Simulation of Nano Fluid Flow and Natural Convection Heat Transfer in an Incinerator Shaped Cavity Containing a Heated Block

Muthuraman Subbiah*
Department of Mechanical Engineering, Higher College of Technology, Muscat, Oman

Abstract

The present work reports a numerical investigation of characteristic convection in an incinerator molded nook with a limited warmed source arranged at the base. Grid Boltzmann Method (LBM) is utilized to reproduce Nano liquid (water-Al₂O₃) stream and warmth exchange. Reproductions have been completed for the relevant parameters: Rayleigh number \((Ra=10^{3}-10^{6})\), relative warmth source high \((0 \leq \delta \leq 0.5)\), and relative warmth source width \((\varepsilon=0.02-0.8)\). The correlation of the acquired outcomes is in amazing concurrence with results from writing. I might be noticed that the increments of the Rayleigh number \((Ra=10^{3}-10^{6})\), the strong volume portion, and the warmth source stature \((\delta=0.1-0.5)\) improve the warmth exchange and impacts the stream design and the warmth structures and the warmth exchange rate measured by the Nusselt number. However for the relative warmth source width \((\varepsilon=0.02-0.8)\), it assumes inverse part for qualities better than 0.4.

Keywords: Heat transfer; Incinerator geometry; Lattice Boltzmann method; Natural convection; Nano fluid

Introduction

Augmentation of heat transfer is an important goal in generating energy systems. Different mechanisms of heat transfer enhancement have been highlighted in the literature focusing mainly on modifying the geometry and other techniques which are well documented [1]. Recently, an innovative way of heat transfer enhancement is the use of nano-suspensions (particles, fibers) of relatively higher thermal conductivities suspended in the base fluids. The obtained solution is called nano fluid which is introduced first by Choi [2]. Nano fluids are referred to the fluids with suspensions of nanoparticles having a diameter below 100nm. According to Mahbubul et al. [3], Nano fluids are a solid-liquid mixture which consists of nanoparticles and a base liquid. Nanoparticles are basically metal (Cu, Ni, Al, etc.), oxides (Al₂O₃, TiO₂, CuO, SiO₂, Fe₂O₃, Fe₃O₄, BaTiO₃, etc.) and some other compounds (AlN, SiC, CaCO₃, graphene, etc.) and base fluid usually include water, ethylene glycol, propylene glycol, engine oil, etc.

The main aim of the present paper is to investigate numerically the heat transfer rate and the fluid flow in nanofluid filled incinerator shaped geometry. A heated block is situated on the bottom wall of the incinerator, whereas the vertical walls are considered cold and the top wall is supposed to be adiabatic. Lattice Boltzmann method (LBM) is applied to solve the coupled momentum and energy equations [4]. The grid independency test and the validation of the present model are conducted on simple cavity cases. The effects of Rayleigh number, heat source width and high on flow, thermal fields and Nusselt number are presented and discussed.

Physical Model and Mathematical Formulation

Figure 1 shows an incinerator shaped enclosure of length \(L\) and high \(H\). The heat source at high temperature \(T_h\) is located at the bottom surface of the cavity and has the width \(a\) and high \(b\). The other parts of the bottom wall and the ceiling are considered adiabatic. The remaining walls of the cavity are cold. The flow is steady, laminar and incompressible; all the thermo physical properties of the fluid are constant, except for the density in the buoyancy term which follows the Bossiness approximation. The base fluid and the nanoparticles are assumed to be in thermal equilibrium and the nano fluid is Newtonian [5,6].

Lattice Boltzmann method

The lattice Boltzmann equation with Bhatnagar-Gross-Krook (BGK) collision mode, for incompressible problems, uses two distribution functions, \(f\) and \(g\), for the flow and temperature fields respectively. For the flow field, the discretized LBM equations can be written as:

\[
\frac{\partial f_i}{\partial t} + u_i \frac{\partial f_i}{\partial x_i} = \frac{1}{\tau} (f_i - f_i^{BGK})
\]

\[
\frac{\partial g}{\partial t} + u_i \frac{\partial g}{\partial x_i} = \frac{1}{\tau} (g - g^{BGK})
\]

*Corresponding author: Subbiah M, Higher college of Technology. Department of Mechanical Engineering, Muscat, Oman, Tel: +968-9618814; Fax: +968-24398814; E-mail: muthu9678@gmail.com

Received January 17, 2017; Accepted June 11, 2017; Published June 20, 2017

Citation: Subbiah M (2017) Simulation of Nano Fluid Flow and Natural Convection Heat Transfer in an Incinerator Shaped Cavity Containing a Heated Block. Fluid Mech Open Acc 4: 160. doi: 10.4172/2476-2296.1000160

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\[ f_i(x + c \Delta t + \Delta t) - f_i(x, t) = \frac{1}{\tau_v} \int f_i(x, t) \cdot f_i^n(x, t) + \Delta F_i \] (1)

For the temperature field

\[ g_i(x + c \Delta t + \Delta t) - g_i(x, t) = \frac{1}{\tau_v} \int g_i(x, t) \cdot g_i^n(x, t) \] (2)

Where \( \Delta t \) denotes the lattice time step which is set to unity and \( \tau_v, \tau_c \) are the relaxation times for the velocity and temperature fields, respectively.

**Boundary conditions**

The solid walls are assumed to be no slip. Thus, by applying the bounce-back scheme at the boundary nodes, the outer distribution functions from the domain are known from the streaming process. The north and south boundaries are adiabatic, as a consequence; bounce back boundary condition is used. Temperatures at the remaining walls of the incinerator walls are known (Figure 1).

**Lattice Boltzmann method for nanofluid**

The nanofluid behavior is assumed to be similar to a single phase fluid. The effective density \( \rho_{ef} \), the thermal expansion coefficient \( \beta_{ef} \), heat capacitance \( C_{p,ef} \), and thermal diffusivity of the nanofluid are defined as follows:

\[ \rho_{ef} = (1-\phi)\rho_f + \phi \rho_p \]  
\[ \beta_{ef} = \beta_f + \phi (\beta_p - \beta_f) \]  
\[ \mu_{ef} = \mu_f \left(1-\phi\right)^{2.5} \]  
\[ \rho C_{p,ef} = (1-\phi)\rho C_{pf} + \phi \rho C_{pp} \]  
\[ \alpha_{ef} = k_{ef}/\rho C_{p,ef} \]  
\[ k_{ef} = k_f \left( k_p + 2k_f - 2\phi(k_p + k_f) \right) \] (8)

**Non dimensional parameters**

In the LBM simulations the Rayleigh number, Prandtl number and Mach number are assigned constant values therefore the viscosity and thermal diffusivity are calculated from the definition of these non dimensional parameters.

\[ \nu = n Ma c_s \sqrt{Pr/ Ra} \] (9)

Where \( n \) is the number of lattice nodes in y-direction. To insure an incompressible flow the Mach number was chosen as \( Ma \leq 0.1 \). The overall heat transfer rate on the heat source is described by the Nusselt number \( Nu \) which is given by:

\[ Nu = \left( \frac{\partial \phi}{\partial X} \right)_{\text{Heat Source Wall}} \] (10)

**Results and Discussions**

In this paper natural convection inside an incinerator shaped enclosure filled with Al\(_2\)O\(_3\)-water nanofluid and having a hot rectangular source situated in the middle of the bottom face have been investigated. Steady state results are presented for different dimensionless parameters: Rayleigh number \((10^3 \leq Ra \leq 10^6)\), relative hot source high \((0 \leq \delta \leq 0.5)\), and relative heat source width \((\varepsilon=0.02-0.8)\). Results are presented as streamlines, isotherms, and average Nusselt numbers (Figure 2).

Effect of Rayleigh number (Ra)

Figure 3 shows the effect of Rayleigh number on streamlines and isotherms inside an incinerator including a hot rectangular heat source \((\varepsilon=0.2, \delta=0.5)\) and filled with pure water (dashed lines) and Al\(_2\)O\(_3\)+H\(_2\)O nanofluid (solid lines). \(x=0.5\) represents a symmetric plane for both isotherms and streamlines. For low Rayleigh numbers \((Ra=10^3-10^4)\), isotherms are parallel to the three faces of the hot source and are perpendicular to the bottom surface of the incinerator and horizontal thermal like stratification is formed around the heater. Streamlines form two counter rotating big cells from either parts of the heater. Increasing Rayleigh number to \(Ra=10^5\), convection currents are more expressed and the isotherms are slightly tightened near hot walls to form a thermal boundary layer and the stratification is distorted. The streamlines still form a symmetric cells more elongated to the top due to the ascendant fluid motion and are occupying the whole medium below \(y=0.7\).

For \(Ra=10^6\) the symmetry of the flow and thermal behavior is broken. One can remark the formation of two new counter rotating cells of different sizes (Figure 3).

These two cells are formed due to the like Rayleigh-Benard convection that hold at the upper wall of the heat source, where the upper corner of the two big cells serve as moving (lid) boundary conditions to the formations of the small cells. It is also worth to mention that the big rotation cells take the geometric forms of the surrounding space due to the intensified pressure. For the isotherms, boundary layers are clearly formed near the isotherm (hot and cold) walls and a like vertical stratification is formed between vertical walls of the heater and those of the incinerator. The former two small cells intensify the heat transfer rate from the upper heater wall.

Figure 3 illustrates the effect of Rayleigh number on streamlines and isotherms inside the incinerator shaped cavity for pure fluid (water) and nanofluid with \(\varphi=4\%\). For \(Ra=10^7\) the isotherms are parallel to the heat source faces indicating a pure conduction regime and the nanoparticles addition does not have any remarkable effect on temperature profiles.

Inside the incinerator two symmetric contrarotative cells are formed. The left cell is rotating anti-clockwise. The right cell is rotating clockwise. For the case of nanofluid, the shape of streamlines is the
same as the case of pure fluid; however the minimum and maximum values of stream function are changed. This is due to the fact that the effective viscosity of Al₂O₃ nanofluid is higher than that of the pure fluid. Therefore the friction inside the nanofluid is augmented and the opposition of the nanofluid to the flow is increased. The problem under consideration is always symmetric and the calculation of the local Nusselt number gives similar results on the left and right walls of the heat source (Figure 4).

Effect of the heater high

The effect of the heater dimensionless height (δ) on the isotherms and streamlines is demonstrated in Figure 3. In this section the heater dimensionless high is varied from 0.1 to 0.5 and its width is fixed at ε=0.2 in the middle of the incinerator for all simulations. For all considered Rayleigh numbers (Ra=10⁵-10⁶) the isotherms and flow structures exhibits a symmetrical patterns from either sides of the heater as shown in Figure 3. For Rayleigh numbers 10⁴ and 10⁵ isotherms are parallel to the heater vertical walls. This behaviour is more pronounced with the augmentation of the heater dimensionless high. At the heater to facet, isotherms are also parallel to the horizontal surface. The distance between isotherms decreases by increasing heater dimensionless high. Two symmetric counter rotating cells are formed. The right cell is rotating clockwise and the let one is rotating anti-clockwise.

For Rayleigh numbers 10⁵ and 10⁶ (Figure 3), isotherms are parallel to the heater vertical walls and are very smoothed near the vertical walls. However for the top face of the heater, isotherms have a parabolic shape. This parabolic shape is well shown with increasing the Rayleigh number. For δ=0.3 and Ra=10⁶, isotherms T=0.05 are perpendicular to the top face of the incinerator which is adiabatic. Increasing δ from 0.3 to 0.4 at Ra=10⁶, the isotherms T=0.05 is at a position equal to 0.82; this can be explained by the fluid motion (stream function) where we can see the formation of two cells on the top face of the heater source which are counter-rotating. The isotherms shape is reversed from the top of the incinerator to top side of the heater source. The thermal boundary layer thickness at the bottom side of heater source is decreased. This can be explained by the formation of two new contra-rotative cells at the top face of the heater. These two cells contribute to the redistribution of energy to the left and right inclined walls and minimize the heat transfer to the top of the incinerator. Therefore on the two inclined sides of the incinerator the thermal boundary layer thickness is shown to decrease.
Figure 4 shows that the average Nusselt number on the left side of the incinerator increases as the relative heat source height increases. This is evident because if $\delta$ is increased more energy is introduced to the medium.

Figure 5 show respectively the effect of relative heat source width on isotherms, streamlines and average Nusselt number for $Ra=10^5-10^6$ and $\varepsilon=0.02-0.8$ in the case of pure water. The height of the heat source $\delta$ is maintained constant at 0.2.

Figure 5 demonstrate that the heater dimensionless width increases (with $Ra=10^5$) leads to formation of two symmetric cells which occupy the whole of the free space of the incinerator. Isotherms are normal to the adiabatic bottom incinerator wall and are tightened near the heater vertical sides.

For $Ra=10^6$ and $\delta=0.4$ the symmetry of isotherms is broken, it is well pronounced for $\delta=0.6$ where we can see that the two symmetric cells are broken to give four cells; one big cell situated at the top side of that heater and three other little eddies two on the right side and the third at the left side of the incinerator. The symmetry of isotherms is also broken and we can see the formation of thin boundary layer on the faces of the heater block and on the cold inclined walls of the incinerator.

For $Ra=10^6$ and $\varepsilon=0.8$, Figure 5 show the formation of six eddies occupying the whole area of the incinerator, results are quasi-symmetric and energy is transferred to the total area of the studied medium which gives also quasi-symmetric isotherms. The regime is unsteady due to the Rayleigh-Bénard like situation.

**Effect of the heater width**

Figure 6 shows the effect of relative heat source width on average Nusselt number on the left side of the hot source. One can see easily that if the relative height $\varepsilon$ is inferior to 0.6 and $Ra=10^5-10^6$, the average Nusselt number increases slightly with increasing relative heat source.

**Conclusion**

Natural convection flow and heat transfer enhancement by Al$_2$O$_3$ nanosuspensions in an incinerator shaped enclosure containing a rectangular hot block is investigated in the present study. An in-depth analysis of the monitoring parameters effects on the flow and thermal structures and the heat transfer enhancement is conducted by help of a SRT thermal lattice Boltzmann model.

From this study, the following conclusions are drawn:

- Based on the quantitative and qualitative validation, the excellent agreement between our results and former experimental and numerical data let us to rely on the powerfulness of the LB method to scrutinize such a two-phase like problem.
The Rayleigh number increase enhances heat transfer for both pure fluid and nanofluid.

The addition of nanoparticles to the base fluid leads to the decrease of the activity of the fluid motion measured by the stream-function magnitude and causes a substantial increase in the heat transfer rate.

The heat source tallness increase enhances the heat transfer for all its tested values and all Rayleigh numbers. However, the relative heat source width plays opposite role for dimensionless values superior to 0.4.

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