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# The Use of Lattice Boltzmann Numerical Scheme for Contaminant Removal from a Heated Cavity in Horizontal Channel

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Abstract

This paper aims to study the effect of mixed convection heat transfer on the contaminant removal in a channel with a rectangular cavity. The lattice Boltzmann method is used to solve the fluid part while, the particle dynamics are modelled using the Lagrangian method. The cold fluid is forced to flow inside channel while the bottom wall of the cavity is heated and kept at a constant temperature. The effect of Grashof number in removal percentage at a constant Reynolds number is addressed in this work. It is found that the rate of contaminant removal can be increased by increasing the Grashof number at particular flow Reynolds number.

*Keywords: Lattice Boltzmann method, Solid particles, mixed convection, Heat transfer*

## 1. Introduction

Knowledge of the particle motion in fluid flow is central in many natural and industrial applications. Examples are sediment grains in rivers, cloud particles in the atmosphere, fluidized beds and fluid-solid cyclone separators. Comprehending the major mean particle- fluid flow phenomena, such as fluid-solid interaction and particle removal or mixing, is crucial for the environmental management and design and operation of such engineering equipment. A major limitation, in the problem of particle motion in fluid flow, is the insufficient information about the interaction between the fluid dynamic parts and solid particle flows. Analyzing the hydrodynamic removal of contaminants from the process equipment is one of the related studies, based on this knowledge. The excellence of the cleaning process is a matter of interest for the product quality, especially in chemical and food industries. On the other hands, the applications of heat transfer are numerous in the mentioned fields. However, there are few studies deal with the hydrodynamic removal under the effect of convective heat transfer.

### *1.1 Literature Review*

Till present day, only a few papers have been reported to experimentally investigate this kind of multiphase flow. It is believed that the main reason of lack of experimental research on the fluid-solid interaction phenomenon is the complicated nature of the problem. The size of

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solid particles can be as big as grains seed or very tiny such as dust pollutant. To the best of authors' knowledge, only Tsorng et al. [1] reported details experimental results on the behaviour of solid particles in lid-driven cavity flow from micro to macro size of particles without thermal effects analysing. Other experimental works are Adrian [2], Matas et al. [3], Ushijima and Tanaka [4], Ide and Ghil [5]. However, according to these papers, high accuracy of laser equipment together with high-speed digital image capture and data interpretation system is required to obtain reliable experimental data. Such these high cost experimental devices will not be affordable if not supported by research fund.

The computational efforts to study fluid-solid interaction have continued in the meantime, in parallel with the advancement in the global interests and technologies. Kosinski et al. [6] provides extensive numerical results on this subject. From the behavior of one particle in a lid-driven cavity flow to thousands of particles in expansion horizontal pipe has been studied in their research works. Kosinski et al. applied the combination of continuum Navier-Stokes equations to predict fluid flow and second Newton's law for solid particle. In the last few decades, lattice kinetic theory in the form of Lattice Boltzmann method has significant success for numerical study at various types of fluid flow problem[7-10]. They have demonstrated that the LBM is a powerful numerical tool in solving fluid flow parameters. There are some valuable LBM studies related to the solid fluid suspensions. Some interesting applications in treatment of fluid- particle interaction areas were carried out by Ladd[11, 12] and Behrend [13]. In the model of Ladd, an approximation was used to simulate the particles moving boundaries, and the distribution function is defined for grid points inside and outside the particle. In the suspensions of macroscopic particles (i.e. larger than 10μm), where the viscous forces alone are important, the fluctuation is ignored in lattice Boltzmann method. Moreover, a lot of research studies addressed the effect of different fluid properties in heat transfer variation by applying the lattice Boltzmann method. Karimipour et al. [14] investigated the effect of the variations of Richardson number and inclination angle on the thermal and flow behaviour of the fluid inside the lid driven cavity. In another attempt, Alamyane and Mohamad [15] simulated the forced convection in a channel with extended surfaces and addressed the effect of Reynolds number variation on heat transfer rate. Subhash et al. [16] in a parametric study compared FVM and LBM in the effects of the conduction – radiation parameter, extinction coefficient, scattering albedo and enclosure aspect ratio. Fattahi et al. [17] investigated the effects of eccentricity on mixed convection heat transfer on eccentric annulus by lattice Boltzmann method base on multi- distribution function double population approach. However, to the best of authors' knowledge, there is no fundamental study on the application of thermal LBM for prediction of solid fluid flow. Current research has two major objectives. The first is to extend the method for the integration between the meso-scale of LBM and the macro-scale of physical condition. The second objective is to shed the light on the fluid-solid interaction phenomenon that take place in an expansion pipe channel under the effects of heat transfer, which has not fully covered in the literature. The parameters of major concern herein are the vortex structure, rate of contaminant removal and the percentage of removal at the steady state.

## 2. Physical model and numerical method

The geometry of duct-cavity configuration utilized in this study is shown in Fig. 1. The cavity is filled with contaminant at zero velocity of surrounding fluid. Then, at the inlet, a parabolic profile of flow velocity is introduced. The properties of contaminated flow supposed to be the same as for the fluid flowing in the channel. As also can be seen from the figure, the bottom of the cavity is constantly heated to investigate the effect of buoyancy force on the rate of contaminant removal. No-slip boundary conditions are imposed at all solid boundaries. The boundary condition for the temperature is T=0 at the inflow boundary. The insulated boundaries are assumed at the walls and at outflow as well. The present study covers the Grashof number 1-4000 for a cavity of aspect ratio 4 and at Reynolds number of 50.

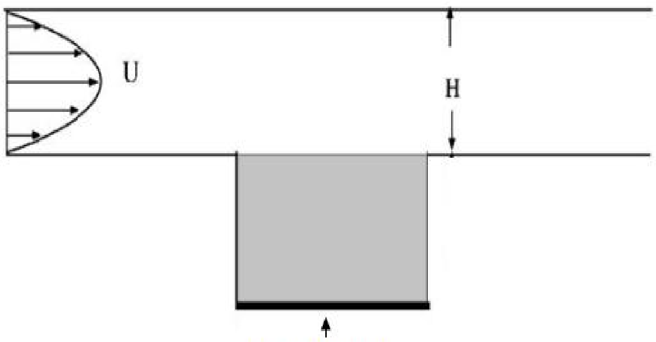


Figure 1. Geometry of the present case study

### 2.1 The lattice Boltzmann Numerical Scheme

The LBM originate from the kinetic Boltzmann equation derived by Ludwig Boltzmann (1844-1906) in 1988. It considers a fluid as an ensemble of artificial particles and explores the mesoscopic features of the fluid by using the propagation and collision effects among these particles. LBM discretizes the whole flow region into a number of grids and numerically solves the simplified Boltzmann equation on the regular lattices. The solution to the lattice Boltzmann equation converged to the Navier-Stokes solution in continuum limit up to second order accuracy in space and time.

The thermal LB model employed two distribution functions, for the flow and temperature fields as follow [18]:

fields as follow [18]:

$$f^i(x + c\Delta t, t + \Delta t) = f^i(x,t) - \frac{1}{\tau f}[f^i - f^{i\,eq}] + F \quad (1)$$

$$g^i(x + c\Delta t, t + \Delta t) = g^i(x,t) - \frac{1}{\tau f}[g^i - g_i^{eq}] \quad (2)$$

where distribution function $f$ and $g$ are used to predict the velocity and temperature fields respectively. $f^{eq}$ and $g^{eq}$ are the equilibrium distribution functions. In order to incorporate buoyancy force in the model, the force term in Eq.(1) need to be calculated as follow:

buoyancy force in the model

$$F = 3w^i g^y \beta (T - Tm) \quad (3)$$

where $w$ is the weighting factor in the lattice fluid density and $T_m$ is the mean temperature. The Boussinesq approximation is applied to include the effects of convection into the lattice Boltzmann formulation. To ensure that the code works in near incompressible regime, the characteristic velocity of the flow for both natural ( $V_{natural} \equiv \sqrt{\beta g_y \Delta T\, H}$) and force ($V_{force} \equiv \frac{Re.v}{H}$) regimes must be small compared with the fluid speed of sound.

The macroscopic variables such as the density, fluid velocity and temperature can be computed in terms of the particle distribution functions as

The macroscopic
computed in terms

$$\rho = \int_i f^i dc$$

$$\rho u = \int_i c_i f^i dc$$

$$T = \int_i g^i \, dc \tag{4}$$

Through the multi-scaling expansion, the mass and momentum equations can be derived for the D2Q9 model of the evolution equation of the density distribution function. Details derivation can be found in [19].

### *2.2 The flow of the particles*

In this investigation, we only consider 500 particles inside the cavity and assume that the presence of solid particles has no effect on the fluid flow. The equation of motion for solid particles can be written as

$$m_p \frac{dV_p}{dt} = f_p \tag{5}$$

where $m_p$, $V_p$ and $f_p$ are the mass of particle, its velocity and drag force acting on particle due to surrounding fluid. According to Kosinski et al, the drag force can be written as follows

$$f_p = \frac{C_D A_p \rho \left(|U - V_p|(U - V_p)\right)}{2} \tag{6}$$

where $A_p$ is the projected area of solid particle in flow direction and $C_D$ is the drag coefficient which is defined as:

$$C_D = \frac{24}{Re_p}\left(1 + \frac{1}{6} Re_p^{\frac{2}{3}}\right) \tag{7}$$

Where $Re_p$ is the Reynolds Number of solid particle. The density of solid particles and fluid to be assumed the same and the size of particle must be smaller than lattice size.

## 3. Results and Discussion

In the present analysis, the transient hydrodynamic removal of solid particles from a bottom heated cavity is presented. In the simulation, the Reynolds number is set at 50 based on the maximum inlet flow velocity and the channel height.

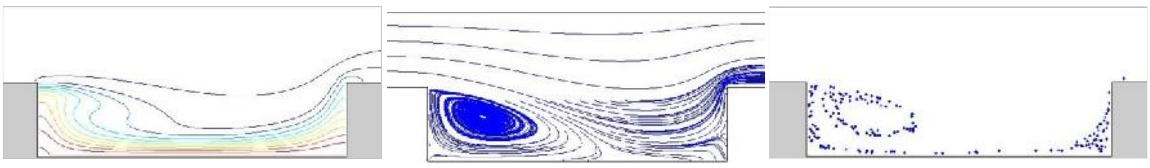

Figure 2. Isotherms, streamline and contaminant scatter for Grashof number = 1

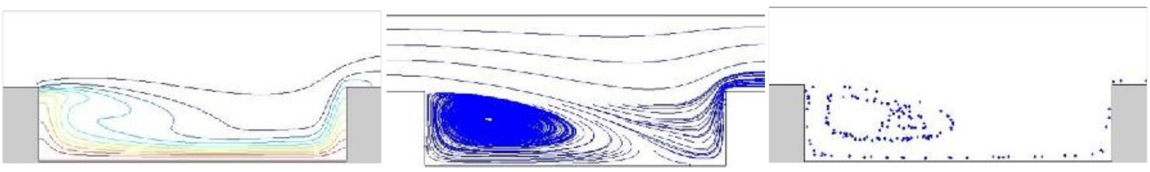

Fig. 3: Isotherms, streamline and contaminant scatter for Grashof number = 1000

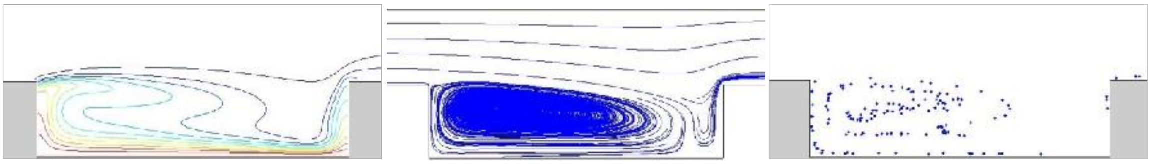

Figure 4. Isotherms, streamline and contaminant scatter for Grashof number = 3000

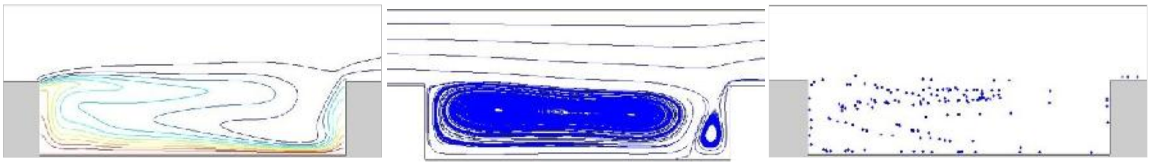

Figure 5. Isotherms, streamline and contaminant scatter for Grashof number = 4000

Figures 2 to 5 show the plots of isotherms, streamline and contaminant scatter for different dimensionless Grashoff number. As can be seen from the figures that the vortex size getting bigger and bigger when we increase the Grashoff number. This indicates that flow is well mixed at high value of Grashoff number.

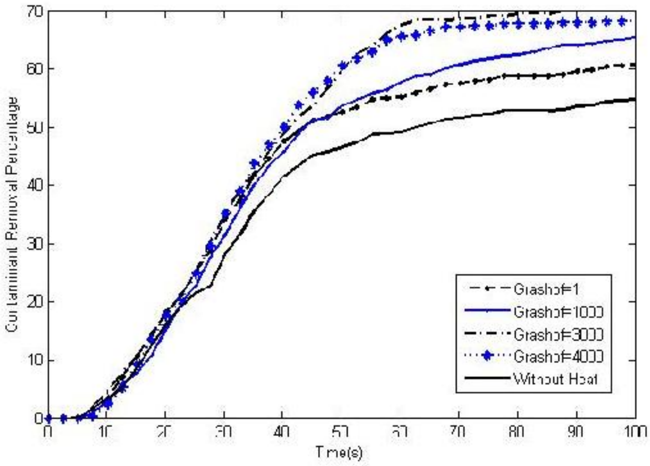


Figure 6. Removal percentage of contaminant from a bottom heated cavity at various values of Grashof number

The current investigation is wrapped by examining the rate of contaminant removal at different values of Grashof number. Figure 6 displays such implication for Re = 50 and Grashof number from 1 to 4000. The figure demonstrate that as we increase the value of Grashof number, the buoyancy force becomes stronger and drag the particles upward before they were flushed by the main stream of the flow. The rate of contaminant removal has a dramatic increase during the unsteady start up and has the maximum value at the early phase of particle motion.

## 4. Conclusion

The effect of temperature gradient inside a cavity in a horizontal channel on the rate of contaminant removal has been numerically studied. The investigation was carried out for a fixed value of Reynolds number and wide range of Grashof number. The presented results captured at the steady state of solution for both fluid and particles. Such results show that the Grashof number has a profound effect on the rate of contaminant removal from the cavity. It can be seen that the cleaning process is improved as Grashof number enlarged due to the interaction between the external duct flow and buoyancy induced flow come up from a thermal source. It should be mentioned for Reynolds number 50, the Grashof number 4000 is critical value and steady state result could not be achieved in higher Grashof number due to oscillatory behaviour of flow.

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