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論 文 要 旨

THESIS SUMMARY

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要旨（英文 800 語程度）
Thesis Summary（approx.800 English Words ）

This study is consisted of 5 chapters in total. Chapter 1 provides a thorough overview of this study, emphasizing the prevalence of moving interface phenomena in natural and industrial processes amid social modernization and industrialization. The research specifically focuses on the challenges posed by computational modeling in the realm of two-phase flows, particularly immiscible two-phase flows. Acknowledging historical limitations in analytical studies and experimental observations, the study underscores the necessity for robust numerical models to simulate complex physical phenomena. Challenges, including enforcing conservation laws, modeling property discontinuities, handling complex topologies, and implementing accurate surface tension forces, are outlined. The historical evolution of two-phase numerical modeling is detailed, highlighting innovative strategies and introducing continuum-based modeling approaches like the two-fluid model and the one-fluid model. Categorizing one-fluid models into interface tracking and interface capturing, the study centers on the latter. Various interface capturing methods are introduced, with a nuanced discussion of their advantages and disadvantages. The research purpose is articulated, focusing on enhancing numerical simulations for interface capturing problems. The study proposes (Tangent of Hyperbola Interface Capturing) THINC based hybrid Volume of Fluid (VOF) and level set techniques to address challenges, offering solutions such as integrated interface capturing, high-order surface representation, adaptive THINC reconstruction, and single-step update procedures. The methodologies aim to improve solution quality and algorithmic efficiency while maintaining mass conservativeness, with a commitment to comprehensive validation through benchmark tests.

Chapter 2 delves into a detailed algorithmic overview of representative VOF and level set interface capturing methods, recognized as mainstream approaches. The chapter begins by introducing the Piecewise Linear Interface Calculation (PLIC) method, a geometrical VOF method with explicit interface reconstruction for non-planar faces on unstructured meshes, addressing challenges in high-dimensional geometrical operations. Additionally, the chapter explores compressive methods as Algebraic VOF approaches, focusing on numerical approximation using polynomials or tangent hyperbolic functions for volume fraction determination. While these methods offer algorithmic simplicity on unstructured meshes, they exhibit reduced numerical accuracy compared to geometrical VOF methods. Within the algebraic VOF scope, the THINC method employs a hyperbolic tangent function to simulate a jump-like VOF field. The chapter details various THINC variants, such as Multidimensional THINC (MTHINC), Unstructured MTHINC (UMTHINC), and THINC method with Quadratic surface representation and Gaussian Quadrature (THINC/QQ), each addressing specific challenges in incorporating geometric information and adapting to diverse element shapes. The level set method, defined by a signed distance function to the interface, is explored as a superior approach for capturing geometrical properties. Seminal level set methods, including those solving Hamilton-Jacobi equations and Conservative Level Set (CLS) methods mitigating conservativeness issues, are discussed in-depth. The chapter concludes with a focus on two THINC-based hybrid VOF and level set methods, THINC/LS and THINC-scaling. While THINC/LS updates VOF and level set fields independently but couples them through a shared THINC function, THINC-scaling achieves simultaneous updating using a shared THINC function, introducing challenges in scenarios with discretely distributed velocity fields.

Chapter 3 details the progress made in developing THINC based VOF and level set methods within the study. The focus is on the algorithmic procedure of the proposed THINC-VOFLS framework, outlining the updating of level set and VOF functions through a consistent cell-wise THINC reconstruction function. Within the THINC-VOFLS framework, the THINC-scaling scheme with Quartic Surface Representation (THINC-scaling/QSR) scheme is introduced, employing a quartic surface polynomial for interface representation. This marks the first instance of utilizing quartic surface representation in THINC schemes and other VOF algorithms on unstructured meshes. Numerical results showcase commendable performance in solution accuracy, sub-grid interface resolution, and smoothness of curved surfaces, even with heavily distorted interfaces like the long-thin tail in the vortex deformation benchmark test. The coupled Level-Set and Tangent of Hyperbola INterface Capturing scheme with a Consistent Single-step time integration (THINC/CSLS) scheme, another interface capturing scheme of the THINC-VOFLS framework, adopts a single-step update procedure for both VOF and level set functions. This scheme is lauded for its accuracy, stability, efficiency, and ease of implementation in interface capturing. The adaptive THINC reconstruction strategy introduced in this chapter ensures the boundedness of the VOF function under various CFL conditions. Numerical results in the 2D solid body rotation test indicate that the THINC/CSLS scheme, with a single-step time integration, achieves similar accuracy and convergence rates while reducing computational costs to 1/3 compared to the THINC-scaling method.

Chapter 4 focuses on the numerical implementation of the proposed hybrid THINC and level set interface capturing scheme in incompressible fluid simulation. Notably, this marks the first successful implementation of such a scheme in fluid simulation conducted on polyhedral unstructured meshes. The study integrates the proposed THINC/CSLS interface capturing scheme with the Consistent and Banlanced-force model with Level set and Volume Of Fluid (CBLSVOF) fluid solver for incompressible fluid simulation. The scheme's advantage lies in the readily updated level set field at each computational time step, offering improved performance in surface tension calculations compared to VOF based schemes. The chapter provides insights from the 2D droplet oscillating test, showcasing the scheme's capability to suppress parasitic currents, confirmed through an examination of the velocity field as the simulation converges to a steady state. Numerical results from various benchmark tests, including the 2D and 3D bubble rising tests, highlight the outstanding interface capturing capabilities of the proposed scheme in the context of fluid simulation with surface tension. The well-defined shape of bubbles during rising and merging processes aligns with experimental data, affirming the scheme's reliability and accuracy in capturing fluid interfaces.

In chapter 5, the primary contributions of the present investigation are emphasized in chapter 5, and prospects for future work are discussed. The introduced novel schemes demonstrate the capability for accurate interface capturing and straightforward implementation in incompressible fluid simulation. These schemes hold considerable promise as effective numerical tools for a diverse range of applications.