APPLICATION OF NUMERICAL SIMULATION IN ASTROPHYSICS

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ABSTRACT

Hydrodynamics (HD) and Magnetohydrodynamics (MHD) numerical analysis have become a very useful tool in astrophysics research. In solar physics, we usually cannot affect the object itself by experiment, so we can only study it through numerical analysis and simulation. In this paper, the fundamental theory of computational fluid dynamics (CFD) and their computational method are introduced, including Lagrange-method and Euler-method. Meantime, one of the most common program used in CFD is also introduced, that is ZEUS. In the end, the recent application of HD in astrophysics is summarized. The goal of this paper is to provide some fundamental theory and research progress about CFD in astrophysics.

1. INTRODUCTION

Numerical simulation has become a significant way of solving complicated problems in physics. Comparing with traditional experiment, numerical simulation is more efficient and economic. Furthermore, in some cases, traditional experiment can be dangerous and hard to proceed. Numerical simulation allows us to simulate the situation safely and gather complete information. It is a powerful tool in astrophysics. CFD is a method based on real physical functions to simulate fluid. HD functions has no analytic solutions because of its complexity. However, through CFD, we can solve it numerically and predict the change of fluid. There are two methods of describing motion: Lagrange Method and Euler Method. Both method lead to a same result [1-3].

HD includes a lot of aspects in astrophysics. Such as: the instability of magnetic rotation in accretion disc, active galactic nucleus feedback and cooling flow, the temperature distribution of intermediate in clusters, studies relate to waves during coronal mass ejection. This easy gives an introduction of these studies. There are lots of computer programs in CFD. This easy only introduce one of the programs: ZEUS.

2. COMPUTATIONAL FLUID DYNAMICS

CFD is an independent subject based on classical hydrodynamics and numerical analysis, which analyze the flux of fluid, thermal conduction and other related physical pheromones through simulation and image data on computer [4]. CFD is the numerical simulation in order to study the basic physical quantities inside fluid including velocity, pressure, temperature and concentration distribution based on the fundamental equations, which are mass conservation equations, momentum conservation equations and energy conservation equations.

CFD is solving the problems: velocity field & pressure field inside to control volume. Velocity vector u , can be separated to three components u , v , w on x , y and z direction.

$$\vec{u} = u_i + v_j + w_k. \quad (1)$$

Conservation laws apply on fluid. Any fluid problems must obey mass conservation and momentum conservation. Using mass conservation, we can get:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0. \quad (2)$$

Where ρ is density, t is time, u is velocity vector, u , v and w is the x , y , z components of u .
 The conversation of momentum can be expressed as follows:

$$\vec{F} = m\vec{a}. \quad (3)$$

Express the equation in 3 directions:

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left(\lambda \nabla \cdot \vec{v} + 2u \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left(u \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) \right) + \frac{\partial}{\partial z} \left(u \left(\frac{\partial w}{\partial z} + \frac{\partial u}{\partial x} \right) \right) + pf_x; \quad (4)$$

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x} \left(u \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) \right) + \frac{\partial}{\partial y} \left(\lambda \nabla \cdot \vec{v} + 2v \frac{\partial v}{\partial y} \right) + \frac{\partial}{\partial z} \left(v \left(\frac{\partial w}{\partial z} + \frac{\partial v}{\partial y} \right) \right) + pf_y; \quad (5)$$

$$\frac{\partial(pw)}{\partial t} + \frac{\partial(puw)}{\partial x} + \frac{\partial(pvw)}{\partial y} + \frac{\partial(pw^2)}{\partial z} = -\frac{\partial p}{\partial z} + \frac{\partial}{\partial x} \left(u \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right) \right) + \frac{\partial}{\partial y} \left(u \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \right) \right) + \frac{\partial}{\partial z} \left(\lambda \nabla \cdot \vec{v} + 2u \frac{\partial w}{\partial z} \right) + p f_z; \quad (6)$$

If we can solve the equations, we can find out the unknowns. However, it is not possible to solve such equation analytically. We can only solve it numerically. Here, we introduce 2 methods: Lagrange Method and Euler Method.

2.1 Lagrange Method

Lagrange method focuses on the motion of mass points. The space region where continuous intermediate is initially being called initial configuration. The space region where continuous intermediate is a time t is called present configuration. In order to measure the motion of intermediate, define t_0 is reference time, and the space region where continuous intermediate is at t_0 is reference configuration. Lagrange method use reference configuration as initial configuration and study the motion of the objects in space. After discrete the objects, net points are mass points and its motion follows the motion of mass points. There is no relative motion between net points and mass points or convective terms in governing equation. This method can define boundary plane and moving plane precisely and the numerical calculation is not very hard. It is a good method for stress and deformation analyze for solid structure [5].

2.2 Euler Method

MHD equations describe the interactions between plasma flow field and magnetic field macroscopically, which usually requires Euler-Method in the program [6]. Euler-Method is named after a Swiss mathematician and physician Leonhard Euler. It is a first order numerical method to solve ordinary differential equations. Euler-Method uses finite-difference method (FDM) and finite-volume Method (FVM) to discrete the equations in Euler cells and express the field by the physics quantities at net points. More specially, through Taylor expense the physics quantities of an arbitrary net point and the net points around it, transfer differential calculus to finite difference. Alternatively, rebuild the distribution of the physics quantities around the net point and solve the Riemann problem to get the flux functions.

3. ZEUS PROGRAM

ZEUS is a Multi-function HD computing software oriented to astrophysics, which is written through Fortran. To be more precisely, ZEUS is not a single software but a series of software. After many years' development and application, ZEUS has been proving to be a convenient, efficient and reliable simulation software. It has been widely used on multi aspects in astrophysics. Such as Star Nebula, Molecular cloud turbulence, solar magnetic field and the formation of spiral arms of galaxies. ZEUS has mutli-function, includes curvilinear coordinate system, magneto fluid, double fluid, dynamics viscosity, gravitation and radiation.

4. THE DEVELOPMENT AND APPLICATION OF ZEUS

ZEUS is a mathematical software designed for hydrodynamics, ideal MHD and radiation hydrodynamics. ZEUS was used to simulate MHD jet at the beginning. Then in 1980s, Stone put it on UNIX and named it ZEUS-2D to solve 2D or 2.5D MHD equations under self-gravitating radiation system. At the same time, many new algorithms were added to ZEUS in order to make simulations in different coordinate systems. After that, David Clarke reprogrammed ZEUS-2D to ZEUS-3D for 3D problems. In 1996, Mike Norman's team developed a new version of ZEUS called ZEUS-MP, which can solve both 2D and 3D problems. In the development of Zeus, Computational astrophysics study has significant accomplishment in Magneto rotational Instability, magnetic decoupling stage in star formation, active galactic nucleus, temperature distribution of the medium in galaxies and coronal mass ejection.

4.1. Instability of Magnetic Rotation in Accretion Disc

Accretion disc is a disk-like structure which contains a massive center and diffused material orbiting the centre. The center can be a star, a protostar, a White dwarf, a black hole and other massive structures. Diffused material falls to the centre because of friction. MRI was first noticed in 1959 by Evgeny Velikhov. In 1991, Balbus and Hawley developed an angular momentum transfer model which gives a clear explanation of MRI [7].

4.2. Active Galactic Nucleus Feedback and Cooling Flow

Active Galactic Nucleus (AGN) is the region located at the centre of a galaxy has much higher luminosity than normal galaxies. AGN is the brightest part of the galaxy, which is only a very small part of the galaxy. AGN is the brightest and most persistent sources of electromagnetic radiation in the universe. Recent years, people start to realize that AGN has some effect on galaxy formation and Large-scale structure. Vernaleo and Reynolds use 3D-CFD to analyze active galaxy and its behavior in an intracluster medium [8]. They found that ideal HD model cannot persist a heating and cooling balance for a long time. Catastrophic cooling can be delayed but it is inevitable. They suggest complicating the calculation or introduce extra physical effects to make a heating term to avoid catastrophic cooling.

4.3. The Temperature Distribution of Intermediate in Clusters

ICM is the super-hot gases in the centre of galaxy clusters. The temperature of these plasma is 10 million to 100 million K. The main component is ionized hydrogen and helium. The heat is from the gravitational potential energy released by smaller clusters while the main cluster was formatting. Reynolds and his team point that ideal HD model cannot explain the temperature distribution in the centre of galaxy clusters [9]. Recent research indicates that under the existence of magnetic field, the thermal conduct process in ICM may have major significance to study temperature layers in many systems. This discovery inspired people that other thermal conduct process may also be significance. With this idea, Reynolds and his team use ZEUS-MP to simulate the evolvement of AGN air hole in ICM. The result shows that even an intermediate level Shear viscosity can have significant impact to the completeness of ICM hole.

4.4. Research on Waves during Coronal Mass Ejection

Coronal mass ejection (CME) is the phenomenon that solar corona releases a large amount of plasma and magnetic field. It usually related with solar flares. Wang and his team use ZEUS-2D to simulate the ejection. They analyze the Morton wave, EIT wave, the effect of the reflection and refraction of shock wave on the formation of EUV wave. Those works have significant meaning for explaining CEM [10].

5. CONCLUSION

Numerical simulation is playing a significant role as a bridge between theory and observation. The accuracy of numerical simulation is improving with the development of computing ability. This makes studies of internal small scale fine structure in astro-system become possible. Moreover, HD also has become a very important part in astrophysics. We have made some significant development in ZEUS and it has been benefit us in various field in MHD. This is also the part that CFD needs to improve. Although computing has been significantly developed recent years, the tremendous amount of calculation in astrophysics is still a major challenge for computing, which requires a more effect way of calculation.

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