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Jie Zhang

The Developments and the Applications of the Numerical Algorithms in Simulating the Incompressible Magnetohydrodynamics with Complex Boundaries and Free Surfaces

Doctoral Thesis accepted by
the University of Chinese Academy of Sciences,
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To my father,
for you endless support on my study
over the last thirty years

Supervisor's Foreword

Magnetohydrodynamics (MHD), which describe the flow behaviors of electrically conducting fluids exposed to the external magnetic fields, have aroused more and more concerns from researchers nowadays. Although it is just a subfield of fluid mechanics, however, it is of great significance in designing some of the key components in the thermonuclear fusion devices, in which the magnetic fields are used to confine the hot plasma. Another respect related to the application of the MHD is the metallurgic industry, which usually employs the magnetic field to control the continuous casting process within the casting mold. Therefore, accurate prediction of the flow behaviors, especially in the multiphase flows, under the influence of the magnetic fields has become a key basic science issue in the fusion and metallurgic engineering. Due to multidisciplinary and multiphysics coupling, it is very difficult to carry out theoretical research work, and thus, experimental studies and numerical methods are excessively relied on to solve the practical engineering problems. Moreover, due to the opacity of the liquid metal, the measuring techniques are rather limited at present to obtain comprehensive information about the flow field. For instance, capturing the vortex structures is rather important in investigating the influence of the magnetic field on the single bubble motion in the liquid metal; however, they are unavailable under the current experimental conditions. Consequently, numerical simulations would be an effective remedy to capture more elaborate structures inside the flow field, whether the fluid is opaque or not.

It should be noted that it is not a simple task to develop a suitable numerical method for the single-phase MHD flows, let alone for the multiphase MHD flows, and the difficulties will be introduced in more detail in this thesis. This Ph.D. thesis by Dr. Jie Zhang has developed a numerical solver aiming to solve the single-phase MHD flows with complex boundaries and the multiphase MHD flows with free surfaces, as being introduced and validated, the algorithms are proved to be accurate and robust by comparing with available analytical and experimental results. It is appropriate and also of important significance that the thought of the engineering science is well inherited in this work, and this solver is applied to simulate some typical interfacial flows probably encountered in the fusion devices, such as the thin liquid lithium film flows, the bubbly flows, and the liquid jet flows. For me, it is a powerful solver to help us in gaining more knowledge in the research community of multiphase MHD flows.

Besides, Dr. Jie Zhang is also skilled in analyzing physical problems involving complicated effects. After completing the coding of the MHD solver, he devoted himself to the numerical research of the bubble motion under the influence of external magnetic fields, since there are corresponding experimental studies on this topic while the results are insufficiently comprehensive because of the opacity of the liquid metal. He has the capability to identify the main or controlling factor in complex situations, to establish the relations between different parameters, and then to discuss the corresponding physical mechanism by analyzing the numerical results. Therefore, one major part of the contents studied in this thesis, i.e., the bubble motion under the influence of either a horizontal or vertical magnetic field, clarifies some interesting phenomena observed but not reasonably interpreted in the experimental studies. In solving these difficulties, Dr. Zhang has demonstrated his broad vision and flexible thinking. He provides plausible explanations on the evolutions of the bubble dynamics when exposed to the external magnetic field, such as why the rising paths of the bubble evolve with different strengths of the magnetic field, and how the vortex structures are modified under the MHD effect. Besides, the anisotropic effect on the flow field induced by the horizontal magnetic field is presented and discussed in this thesis, enriching our knowledge of the MHD effect on the fluid flows although parts of them are predicted by traditional theories.

In addition, after getting more knowledge on the topic of the bubble dynamics, Dr. Zhang tries to answer more general questions in this research community, one of them is why the single bubble always transits from zigzag to spiral, which is another contribution of this thesis. He ascribes this transition to the asymmetric deformation of the bubble shape in the low *Re* regime, and hence, the double-threaded vortex structures behind the bubble will lose symmetry later, leading an angular velocity between them, and finally, the spiral motion is generated. This result, on the one hand, significantly deepens our understanding of the developments of the vortex structures during the bubble rising, and on the other hand, could provide us with the possible way to trigger the bubble rising path transiting from one stage to another.

This thesis has been highly praised by the eight Ph.D. thesis reviewers, and as supervisor of Dr. Zhang, I am glad to recommend this thesis to readers, particularly those specialized or interested in the bubble dynamics and the MHD flows.

Beijing, China Mingjiu Ni
January 2018

Acknowledgements

First of all, I would like to appreciate the time period of my Ph.D. career from 2009 to 2014, during which time I devoted myself to fluid mechanics from the very beginning to know it, then to research into it and eventually to understand it. It has ever been the most difficult heart-wrenching time, and also the happiest time, over the past years for me. More importantly, it also thought me to keep an average heart with repeated delays and frustrations in research, they were not accidents but certainties.

I would foremost like to express my sincere gratitude toward my supervisor, Prof. Mingjiu Ni, for his continued guidance and generous support throughout my Ph.D. endeavors. Nearly 8 years ago, it was his very presence to bring me into the research community of the fluid mechanics and the magnetohydrodynamics, more than that, it was still him to provide expert advice and encouragement which led me through my Ph.D. career. I am impressed by his experience in academic scholarship and his visions in the academic frontier, and they are unremittingly passed to me during his daily education work. Owing to the 5 years imperceptible influence, both my scientific literacy and ideological level have been greatly promoted. What I am trying to say is, without Prof. Ni, I probably missed the entrance into the hall of sciences.

This thesis could not have reached the same quality without cooperating with professor, also academician of the French Academy of Sciences, René Moreau during his short stay in Beijing. Although I just spent one month with him, however, it was rather a particular period for me that what I learnt from him included, but not limited to, doing research and writing papers. Academician Moreau, in spite of his 75 years ripe old age at that time, still taught me how to analyze the numerical results in detail and how to present them properly in the manuscript. He not only discussed the big-picture ideas with me but also carefully weighed every word and text layout, and even helped to correct punctuation errors many times. Such a spirit and style is worthy to be forever remembered and learned by us younger generation. I wish academician Moreau and his wife good health and longevity!

Second, I am thankful to some other seniors in our research group: Prof. Nianmei Zhang, Prof. Xingang Yu, and Prof. Zenghui Wang; they gave me a lot of help and supports, not only in the academic research but also in my everyday life. I have also benefited a lot from discussions with Prof. Yongling Yu and Prof. Huiyang Ma, who are real experts in fluid mechanics, particularly in the research field of the vortex dynamics; they provide me with the inspiration for the interactions between the bubble motion and the vortex evolutions. I am also grateful to Prof. Stéphane Popinet for sharing the Gerris code he developed, and his dedicated support.

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Contents

Acronyms

AMR	Adaptive Mesh Refinement
CCM	Cut-cell Method
CFD	Computational Fluid Dynamics
CSF	Continuous Surface Force
CSS	Continuous Surface Stress
DNS	Direct Numerical Simulations
FT	Front Tracking
GCM	Ghost-cell Method
IBM	Immersed Boundary Method
ITER	International Thermonuclear Experimental Reactor
LS	Level-set
LSA	Linear Stability Analysis
MF	Magnetic Field
MHD	Magnetohydrodynamics
PIV	Particle Image Velocity
PLIC	Piecewise Line Interface Calculation
Tokamak	toriodal'naya kamera magnitnymi katushkami
UDV	Ultrasound Doppler Velocimetry
VOF	Volume of Fluid