

IMMERSED BOUNDARY BASED SIMULATIONS OF FLUID-PARTICLE INTERACTIONS: EFFECTS OF THE PARTICLE SHAPE AND COLLISIONS

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INDIAN INSTITUTE OF TECHNOLOGY DELHI

DEPARTMENT OF MECHANICAL ENGINEERING

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by

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DEPARTMENT OF MECHANICAL ENGINEERING

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I dedicate this work to my parents...

C E R T I F I C A T E

This is to certify that the thesis entitled “ **Immersed Boundary Based Simulations of Fluid-Particle Interactions: effects of the particle shape and collisions**” being submitted by Mr. Govind Sharma to the Indian Institute of Technology Delhi for the award of the degree of Doctor of Philosophy is a bonafide record of original research work carried out by him under my supervision in conformity with rules and regulations of the institute. The results presented in this thesis have not been submitted, in part or in full, to any other University or Institute for the award of any degree or diploma.

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Govind Sharma

ABSTRACT

Direct numerical simulations are carried out to analyze the fluid-particle interactions. This thesis relies on the customization of opensource C++ library —Immersed Boundary Method Adaptive Mesh Refinement (IBAMR)—to model the fluid-particle interactions. Numerical study considers the effect of geometric configuration of particles and particle collision on overall fluid-particle interaction process. The IBAMR is a dedicated Immersed Boundary based software to deal with fluid-structure interactions, and the feature *ConstraintIB* deals with the prescribed kinematic of rigid-body motion based on distributed-Lagrangian-multiplier (DLM) formalism. Utilizing this feature, settling behavior of different-shaped particles are discussed. The settling characteristics are analyzed in terms of Fast-Fourier-transform and phase-space plots.

To realize the effects of particle collision on fluid-particle interaction, a collision strategy is implemented in IBAMR framework. The proposed collision strategy is based on soft-sphere discrete element model; and particles' material properties determine the stiffness parameters. Adopted collision strategy is first validated against the benchmark case of drafting-kissing-tumbling for particle-particle collision. The simulations of varying particle-to-fluid density ratio are conducted using the presented collision model, and results are discussed. To show the efficacy of proposed collision strategy to model the particle-wall interaction, bouncing of a spherical-particle on the rigid wall is studied from viscous to inertial flow-regime. Near wall fluid-particle interactions show the effects of viscous-dissipation on particle rebounding, and particle comes to rest in subsequent rebounds after losing kinetic energy.

The final part of thesis focuses on the interaction between a single-particle and the cluster to mimic the situation of dense and dilute clusters. A statistical observation is presented for cluster sedimentation and its interaction with the single-particle at different Reynolds numbers. The interaction of a single-particle with the cluster reduces the formation of smaller sub-clusters, as the sedimentation is accompanied by horizontal displacement. Vorticity field of cluster evolution shows how a single-particle affects the sedimentation process. This interaction and sedimentation behavior are further analyzed in the context of polydispersity and varying cluster-size.

अमूर्त

द्रव-कण अंतःक्रियाओं का विश्लेषण करने के लिए प्रत्यक्ष संख्यात्मक सिमुलेशन किए जाते हैं। यह थीसिस द्रव-कण इंटरैक्शन को मॉडल करने के लिए ओपनसोर्स सी ++ लाइब्रेरी - इमर्सड बाउंड्री मेथड एडेप्टिव मेश रिफाइनमेंट (आईबीएमआर) के अनुकूलन पर निर्भर करती है। संख्यात्मक अध्ययन समग्र द्रव-कण संपर्क प्रक्रिया पर कणों के ज्यामितीय विन्यास और कण टकराव के प्रभाव पर विचार करता है। आईबीएमआर द्रव-संरचना अंतःक्रियाओं से निपटने के लिए एक समर्पित विसर्जित सीमा आधारित सॉफ्टवेयर है, और कॉन्स्ट्रेंटआईबी सुविधा वितरित-लैंग्रेंजियन-मल्टीप्लायर (डीएलएम) औपचारिकता के आधार पर कठोर-शरीर गति की निर्धारित गतिज से संबंधित है। इस सुविधा का उपयोग करते हुए, विभिन्न आकार के कणों के निपटान व्यवहार पर चर्चा की जाती है। निपटान विशेषताओं का विश्लेषण फास्ट-फूरियर-परिवर्तन और चरण-स्थान भूखंडों के संदर्भ में किया जाता है।

द्रव-कण संपर्क पर कण टकराव के प्रभावों का एहसास करने के लिए, आईबीएमआर ढांचे में एक टकराव रणनीति लागू की गई है। प्रस्तावित टकराव की रणनीति नरम-क्षेत्र असतत तत्व मॉडल पर आधारित है; और कणों के भौतिक गुण कठोरता मापदंडों को निर्धारित करते हैं। अपनाई गई टकराव की रणनीति को सबसे पहले कण-कण टकराव के लिए ड्राफ्टिंग-किसिंग-टंबलिंग के बेंचमार्क मामले के खिलाफ मान्य किया गया है। प्रस्तुत टकराव मॉडल का उपयोग करके अलग-अलग कण-से-द्रव घनत्व अनुपात का सिमुलेशन आयोजित किया जाता है, और परिणामों पर चर्चा की जाती है। कण-दीवार अंतःक्रिया को मॉडल करने के लिए प्रस्तावित टकराव रणनीति की प्रभावकारिता दिखाने के लिए, कठोर दीवार पर एक गोलाकार कण के चिपचिपे से जड़त्वीय प्रवाह-शासन तक उछलने का अध्ययन किया जाता है। दीवार के पास द्रव-कण अंतःक्रिया कण रिबाउंडिंग पर चिपचिपापन-अपव्यय के प्रभाव को दर्शाती है, और कण गतिज ऊर्जा खोने के बाद बाद के रिबाउंड में आराम करने के लिए आता है।

थीसिस का अंतिम भाग घने और पतले समूहों की स्थिति की नकल करने के लिए एकल-कण और क्लस्टर के बीच बातचीत पर केंद्रित है। क्लस्टर अवसादन और विभिन्न रेनॉल्ड्स संख्याओं पर एकल-कण के साथ इसकी बातचीत के लिए एक सांख्यिकीय अवलोकन प्रस्तुत किया गया है। के साथ एकल-कण की अंतःक्रिया क्लस्टर छोटे उप-समूहों के गठन को कम करता है, क्योंकि अवसादन क्षैतिज विस्थापन के साथ होता है। क्लस्टर विकास का वर्टिसिटी क्षेत्र दिखाता है कि एक एकल कण अवसादन प्रक्रिया को कैसे प्रभावित करता है। इस अंतःक्रिया और अवसादन व्यवहार का आगे बहुविक्षेपण और भिन्नता के संदर्भ में विश्लेषण किया गया है समूह का आकार।

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Nomenclature

ν	Kinematic viscosity
μ	Dynamic viscosity
ρ_r	Particle-to-fluid density ratio
\mathbf{u}	Eulerian velocity field
\mathbf{f}	Eulerian constraint force
\mathbf{g}	Gravitational acceleration
p	Pressure
\mathbf{F}	Lagrangian constraint force
\mathbf{X}	Lagrangian coordinate position
\mathbf{x}	Eulerian coordinate position
ϕ	Angle
D	Diameter
W	Domain width
A_{FFT}	Fast Fourier transform amplitude
f_{FFT}	Fast Fourier transform frequency
\mathbf{U}	Particle velocity field
Re	Reynolds number
Re_p	Particle Reynolds number
H	Domain Height
V_c	Convective velocity
C_d	Drag coefficient
ρ_f	Fluid density
ρ_p	Particle density

Abbreviations

IB	Immersed boundary
LES	Large eddy simulations
IBM	Immersed boundary method
DLM	Distributed Lagrangian multiplier
ALE	Arbitrary Lagrangian-Eulerian
DNS	Direct numerical simulation
AMR	Adaptive mesh refinement
IBAMR	Immersed boundary adaptive mesh refinement
FEM	Finite element method
DKT	Drafting-kissing-tumbling
DEM	Discrete element method
FBM	Fictitious boundary method
FFT	Fast Fourier transform
IBAMR	Immersed Boundary Method Adaptive Mesh Refinement

r	Position vector
ω	Angular velocity
δ	Delta function
d	Distance function
t	Time
D_k	Distance matrix
\mathbf{U}_l	Lagrangian velocity field
Re_t	Reynolds number based on terminal velocity
Re_c	Reynolds number based on convective velocity