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MHD Computational Study on Pellet Injection

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Abstract

A fluid code is developed to study pellet injection into magnetically confined plasma. Since there are large differences between orders of pellet and plasma quantities, the code uses the Cubic-Interpolated Psudoparticle method that gives stable and less diffusive results. It is successfully applied to a one dimensional shock-tube problem. In result, when a cold plasma is in a hot plasma, a shock wave is driven toward the hot plasma and an ablation-like structure is induced between the cold plasma surface and the shock front.

Keywords:

pellet, ablation, MHD, CIP, ADI

1. Introduction

It has been pointed out that tritium and deuterium fueling could be a problem in toroidal fusion reactors. In the present experiments, there are two ways for the particle supply to keep or increase the plasma density. One is neutral gas puffing, which is a standard method used as a particle source from the edge region of the plasma column. The other is pellet injection, which has been mainly used to obtain a high density plasma and control a density profile [1]. The latter approach to fueling may work even in fusion reactors in which the pellet velocity exceeds several km/s.

When a pellet is injected into a bulk plasma (hot plasma), the pellet surface is evaporated by hot electrons and is shielded by a neutral cloud generated by the evaporated material. Since the neutral particles around the cloud surface are ionized by the hot electrons, a plasma with high density and low temperature (cold plasma) [compared with the bulk plasma with low density and high temperature] is created between the neutral cloud and bulk plasma. As a result, outside of the neutral rich cloud, two types of plasma, namely, the cold plasma and hot plasma coexist with steep gradients of density and temperature.

A theoretical analysis of pellet injection was started by Rose [2]. After this work, several ablation models for the pellet based on different physics were developed, e.g., a neutral gas shielding model set up by Parks and Turnbull [3]. The ablation models include the effect that the pellet is shielded from the incident electron heat flux by the surrounding neutral cloud. However, they do not include the effect that the neutral cloud is shielded by the cold plasma generated by the ablated material that are distorted and diffused along magnetic lines. Therefore, we have examined interaction between the cold and hot plasmas where an electromagnetic force is neglected from the sense of a benchmark test. Our final goal is to investigate the bulk plasma motion induced by the pellet injection including pellet dynamics by developing a three dimensional fluid code with a neutral fluid and MHD plasma, and the work in this paper is its first step. Since there is a contact surface between the cold and hot plasmas and the shock wave is driven by

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heating, we use the Cubic-Interpolated Psudoparticle (CIP) method [4] which can treat sharp discontinuities. Here, we introduce the CIP method and show a result of the bench mark test in a shock-tube problem. Thermal conduction is calculated with the Alternating Direction Implicit (ADI) method [5] that is one of implicit methods. We have shown that when a cold plasma is in a hot plasma, a shock wave is driven toward the hot plasma and an ablation-like structure is induced between the cold plasma surface and the shock front.

2. CIP Method

Fully magnetohydrodynamic equations can be written as:

$$\frac{\partial \rho}{\partial t}+\boldsymbol{u}\cdot\nabla\rho=-\rho\nabla\cdot\boldsymbol{u}, \tag{1}$$

$$\rho\left(\frac{\partial \boldsymbol{u}}{\partial t}+\boldsymbol{u}\cdot\nabla\boldsymbol{u}\right)=-\nabla p+\boldsymbol{J}\times\boldsymbol{B}, \tag{2}$$

$$\rho\left(\frac{\partial e}{\partial t}+\boldsymbol{u}\cdot\nabla e\right)=-p\nabla\cdot\boldsymbol{u}+\boldsymbol{Q}, \tag{3}$$

where ρ is the density, $\boldsymbol{u}$ the velocity, p the pressure, e the specific internal energy, and $\boldsymbol{Q}$ includes thermal conduction and heat source. In solving Eqs. (1)–(3), the CIP method is one of the most convenient ones because the equations are split into non-advection and advection phases:

$$\frac{\partial f}{\partial t}=\boldsymbol{G}, \tag{4}$$

$$\frac{\partial f}{\partial t}+\boldsymbol{u}\cdot\nabla f=0, \tag{5}$$

where f represents ρ, $\boldsymbol{u}$ and e, and $\boldsymbol{G}$ represents the terms on the righthand side of Eqs. (1)–(3). In the non-advection phase, Eq. (4) is solved with a finite difference or finite volume method. On the other hand, in the advection phase, a spatial profile within each grid interpolated with a cubic polynomial is shifted in space according to Eq. (5). In determining this profile, we use both f and spatial derivatives of f. This key issue of the CIP method is in the way of determining the time evolution of spatial derivatives. They are determined from spatial derivatives of the master equations, namely Eqs. (1)–(3). Therefore, the profile is totally determined so as to be consistent with the master equations without any artificial constraint such as smoothing that is frequently used in other algorithm with conventional spline.

By a simple extension, the CIP can be used for both compressible and incompressible fluids. Namely, the pellet, neutral cloud, and plasma can be treated simultaneously. We will develop 3D-MHD code by using the CIP method, and investigate the behavior of the magnetically confined plasma induced by pellet injection.

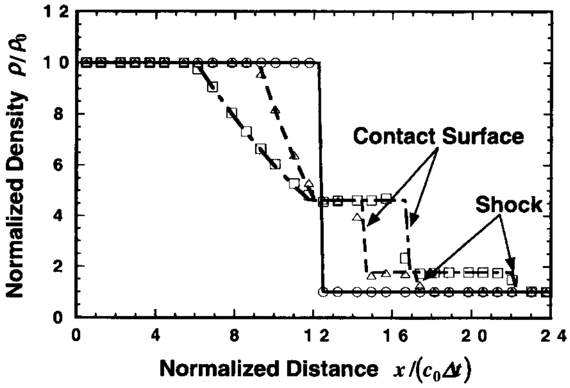

Fig. 1 Normalized density, ρ/ρ_0, as a function of normalized distance, $x/(c_0\Delta t)$. Circles, triangles, and squares show simulation results at $t = 0$, $10\Delta t$, and $20\Delta t$, respectively. Solid, dashed, and dot-dashed lines are corresponding theoretical values.

This scheme has been tested with a typical shock-tube problem [6]. Here, we have added the numerical viscosity to the pressure term as shown in Ref. [7]. Figure 1 shows the normalized density, ρ/ρ_0, as a function of the normalized distance, $x/(c_0\Delta t)$. An initial profile has a step structure as shown by a solid line. The right and left regions of that profile are labeled as 0 and 1, respectively. The subscripts of variables denote the regions, and c and Δt are sound speed and width of time step, respectively. Initial conditions are the density ratio of $\rho_1/\rho_0 = 10$, the pressure ratio of $p_1/p_0 = 10$, velocity of $u_0 = u_1 = 0$, and isentropic exponent of $\gamma = 5/3$, where the pressure is $p = (\gamma - 1)\rho e$. We show the comparison between simulation results (symbols) and the theoretical values (lines) in the temporal evolution. Solid line with circles, dashed line with triangles, and dot-dashed line with squares represent density profiles at time $t = 0$, $10\Delta t$, and $20\Delta t$, respectively. Simulation results agree quite well with the theoretical values. We have found that both the shock wave and the contact surface are described with several meshes.

3. Thermal Conduction

When a pellet is subject to plasma, it is bombarded by electrons, ions and radiation. If the electron and ion temperatures are equal, the electron energy flux is the dominant term of energy transport to the pellet since the ratio of the electron-to-ion energy flux is $\sqrt{m_i/m_e}$, where m_i and m_e are the masses of the ions and electrons, respectively. It can indeed be shown that the ions are found to be even less effective than the electrons since their ranges are shorter by a factor of $\sim m_e/m_i$. The neutral cloud and cold plasma surrounding the pellet are transparent to the hard thermal radiation on the plasma. In addition, this radiation is several orders of magnitude less than the electron energy flux [2]. Therefore, the plasma electrons are the primary energy carriers to the pellet.

The heat flow of the plasma is:

$$Q = \nabla \cdot \boldsymbol{q} = \nabla \cdot (-\kappa_e \nabla T), \quad \kappa_e = \frac{1}{3} l_e v_e, \qquad (6)$$

where $\boldsymbol{q}$, κ_e, l_e and v_e are the electron heat flux, thermal conductivity, mean free path, and thermal velocity, respectively. In ideal plasma, $l_e \propto T^2$ and κ_e has the well-known form of Spitzer-Härm thermal conductivity (Spitzer-Härm, 1953). Since the electron thermal conductivity is nonlinear and proportional to $T^{5/2}$, a steep gradient of the temperature is generated near the cold plasma surface. In order to defend calculation of the thermal conduction against numerical divergence, we use the ADI method [5] that is one of implicit methods.

4. Simulation of Interaction between Cold and Hot Plasmas with Steep Gradients

In this section, we show a simulation result of interaction between a cold and hot plasmas with steep gradients of density and temperature when the cold plasma is in the hot one in which the $\boldsymbol{J} \times \boldsymbol{B}$ force is not included. An initial profile is assumed to be given by Fig. 2(a) that shows the number density, n, (dot-dashed line) and temperature, T, (solid line) as a function of the distance, x. There are a region of number density of n = $6 \times 10^{24}\text{m}^{-3}$ and temperature of T = 5eV within 0cm $\leq x \leq$ 0.5cm and one of number density of n = $6 \times 10^{19}\text{m}^{-3}$ and temperature of T = 1keV within 0.5cm $\leq x \leq$ 5cm. The free boundary condition is used at x = 0cm and 5cm. Figure 2(b) shows the number density (dot-dashed line), temperature (solid line), and velocity (dashed line) as a function of the distance at $t = 4 \times 10^{-8}$s. Since thermal conduction is dominate rather than fluid motion in the hot plasma, the hot plasma is cooled down to about 800eV by the cold plasma. The profile of the velocity has a jump structure around $x \sim$ 3cm that expresses a shock wave. The shock is driven toward the hot plasma because the expansion speed caused by the thermal conduction is larger than the sound speed. The density decreases, and the temperature and velocity increase in the direction from the cold plasma surface to the shock front. These structures are similar to an ablation one and are induced by non-linear thermal conduction. It should be noted that the velocity ahead of the shock front is a negative value. This is due to the fact that the hot plasma is cooled by the cold plasma before the shock propagation.

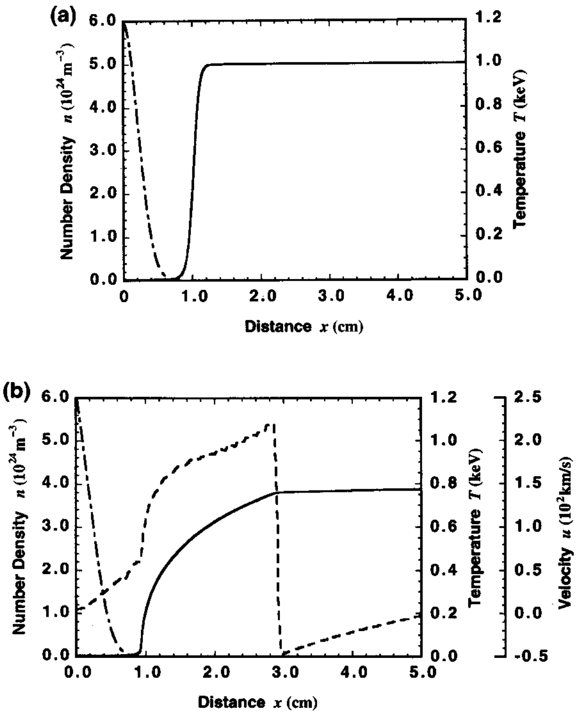

Fig. 2 (a) Number density, n, (dot-dashed line) and Temperature, T, (solid line) as a function of distance, x, in t = 0s. (b) Number density, n, (dot-dashed line), Temperature, T, (solid line), and velocity, u, (dashed line) as a function of distance, x, in t = 4 \times 10^{-8}s.

5. Conclusions

We are developing a fluid code to investigate physics on the pellet injection. The CIP method is used in this code in order to treat a shock wave and contact surface with sharp discontinuities. In a shock-tube problem, these discontinuities are described with several meshes. The ADI method is used in calculating the thermal conduction. When a cold plasma is in a hot plasma, we have obtained the result that a shock propagates toward the hot plasma and an ablation-like structure is induced between the cold plasma surface and the shock front. In the future work, we will extend this code to the fluid code with a neutral fluid and MHD plasma and investigate the bulk plasma motion induced by the pellet injection including pellet dynamics.

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