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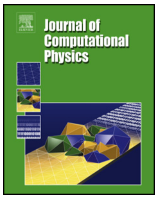

Self-consistent treatment of the sheath boundary conditions by introducing anisotropic ion temperatures and virtual divertor model

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ABSTRACT

One-dimensional SOL-divertor plasma fluid simulation code which considers anisotropy of ion temperature has been developed so as to deal with sheath theory self-consistently. In our fluid modeling, explicit use of boundary condition for Mach number M at divertor plate, e.g., $M = 1$, becomes unnecessary. In order to deal with the Bohm condition and the sheath heat transmission factors at divertor plate self-consistently, we introduced a virtual divertor (VD) model which sets an artificial region beyond divertor plates and artificial sinks for particle, momentum and energy there to model the effects of the sheath region in front of the divertor plate. Validity of our fluid model with VD model is confirmed by showing that simulation results agree well with those from a kinetic code regarding the Bohm condition, ion temperature anisotropy and supersonic flow. We also show that the strength of artificial sinks in VD region does not affect profiles in plasma region at least in the steady state and that sheath heat transmission factors can be adjusted to theoretical values by VD model. Validity of viscous flux is also investigated.

1. Introduction

In order to realize tokamak fusion reactors, such as ITER and DEMO, reduction of the heat load on divertor plates is one of the most important issues [1]. Simulation studies are inevitable to predict plasma profiles in the scrape-off layer (SOL) and divertor regions and to estimate the divertor heat load for the future devices. SOL-divertor code pakages such as SOLPS [2], SONIC [3,4], UEDGE [5] and EDGE2D/NIMBUS (EIRENE) [6] are utilized worldwide. For the prediction of SOL-divertor plasma of ITER in particular, SOLPS-ITER code package has been developed recently by coupling of the up-to-date parallelized Monte-Carlo code EIRENE for neutrals and the fluid code B2.5 for plasma [7]. As for DEMO reactors such as Slim-CS, in which the handling of divertor heat load is more crucial than ITER due to its higher fusion power and lower thermal tolerance of F82H cooling tube, simulations with advanced divertors such as long-leg divertor [8] and super-X divertor [9] were conducted by SONIC.

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Verification and validation (V&V) of these simulation codes have been carried out in parallel with the prediction studies. Numerical results from these conventional SOL-divertor codes, however, sometimes do not satisfactorily accord with experimental results. Many researchers have been making efforts to resolve this issue from various aspects. For example, Chankin et al. reported the comparison of simulation results from SOLPS and experimental data from ASDEX-Upgrade (AUG), where discrepancies might be attributed to incorrect neutral model, fluctuations in the plasma and non-local kinetic effect of parallel heat transport [10]. Wischmeier et al. investigated the effects of drifts and complex atomic–molecular processes on the asymmetry of inner and outer particle fluxes to the divertor plates by comparing SOLPS simulations and AUG experiments, but they did not obtain satisfactory agreement for the high recycling regime [11]. Groth et al. reported that when cross-field drifts and enhanced chemical sputtering yields were applied to UEDGE simulations, an agreement with experiments of AUG, JET and DIII-D was achieved within a factor of 2, or better [12]. By focusing on code V&V for the detachment case, Coster carried out various comparisons between fluid and Monte-Carlo neutrals, pure D plasma and D plasma with C impurities, activated and inactivated drifts, horizontal and vertical targets, and ELMy and ELM-free [13]. To improve the detachment modeling, Hoshino et al. investigated the particle-flux rollover observed in JT-60U divertor by using SONIC [14,15]. Besides the volume recombination, effects of increased radial diffusion, supersonic flow and wall pumping were evaluated.

Although the above comprehensive codes are the main tools to predict the divertor performance for future devices, one-dimensional (1D) simulation codes still have advantage for investigating the physics of SOL-divertor plasmas, because of their simplicity and small computational cost compared to code packages. With a 1D code of the fluid modeling, Nakazawa et al. studied the stability of the detachment state, and found the unstable radiation front moving from the divertor region to the X-point [16]. Nakamura et al. reported that the cross-field transport in partially detached divertor plasmas stabilizes the movement of detachment fronts [17]. Goswami et al. studied the boundary-condition problem, and reproduced the self-consistent supersonic plasma flows by relaxing the boundary condition for Mach number at the divertor plate [18].

We have been focusing on improvement of 1D fluid modeling of SOL-divertor plasmas [19]. In conventional SOL-divertor codes of the fluid modeling, Braginskii's equations [20] are applied, where the density n, flow velocity parallel to the magnetic field V, ion temperature T_i and electron temperature T_e are treated. In the parallel momentum transport equation, a second-order derivative parallel ion viscosity term is included. The parallel ion viscous flux is an approximation of the stress tensor under the assumption that the stress tensor is much smaller than the ion pressure [21]. This means that the difference in the ion temperature between the parallel component $T_{\mathrm{i},//}$ and the perpendicular component $T_{\mathrm{i},\perp}$ is considered small enough. Thus, these two components are reduced to an isotropic ion temperature, and the number of equations becomes fewer. In addition, the numerical calculation becomes more stable with the second-order derivative terms. In the SOL-divertor plasmas, however, $T_{\mathrm{i},//}$ and $T_{\mathrm{i},\perp}$ are generally different from each other. Because the convective loss of the heat along the open-field line is larger for the parallel component than that for the perpendicular component, $T_{\mathrm{i},//}$ becomes lower than $T_{\mathrm{i},\perp}$ unless the collisional relaxation is sufficiently large. This anisotropic nature was clearly demonstrated by kinetic simulations which use Particle-in-Cell model combined with a Monte-Carlo binary collision model, where the remarkable anisotropy in T_i remains even for the medium collisional regime [22,23]. Thus, it is better to treat $T_{\mathrm{i},//}$ and $T_{\mathrm{i},\perp}$ separately in the fluid modeling for SOL-divertor simulations.

Because the conventional parallel momentum transport equation is a second-order partial differential equation, the Mach number M at the divertor plate has to be given as a boundary condition. The condition $M = 1$ is usually used in the conventional SOL-divertor codes. Meanwhile, so-called the Bohm condition, which is given by the formula $M \geq 1$, was derived from the stability condition of the sheath formation in front of the divertor plate [21]. In addition, the boundary condition of the given M at the divertor plate requires iteration and makes the numerical algorithm complex. This boundary-condition issue can be untangled by introducing the anisotropic ion temperature. Generalized fluid modeling, which treats $T_{\mathrm{i},//}$ and $T_{\mathrm{i},\perp}$ separately, was proposed in Refs. [24–27], but was not adopted in the SOL-divertor codes described above. Recently, we introduced the anisotropic ion temperature directly into a fluid modeling [19]. By direct use of anisotropic ion temperature, the effect of parallel ion viscosity is automatically counted and the parallel momentum transport equation becomes a first-order partial differential equation [28]. Thus, the Mach number at the divertor plate is determined self-consistently by the upstream condition and it is no longer necessary to give it as a boundary condition.

In order to satisfy automatically the boundary condition at the divertor plate, a "virtual divertor (VD) model" is developed for the generalized fluid modeling. We introduce an artificial region (VD region) beyond the divertor plates and set artificial sinks for the particle, momentum and energy according to the image of a "waterfall". In addition, by connecting the two divertor plates through a VD region, the periodic boundary condition is able to be applied, and complex boundary-condition problems in the numerical algorithm are fully avoided. This concept of VD model is similar to the penalization scheme which has been developed in the fluid mechanics in order to mimic the no-slip boundary condition on the surface of an obstacle by adding the penalization terms on the volume of an obstacle [29]. The penalization scheme has been applied to the plasma–wall interaction in a limiter configuration of a tokamak based on a simple idea that solid surfaces work as pure sinks for the charged particles [30,31]. Recently, it has been adopted to SOLEDGE2D code where the plasma transport up to the first wall is modeled by the penalization scheme [32].

The simulation model is described in Section 2. The concept of a VD model is also explained there. Simulation results are shown in Section 3. After we explain the numerical scheme and simulation parameters in Sec. 3.1, we examine in Sec. 3.2 the effect of the VD model (characterized by a decay time of artificial sinks τ^{VD}) on the Bohm condition. In Sec. 3.3, typical simulation results for collisional and collisionless cases are shown, and the dependence of the ion temperature anisotropy on the normalized mean free path is presented. The relation between the sheath heat transmission factors and the strength