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Numerical methods-VI

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[10-A-02] Simulating Conjugate Heat Transfer Phenomena with Significant Heat Transfer Using the Immersed Boundary Method on a Massively Parallelized System

*ChungGang Li[1], Chien-Chou Tseng[1] （1. Department of Mechanical Engineering, National Cheng Kung University）

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Simulating Conjugate Heat Transfer Phenomena with Significant Heat Transfer Using the Immersed Boundary Method on a Massively Parallelized System

ChungGang Li* and Chien-Chou Tseng*
Corresponding author: cgli@gs.ncku.edu.tw
* Department of Mechanical Engineering, National Cheng Kung University, Taiwan

1 Introduction

Conjugate heat transfer, a fundamental issue with diverse engineering applications including film cooling, heat flux assessment for engines, and heat sink fin design, requires careful consideration, especially in practical scenarios characterized by significant heat transfer. Recognizing the influence of density variation becomes crucial in such instances. The aim of this study is to develop a framework that effectively simulates conjugate heat transfer problems, taking into account the impact of density variation using supercomputer.

2 Numerical Method

To accurately capture the phenomenon of conjugate heat transfer at the interface between the solid and fluid, a solver capable of handling significant heat transfer at low-speed regions is employed. Specifically, the Roe scheme with fifth-order MUSCL and a preconditioning matrix developed by Weiss and Smith [1] are adopted to resolve the Navier-Stokes equation. Furthermore, the Adaptively switched time stepping scheme based on dual time stepping [2] is incorporated to improve temporal accuracy.

3 IBM for Conjugate Heat Tansfer

The authors in [3] have developed an immersed boundary for compressible flow based on a hierarchical grid structure known as the Building Cube Method [4]. This method is employed to handle complex geometries with high computational efficiency.
To address thermal conduction within the solid, a preconditioning approach is used. In this approach, the thermal conduction equation, as shown in Eq. (1), is derived by setting the velocity equal to zero and omitting the pressure derivative to eliminate the pressure wave inside the solid.

$$\frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right).$$

where k is the thermal diffusivity coefficient according to the material.
With this unified scheme, the conjugate heat transfer problem can be effectively solved by the compressible solver. Nevertheless, addressing the fluid-solid interface for IBM remains a challenging aspect. Typically, the condition of identical temperature and heat flux values is applied at the interface using Eq. (2) and (3).

$$T_w = T_f = T_s$$

$$Q_w = -k_f \frac{\partial T_f}{\partial n_f} = -k_s \frac{\partial T_s}{\partial n_s}$$

In this study, the subscripts w, f, and s represent values at the solid body surface, the fluid boundary, and the solid boundary, respectively.
Data communication across the interface between the fluid and solid is essential. However, in the context of IBM and MPI environment, this communication becomes time-consuming and ambiguous.

To address this challenge, a novel approach using IBM for interface treatment is proposed in this research.
Based on the interface boundary condition, three conditions must be satisfied for both the fluid and solid sides:
(i) The no-slip condition for velocity, which is fulfilled in this study using the Immersed Boundary Method (IBM) to ensure the no-slip condition.
(ii) The Neumann condition for pressure, where the gradient of pressure equals zero, commonly adopted in compressible solvers. This condition is also applicable to the solid side as the pressure derivative is eliminated.
(iii) Conservation of energy equation: Instead of using Eq. (2) and (3), the energy conservation principle must be obeyed. Thus, the temperature can be determined through the continuity and energy equations.

4 Results and Discussion

The simulation of the natural convection and heat conduction around and in a horizontal circular pipe is conducted with three different resolutions (0.5mm, 0.25mm and 0.125mm). The computational parameters are listed in Table 1. Figure 2 displays the contours of velocity and temperature. The figures clearly depict the heat conduction within the solid and the flow induced by natural convection resulting from the conjugate transfer on the outer cylinder's surface. Fig. 3 illustrates the normalized temperature distributions on normal lines from the pipe surface at 90 degrees for three different resolutions. The method accurately predicts the temperature on the surface, approximately 0.76, indicating its ability to effectively capture the phenomenon of conjugate heat transfer.

Table 1 Computational Parameter

Diameter	33.5mm (Out) / 16.75mm (In)
Ra. Num	10^5
Temperature (Inner)	325.5 K
Grid size	0.5mm, 0.25mm, 0.125mm
Cell Num.	4,390,912
Thermal diffusivity	0.02563 $Wm^{-1}K^{-1}$(Air) 0.2563 $Wm^{-1}K^{-1}$ (Conduction)
Time step	0.002s

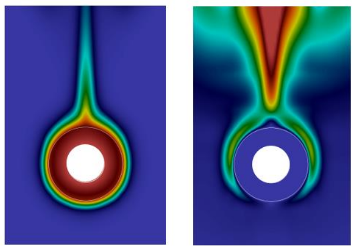

Fig. 2 The contour of the velocity and temperature contour.

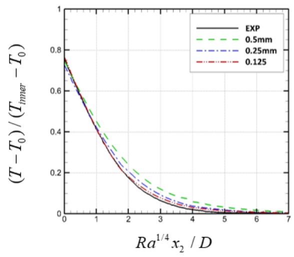

Fig. 3 Temperature distribution.

5. Concluding Remarks

A novel method is developed for conjugate heat transfer using Immersed Boundary Method (IBM) with a compressible solver. This approach unifies governing equations for convection and conduction by setting uniform pressure and zero velocity inside the solid. Velocity and pressure are obtained from IBM, and temperature is determined through energy conservation. This allows direct application of the fluid's numerical algorithm to simulate heat conduction in the solid without modification. Validation through simulations of natural convection and heat conduction around a horizontal circular pipe demonstrates accurate and promising results.

References

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