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Direct-Forcing Immersed Boundary Method for Mixed Heat Transfer

Ming-Jyh Chern[1], Dedy Zulhidayat Noor[2], Ching-Biao Liao[3] and Tzyy-Leng Horng[4,*]

[1] *Department of Mechanical Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan.*
[2] *Department of Mechanical Engineering, Institut Teknologi Sepuluh Nopember Sukolilo, Surabaya, Indonesia.*
[3] *Department of Water Resources Engineering and Conservation, Feng Chia University, Taichung, Taiwan.*
[4] *Department of Applied Mathematics, Feng Chia University, Taichung, Taiwan.*

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Abstract. A direct-forcing immersed boundary method (DFIB) with both virtual force and heat source is developed here to solve Navier-Stokes and the associated energy transport equations to study some thermal flow problems caused by a moving rigid solid object within. The key point of this novel numerical method is that the solid object, stationary or moving, is first treated as fluid governed by Navier-Stokes equations for velocity and pressure, and by energy transport equation for temperature in every time step. An additional virtual force term is then introduced on the right hand side of momentum equations in the solid object region to make it act exactly as if it were a solid rigid body immersed in the fluid. Likewise, an additional virtual heat source term is applied to the right hand side of energy equation at the solid object region to maintain the solid object at the prescribed temperature all the time. The current method was validated by some benchmark forced and natural convection problems such as a uniform flow past a heated circular cylinder, and a heated circular cylinder inside a square enclosure. We further demonstrated this method by studying a mixed convection problem involving a heated circular cylinder moving inside a square enclosure. Our current method avoids the otherwise requested dynamic grid generation in traditional method and shows great efficiency in the computation of thermal and flow fields caused by fluid-structure interaction.

AMS subject classifications: 74F10, 65M06, 76D05

Key words: Direct-forcing immersed boundary method, fluid-structure interaction, mixed convection.

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*Corresponding author. *Email address:* `tlhorng123@gmail.com` (T.-L. Horng)

Nomenclature

A	dimensionless amplitude
d	dimensionless displacement
D	dimensionless diameter
$\mathbf{f}$	virtual force
$\mathbf{F}$	total force acting on a solid body
H	total heat transfer over body surface
L	dimensionless length
n	normal direction
$\overline{\mathrm{Nu}}$	average Nusselt number
p	dimensionless pressure
P	dimensionless parameter
Pr	Prandtl number
q	virtual heat source
r	dimensionless gyration radius
R	dimensionless radius
Ra	Rayleigh number
Re	Reynolds number
St	Strouhal number
t	dimensionless time
T	temperature, K
$\mathbf{u}$	dimensionless velocity
V	volume of a solid object
W	dimensionless area
x,y	horizontal and vertical cartesian coordinate
x_r	dimensionless recirculation length
Greek symbols	
η	volume of solid (VOS)
ϖ	non-dimensional oscillation angular frequency, $\omega D/u_s$
ω	oscillation angular frequency, s^{-1}
θ	non-dimensional temperature
α	thermal diffusivity
Superscript	
m	time step level
Subscripts	
f	fluid
s	solid
x	Position

1 Introduction

Fluid-structure interactions are common phenomena in flow physics and heat transfer problems, e.g. a uniform flow past cylinders and wind past rotating blades. Simulations of fluid-structure interactions are challenging and difficult. First of all, the configuration of a structure is often complex, so a distorted or unstructured grid is necessary. In addi-