Amirkabir University of Technology
(Tehran Polytechnic)
Vol. 47, No. 1, Summer 2015, pp. 21- 23

Amirkabir Journal of Science & Research (Mechanical Engineering)
(AJSR - ME)

Immersed Boundary–Thermal Lattice Boltzmann Method with Sharp Interface: Heat Transfer of Non-Newtonian Fluid over a Cylinder

A. Amiri Delouei[1], M. Nazari[2*], M.H. Kayhani[3]

1-Ph.D. Student, Mechanical Engineering Department, Shahrood University of Technology, Shahrood, Iran
2-Asistant Professor, Mechanical Engineering Department, Shahrood University of Technology, Shahrood, Iran
3-Professor, Mechanical Engineering Department, Shahrood University of Technology, Shahrood, Iran

(Received 17 April, 2014, Accepted 23 December, 2014)

ABSTRACT

In the current study, the problem of heat transfer in non-Newtonian fluid flow over a cylinder has been simulated using the Immersed Boundary – thermal lattice Boltzmann method and direct forcing algorithm. The sharp interface scheme is used to transfer the values of velocity and temperature between the fluid Eulerian and boundary Lagrangian nodes. In order to consider the effects of both discrete grid and boundary forces (thermal forces), the split-forcing lattice Boltzmann method is developed for non-Newtonian power-law fluids**.** A simple technique for calculating the Nusselt number based on the sharp immersed boundary method is extracted. Heat transfer of different fluid regimes consist of steady and unsteady flow in wide ranges of Reynolds numbers (20<Re<80) and power-law indices (0.6<n<1.4) has been investigated. It is found that the increment of the shear-thinning and shear-thickening behavior of the fluid leads to an increase and decrease of heat transfer rate of immersed body, respectively. In future studies, the proposed algorithm will be used as a suitable method for thermal modeling of moving bodies in non-Newtonian fluids.

KEYWORDS

Immersed Boundary Method, Thermal Lattice Boltzmann Method, Sharp Interface Scheme, Non-Newtonian Fluid, Heat Transfer.

* Corresponding Author, Email: mnazari@shahroodut.ac.ir

1- BRIEF INTRODUCTION

Recently, new methods based on “Immersed boundary” idea of Peskin [1] are developed which are suitable for solving the problems with complicated geometries. In the immersed boundary method (IBM), a fixed Eulerian mesh grid represents the fluid domain and the immersed body is considered as Lagrangian points. Immersed boundary method can be defined as a non-body-conformal grid method that satisfies the no-slip boundary condition (or thermal boundary condition) by implementing a force density (or an energy source density) term to the flow governing equation (or the energy equation). The momentum equation can be solved using common methods like finite difference and finite volume methods or by using the more progressive lattice Boltzmann method. The common feature of “Cartesian grid” for immersed boundary method and Lattice Boltzmann methods is the main factor in the development of the hybrid immersed boundary thermal lattice Boltzmann method (IB-LBM). Although IB-LBM is used for investigating the Newtonian flow and heat transfer problems, the implementation of this method for Non-Newtonian mediums is so rare. Developing an immersed boundary-thermal lattice Boltzmann method (IB-TLBM) with sharp interface scheme for non-Newtonian flows is the main contribution of the current study. Introducing a simple technique for calculating the Nusselt number based on the predetermined parameters of sharp IB-TLBM is another object of this paper. In addition, the split-forcing algorithm is used to apply the effect of non-isothermal body on non-Newtonian fluid domain which leads to recover the both momentum and energy equation with second-order accuracy.

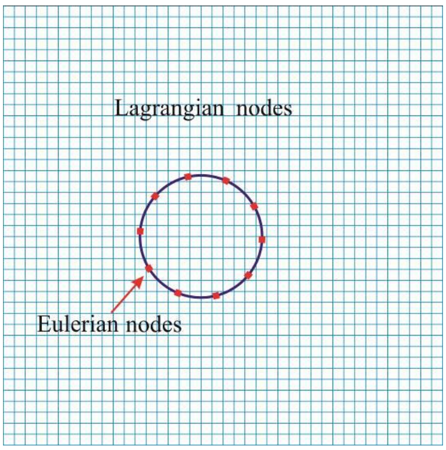

Fig.1. Schematic of immersed boundary method

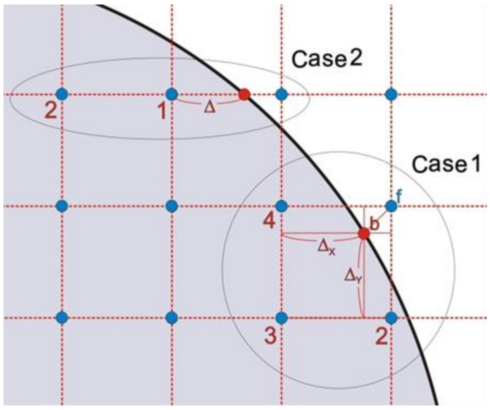

Fig.2: Schematic of sharp interface scheme

2- NUMERICAL METHOD

In this study, a two population thermal lattice Boltzmann approach is used for solving the momentum and energy equation on Eulerian nodes [2]. Likewise, the split-forcing approach [3] is employed to more accurate apply of the immersed body on flow field. The power-law non-Newtonian model [4] has been selected to investigate the shear-thinning and shear-thickening non-Newtonian flow around a heated cylinder at different regimes. A direct-forcing method has been applied to calculate the boundary forcing and energy forcing on immersed body. This method is extracted based on split-forcing immersed boundary method [2]. The sharp interface scheme proposed by Kim et al. [5] is used to link between Eulerian and Lagrangian nodes both in momentum and energy equations. Concerning the accessible unforced fluid nodes, the following bilinear and linear interpolations are applied for case 1 and case2 (which are addressed in Fig. 2), respectively:

$$\vec{u}_f = \frac{1}{\Delta_x \Delta_y}\{\vec{U}_b - (\Delta_x(1-\Delta_y)\vec{u}_2 + (1-\Delta_x)(1-\Delta_y)\vec{u}_3 + (1-\Delta_x)(1-\Delta_y)\Delta_y \vec{u}_4)\}, \tag{1a}$$

$$\vec{u}_f = \begin{cases} \dfrac{1}{\Delta}\vec{U}_b - \dfrac{1-\Delta}{\Delta}\vec{u}_1 & if \ ,\Delta \ge 0.5 \\ 2\vec{U}_b - 2\Delta\vec{u}_1 - (1-2\Delta)\vec{u}_2 & if \ \Delta \le 0.5 \end{cases} \tag{1b}$$

The same interpolation processes can be considered for temperature, too. Also, A simple technique has been developed for calculating the Nusselt number in the direct-forcing IB-TLBM inspired by the scheme of Wu et al. [6].

3- RESULTS

The present numerical simulation has been successfully validated thoroughly by comparing the present results for two test cases: first, a pressure driven flow of power-law fluid inside a channel; second, the flow of Newtonian fluid past a heated circular cylinder (Table 1).

Table 1. Average Nusselt number for steady and unsteady Newtonian fluid flows over a heated cylinder.

	Year	Re=40, Pr=1.0	Re=80, Pr=0.7
Soares et al. [7]	2005	3.569	---
Beharti et al. [8]	2007	3.703	---
Patnana et al. [9]	2010	3.675	---
Wu et al. [6]	2012	---	4.611
Current study	2015	3.685	4.597

Table 2 shows the values of average Nusselt number and drag coefficient at different Reynolds numbers for Newtonian, shear-thinning, and shear-thickening fluids. Regarding Table 2, the values of average Nusselt number increase with the growth of Reynolds number in all power-law indices. Nevertheless, for the drag coefficient, a contrary trend is observed in both steady and unsteady flows.

Table 2. Values of average Nusselt number and drag coefficient in different Reynolds number for shear-thinning, Newtonian and shear thickening fluid flow (Pr=1).

		n=0.6	n=0.8	n=1.0	n=1.2	n=1.4
Re=20	Nu	3.063	2.917	2.771	2.681	2.592
	C_D	1.779	1.994	2.075	2.173	2.258
Re=40	Nu	4.134	3.885	3.685	3.540	3.394
	C_D	1.232	1.400	1.537	1.647	1.749
		n=0.7	n=0.85	n=1.0	n=1.2	n=1.4
Re=60	Nu	4.864	4.634	4.403	4.217	4.032
	C_D	1.214	1.290	1.407	1.472	1.533
Re=80	Nu	5.731	5.454	5.180	4.856	4.535
	C_D	1.168	1.244	1.377	1.463	1.564

4- CONCLUSION

The split-forcing IB-TLBM can be considered as a suitable method for investigating the non-Newtonian fluid flow and heat transfer. Employing the sharp interface scheme in IB-TLBM is the cause of exact satisfying the no-slip and thermal boundary conditions in both steady and unsteady flows. The simple technique based on predetermined parameters of sharp IB-TLBM is developed for calculating the Nusselt number which can reduce the complexity and numerical cost of simulation. The results of this study show that the hydrodynamic and thermal properties of fluid flow are very sensitive to power-law index.

5- MAIN REFERENCES

[1] Peskin, C.S., "Flow patterns around heart valves: a digital computermethod for solving the equations of motion", PhD thesis, Physiol, Albert Einstein Coll. Med., Univ. Mi- crofilms., Vol. 378, 1972.

[2] Kang, S.K., Hassan, Y.A., "A comparative study of direct-forcing immersed boundary-lattice Boltzmann methods for stationary complex boundaries", Int. J. Numer. Meth. Fluids., vol. 66, pp. 1132– 1158, 2011.

[3] Guo, Z., Zheng, C., Shi, B., "Discrete lattice effects on the forcing term in the lattice Boltzmann method", Physical Review E., vol. 65, pp. 046308, 2002.

[4] Wang, C.H., Ho, J.R., "A lattice Boltzmann approach for the non-Newtonian effect in the blood flow", Comput. Math. Appl., vol. 62, pp. 75– 86, 2011.

[5] Kim, J., Kim, D., Choi, H., "An immersed-boundary finite-volume method for simulations of flow in complex geometries", J. Comput. phys., vol. 171, pp. 132– 150, 2001.

[6] Wu, J., Shu, C., Zhao, N., "Simulation of Thermal Flow Problems via a Hybrid Immersed Boundary-Lattice Boltzmann Method", Journal of Applied Mathematics, Article ID 161484, 2012.

[7] Soares, A.A., Ferreira, J.M., Chhabra, R.P., "Flow and forced convection heat transfer in cross flow of non-Newtonian fluids over a circular cylinder". Ind. Eng. Chem. Res., vol. 44, pp. 5815– 5827, 2005.

[8] Bharti, R.P., Chhabra, R.P., Eswaran, V., "Steady forced convection heat transfer from a heated circular cylinder to power-law fluids". Int. J. Heat Mass Transfer, vol. 50, pp. 977– 990, 2007.

[9] Patnana, V.K., Bharti, R.P., Chhabra, R.P., "Two-dimensional unsteady forced convection heat transfer in power-law fluids from a cylinder". International Journal of Heat and Mass Transfer, vol. 53, pp. 4152– 4167, 2010.