S3-5

Numerical Simulation of Free Surface Liquid Metal Flows by SPH Method

Changhong HU[1], Jabir AL SALAMI[2], Kazuaki HANADA[1]

1. Research Institute of Applied Mechanics, Kyushu University
2. Interdisciplinary Graduate School of Engineering Sciences, Kyushu University

The divertor is an essential component of tokamak fusion reactors not only to extract the energy from the plasma to generate electricity, but also to expel reactor byproducts, also known as fusion ash, which adversely affect the quality of plasma confinement and temperature.

One of the main challenges facing divertor design is the tremendous energy fluxes (~ 10^7 W/m^2) that divertors are projected to experience in electricity-producing scale reactors[1]. At such thermal loads, even Tungsten, the material of choice for the divertors in ITER and DEMO, can sustain cracks due to thermal shock and fatigue in addition to high rates of sputtering due to plasma influx[2]. Also, the ductile-to-brittle transition temperature (DBTT) for tungsten increases with neutron irradiation, which may cause cracking of tungsten plasma facing components (PFCs)[3]. Such limitations of solid PFCs have motivated the consideration of liquid metals as viable alternatives for future tokamak designs.

The operation of a liquid metal (LM) divertor involves phenomena spanning multiple disciplines of physics such as fluid dynamics, electromagnetism, thermodynamics and plasma physics. The evaluation and refinement process of engineering designs of such a device must involve numerical simulations to avoid the prohibitive costs and durations of experiments. Here we list some important problems which need to study by numerical simulations before conducting experiments.

- Design of a rational LM circulation system
- Sheet-like LM flow creation
- Behavior of magnetically guided LM PFC
- Stability of LM free surface
- Influence of turbulence
- Prediction of heat recirculation
- Phenomena associated with disruption

Computational fluid dynamics (CFD) methods have been widely used in many industrial applications. CFD method for magnetohydrodynamics (MHD) has also been studied and applied to simulation of liquid metal flows[4], which is called CMHD (computational magnetohydrodynamics) method. Due to multi-physics nature of the LM flows in the diverter, directly application of an existing CFD code will not be effective. The purpose of the present research is develop an new CMHD code that is capable of LM divertor simulations. The strategies of our research are as follows.

- To develop our own CMHD code based on smoothed particle hydrodynamics (SPH) method
- To incorporate the best available schemes in engineering CFD, with which we have been working in the ocean engineering field for more than 20 years
- As a short term objective, to perform numerical simulation of the LM flow which will be used in the scale model experiment in QUEST
- As a long term goal, to perform numerical simulation of a full scale LM divertor under real conditions

Among the existing well-established CFD methods, we chose SPH for numerical simulation of liquid metal flows. SPH is a mesh-free, Lagrangian method that is well-suited for multiphysics applications such as the problem associated with the liquid metal divertors. This method has many advantages over other CFD methods as described below.

- In particular, SPH is better adapted and is easier to implement in cases of highly non-linear phenomena, such as violent free-surface flows, splashing and fragmentation when compared to mesh-based Eulerian methods.
- SPH spares the user the often time-consuming and complicated task of mesh-generation, especially for intricate geometries.
- The SPH framework facilitates the integration of multi-physics without the need for extensive

and computationally demanding special treatments or interfacing with other methods.

- SPH's inherent ability to bridge the gap between continuity and fragmentation with little effort carries over well to hydrodynamic and solid-mechanical applications, such as fluid-structure interaction, melting and solidification and industrial processing[5,6].

The development of a hydrodynamics version of the SPH code has been completed. Figure 1 shows a recently obtained dam-break simulation to demonstrate the ability of capturing the complicated and highly non-linear free-surface phenomena by our code.

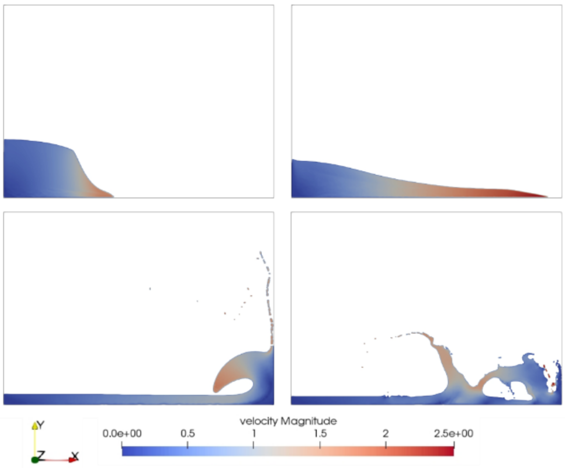

Figure 1: Dam-break simulation using SPH

The above mentioned SPH features have motivated us to choose SPH for simulation of liquid metal divertor. However, since SPH for MHD has not be well studied yet, in this research at first we extend the hydrodynamic SPH code to the SPMHD (smoothed particle magnetohydrodynamics) code.

Governing equations for MHD can be described as follows.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \qquad (1)$$

$$\frac{D\mathbf{u}}{Dt} = -\frac{1}{\rho}\nabla p + \frac{1}{\rho}\nabla \boldsymbol{\tau} + + \frac{1}{\rho}(\mathbf{j} \times \mathbf{B}) + \mathbf{g} \qquad (2)$$

where $\boldsymbol{\tau}$ is the viscous stress tensor, $\mathbf{j}$ is the current density and $\mathbf{B}$ the magnetic field vectors. The latter two are governed by the following Maxwell equations.

$$\nabla \times \mathbf{B}_i = \mu_0 \mathbf{j} \qquad (3)$$

$$\mathbf{j} = \sigma(\mathbf{E} + \mathbf{u} \times \mathbf{B}) \qquad (4)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}_i}{\partial t} \qquad (5)$$

In the SPH framework, the fluid is discretized into material particles that in addition to carrying the fluid properties, serve as interpolation nodes for the discretized fields. In this work, the weakly compressible formulation of SPH is adopted.

As the first result of our SPMHD development, a 2-dimensional simulation of a Hartmann flow versus the analytical solution for Hartmann numbers ($Ha = BL\sqrt{\sigma/\nu\rho}$) of 8, 25 and 50 are presented in Figure 2, where the Hartmann number is a non-dimensional number signifying the ratio of electromagnetic forces to viscous forces. Comparison between the SPMHD result and the analytical solution is satisfactory.

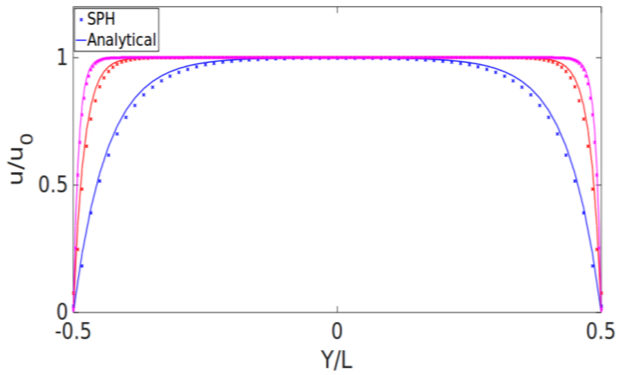

Figure 2: Hartmann Flow simulation using SPH for Ha = 8 (blue), Ha= 25 (red) and Ha = 50 (magenta)

This research has just been started. Future work includes extending the present 2D code to 3D, comprehensive comparison between ϕ and B formulations for liquid metal flows, implementation of turbulence model and surface tension model, extending the present model to non-uniform, time varying magnetic field, etc.

REFERENCES

1 S.V. Mirnov, V.N. Dem'yanenko, E.V. Murav'ev, J. of Nuclear Materials,Vol. 196–198, (1992).
2 T. W. Morgan, P. Rindt, G. G. van Eden, V. Kvon, M. A. Jaworksi and N J. Lopes Cardozo, Plasma Physics and Controlled Fusion, Volume 60, N. 1 (2017).
3 P. Krautwasser, H. Derz, Kny, E, Plasma Physics And Fusion Technology (1995)
4 T. Yanagisawa, et al., Phys Rev E Stat Nonlin Soft Matter Phys. (2013)
5 J. Monaghan,Reports on Progres in Physics, vol. 68 (2005)
6 H. Kumamaru, J. of Nuclear Science and Technology, Vol 54, No.2 (2017)