TSUBAME 共同利用 令和 2 年度 学術利用 成果報告書

利用課題名 液体金属流れ CFD 手法の開発及び核融合研究への応用

英文：Development of a High Order Flux Reconstruction Interface Capturing Method for Multiphase Simulations

利用課題責任者 胡 長洪
Changhong Hu

所属 九州大学応用力学研究所
Research Institute for Applied Mechanics, Kyushu University
https://www.tj.kyushu-u.ac.jp/

邦文抄録（300 字程度）
高次精度の計算手法は従来の低次精度の解放と比較して，計算精度と計算性能などが優れている．しかし，高次精度方程式はギブズ現象の影響を受けやすく，シャープな界面を正確に扱うことが困難である．本研究では，高次精度 Flux Reconstruction 法（FR 法）を用いて，シャープな界面を捉える手法を提案する．局所的な人工粘性を課したレベルセット関数の前処理を利用することで，界面の法線ベクトルの計算精度を向上した．

英文抄録（100 words 程度）
High-order numerical methods can offer several advantages over conventional, low order methods for fluid dynamics simulations such as higher accuracy and computational performance. A major limitation of high-order methods is their susceptibility to the Gibbs phenomenon, preventing them from accurately resolving sharp interfaces. This work presents a method for capturing sharp interfaces using the high-order Flux Reconstruction approach. The numerical accuracy of interface normal vectors is improved by utilizing a preconditioning procedure based on the level set method with localized artificial viscosity stabilization.

Keywords: Flux-reconstruction, High-order methods, Multiphase, Phase-field, GPU computing

背景と目的

Recent trends in CFD research indicate a steadily increasing interest in high-order numerical methods. The ability of such methods to produce results with more accuracy on coarser grids when compared to conventional low order methods resulted in a growing consensus among CFD practitioners that high-order methods may constitute the basis of next-generation CFD research tools. Furthermore, high-order methods, such as the flux-reconstruction and discontinuous Galerkin methods have compact stencils which renders them particularly suitable for computation on modern hardware such as general purpose graphical processing units (GPGPUs). However, these methods have seen little use for multiphase simulations due to their susceptibility to the Gibbs phenomenon; the appearance of spurious oscillations in the vicinity of discontinuities and steep gradients makes it difficult to accurately resolve shocks or sharp interfaces.

In order to address this issue in the context of sharp interface capturing, a novel, preconditioned and localized phase-field method is developed in this work and hereafter referred to as the Flux Reconstruction Preconditioned Phase Field method (FR-PCPF). The numerical accuracy of interface normal vectors is improved by utilizing a preconditioning procedure based on the level set method with localized artificial viscosity stabilization. The developed method was implemented in the framework of the multi-platform Flux Reconstruction open-source code PyFR [1]. Kinematic numerical tests in 2D and 3D conducted on different mesh types showed that the preconditioning procedure significantly improves accuracy with little added computational effort.

概要

This research aims to develop next generation CFD techniques for solving incompressible, free surface flows. Such phenomena are important in a variety of fields and applications such as flooding and tsunami simulations, applications in naval and marine engineering, and nuclear fusion applications (flow of liquid metal as plasma-facing material). This development is based on the high-order Flux Reconstruction method, which allows obtaining more accurate results while utilizing modern hardware more efficiently when compared to conventional CFD techniques. The TSUBAME super-computer was used to carry out simulations for testing and validation of GPU-accelerated, high-order CFD code for solving free surface incompressible flows. The simulations aimed to test the accuracy and computational efficiency and scaling of the code for problems involving a large number of degrees of freedom.

結果および考察

Results from numerical benchmark tests that were carried out have shown that the FR-PCPF method is able to produce results that are comparable to some of the most accurate low and high order methods by using second order polynomial basis. Increasing the polynomial order further improves numerical accuracy. Figure 1 shows simulations of the Rider-Kothe vortex benchmark case [2], where the black dashed line is the initial state of the droplet, and the red line shows the final state, which demonstrates the good accuracy of the method.

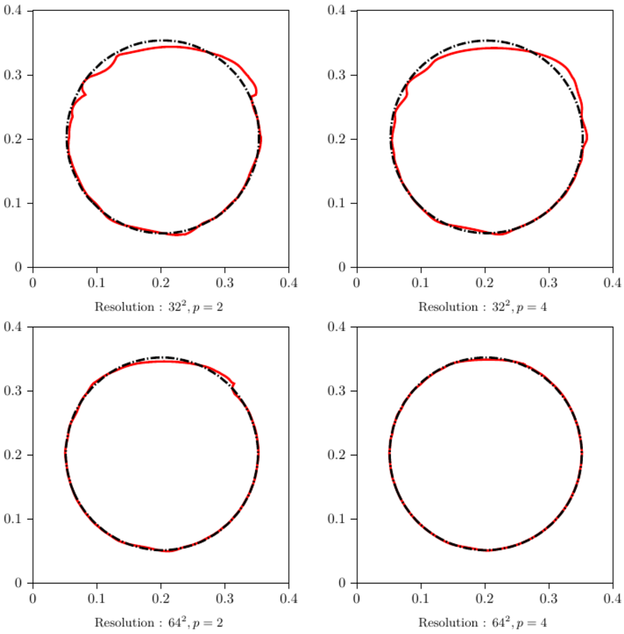

Figure 2: Rider-Kothe simulation using the FR-PCPF method (red line is final state and black line is initial state of droplet)

The FR-PCPF method is shown to be able to conserve mass and resolve challenging interface features even with long time integration. Increasing effective resolution (by either increasing the polynomial order per computational element or by increasing the mesh resolution) was shown to produce consistent improvements in global mass conservation, accuracy and the ability to resolve complicated interface features.

The FR-PCPF method's applicability to multi-phase flows has been demonstrated by coupling the interface capturing algorithm to the Entropically Damped Artificial Compressibility (EDAC) Navier-Stokes system of equations, and simulations of the Rayleigh-Taylor instability (in figure 2) and bubble rise problems yielded good matching with previously published results.

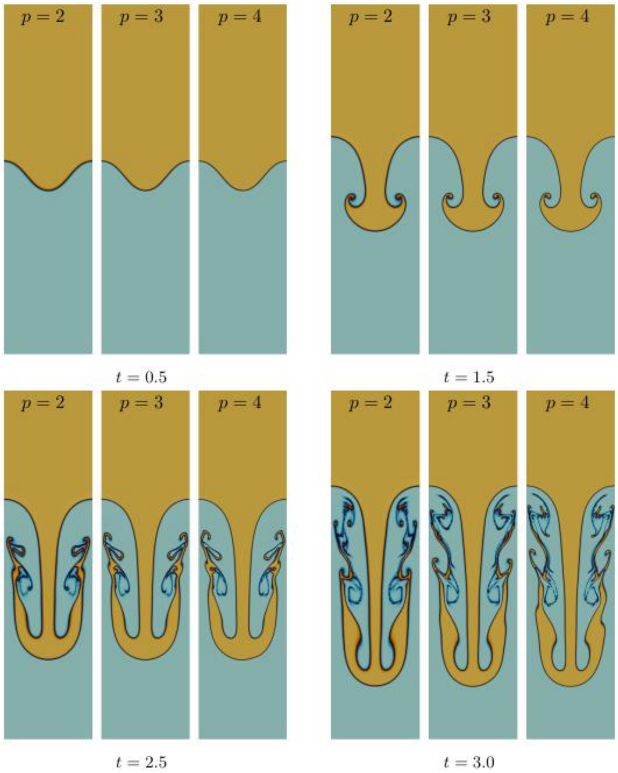

Figure 1: Simulation of the Rayleigh-Taylor instability using the FR-PCPF coupled with the EDAC formulation using different polynomial orders

まとめ、今後の課題

In this report, progress on the development of a high-order method for interface capturing for use in high-accuracy and large-scale simulations has been summarized. Satisfactory results of benchmark tests were obtained. Future work includes optimization of model parameters and extending the range of tractable density ratios to cover those needed in applications such as liquid metal flow in low pressure environments.

References

[1] Witherden FD, Farrington AM, Vincent PE. PyFR: An open source framework for solving advection–diffusion type problems on streaming architectures using the flux reconstruction approach. Computer Physics Communications. 2014 Nov 1;185(11):3028-40.

[2] Rider WJ, Kothe DB. Reconstructing volume tracking. Journal of computational physics. 1998 Apr 10;141(2):112-52.