^1-penalization, and in [11] for general boundary conditions showing the efficiency of the method.

As far as the authors know, we were the first to apply such a technique to model plasma–wall interaction [12,13] within a minimal transport model for ionic density and parallel momentum. The limiter was considered as a pure particle sink for the plasma and consequently the density and the momentum were enforced to be zero inside using volume Dirichlet conditions. A remarkable feature of the method was to recover an almost sonic plasma at the plasma–obstacle interface – the Bohm boundary condition – without having implemented the physics of non-neutral plasmas involved in the so-called "sheath acceleration". Such attractive results were understood and justified in a general framework, also validated in dealing with plasma detachment with volumetric recombination and momentum losses, in subsequent work in [14]. In particular, it was shown that the penalization enforces appropriate variations of both particle and momentum fluxes between the plasma and the obstacle, leading to a bifurcation to supersonic flows within the limiter that corresponds to the Bohm-like conditions.

The present work extends the penalization technique to plasmas with temperature variations. In addition to density and parallel momentum penalized within the obstacle volume, temperature dependence involves complex Neumann boundary conditions on ion and electron temperatures, which require to penalize temperature gradients at the obstacle surface, on both sides of the limiters along the magnetic field lines.

Geometrical aspects of tokamaks are first described in Section 2. he Braginskii fluid equations together with appropriate boundary conditions are presented in Section 3. The penalization technique is introduced in a one-dimensional model in Section 4. The spatial and time discretization schemes are described in Section 5. In Section 6, the validation of the method is provided and the convergence rate of the numerical scheme is presented. A refinement of the physical model allowed by the penalization and taking into account some kinetic features of the plasma in the close vicinity of the plasma–wall interaction is introduced in Section 7. Finally in Section 8, computations performed in a complex, realistic geometry modeling the Tore Supra machine in Cadarache are presented to illustrate the capabilities of the method.