



# Numerical Simulation of Flow, Natural Convection and Distribution of Nano Particles inside Trapezoidal Cavity using Buongiorno's Model

M. Bashiri\*, S. Jafarmadar, S. Yekani Motlagh, S. Khalil Arya

Department of Mechanical Engineering, Urmia University, Urmia, Iran

**ABSTRACT:** In the present study, natural convection of  $Al_2O_3$ -water nanofluid and nano-particles local distribution inside the trapezium enclosure has been investigated using non-homogenous two-phase Buongiorno's model. The governing equations of the problem are momentum, energy and volume fraction of nanoparticles that are solved using the finite volume method and the SIMPLE algorithm. Diffusion and convective terms are discretized using a second-order central difference and upwind schemes. The left and right walls of cavity are kept at constant temperatures, while the other walls are thermally insulated. Simulations have been carried out for different inclination angles, including  $0^\circ$ ,  $30^\circ$ , and  $45^\circ$ , Rayleigh number ( $102 \leq Ra \leq 104$ ) as well as particle average volume fraction ranging from 0.01 to 0.04. Results show that at low Rayleigh number for a specific particle volume fraction, with increasing the inclination angle from zero to 45 degree, the average Nusselt number and heat transfer decreases 81%. On the other hand, optimum results were obtained for the inclination angle of 30 degree. The Nusselt enhancement percent was obtained 5.5 compared to the square enclosure and 6.8 compared to the inclination angle of 45 degrees. Results also showed a uniform distribution for nanoparticles in high Rayleigh numbers and in enclosures with different inclination angles.

## Review History:

Received:  
Revised:  
Accepted:  
Available Online:

## Keywords:

Trapezoidal cavity  
Natural convection  
Nanofluid  
Thermophoresis  
Buongiorno model.

## 1. Introduction

In conventional heat transfer fluids, nanofluids refer to fluid suspensions of solid nano-sized particles as was mentioned first by Choi [1]. Recently, a number of investigations have been conducted based on the transport equations derived by Buongiorno [2]. Numerical heat transfer by nanofluids in a wavy walls microchannel using dispersion method investigated by Rostami et al. [3]. To investigate the effects of Brownian diffusion and thermophoresis, natural and mixed convection heat transfer analyses of a nanofluid ( $Al_2O_3$ -water) in a laterally heated square cavity using Buongiorno's model was presented by Garoosi et al [4].

This research intends to explore the nano-particles local distribution and the rate of heat transfer of natural convection in an inclined trapezoidal cavity using Buongiorno's model. The effects of Rayleigh number ( $10^2 \leq Ra \leq 10^4$ ), volume fraction  $0 < \phi_{ave} \leq 0.04$  and inclination angle  $0 \leq \theta \leq 45^\circ$  are investigated. To the best of our knowledge, this study is the first one that used two-phase (inhomogeneous) Buongiorno's model to investigate the effect of the inclination angle of the trapezoidal cavity on nanoparticle distribution and natural convection of  $Al_2O_3$ -water nanofluid.

## 2. Methodology

The schematic of the considered problem in the present investigation is shown in Fig. 1. A two-dimensional cavity

\*Corresponding author's email: [morteza.bashiri1597@gmail.com](mailto:morteza.bashiri1597@gmail.com)

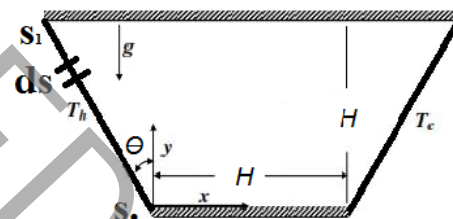


Fig. 1. Geometry of a trapezoidal cavity.

with an inclination angle ( $\theta$ ) and height of  $H$  is filled with  $Al_2O_3$ -water nanofluid. The top and bottom walls are thermally insulated whereas two left and right walls are at constant but different temperatures  $T_h$  and  $T_c$ , respectively. As shown, the gravity force acts in the vertical direction.

The flow is assumed to be 2D, steady, incompressible and laminar. Nanoparticles are assumed to have uniform shape and size and in thermal equilibrium with the base fluid [2]. The density variation with the temperature in the body force term is considered to be linear based on the Boussinesq's model [5].

Moreover, dissipation and pressure work are ignored in the present study. Thermo-physical properties of water and nanoparticles are summarized in Table 1.

## 3. Discussion and Results

The governing equations with the associated boundary



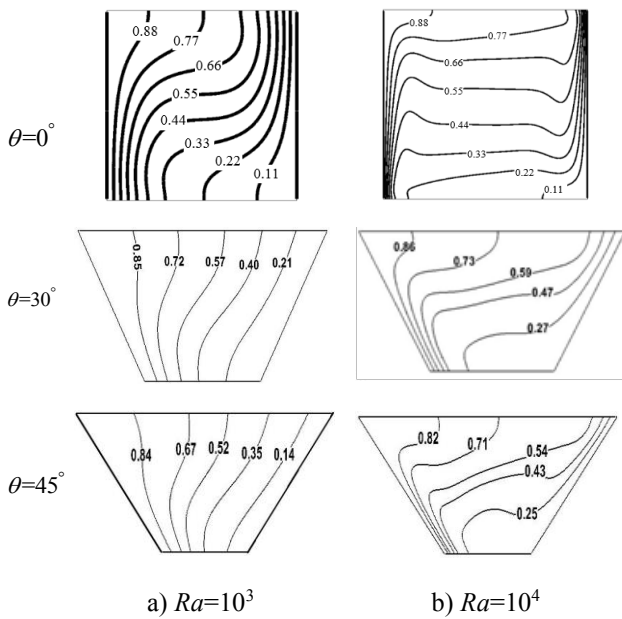
**Table 1. Thermo-physical properties of water and nanoparticles [5].**

	$\rho(\text{kg/m}^3)$	$k(\text{W/m.K})$	$C_p(\text{J/kg.K})$	$\beta \times 10^5$ (1/K)	$\mu \times 10^6$ (kg/m.s)	$d_p(\text{nm})$
Al <sub>2</sub> O <sub>3</sub>	3970	40	765	0.85	-	33
Water	993	0.628	4178	36.2	695	-

conditions are numerically solved using the SIMPLE-based finite volume method on a co-located grid. Diffusion terms in the governing equations are discretized using a second-order central difference scheme while an upwind scheme is used to discretize the convective terms. The thermo-physical properties such as density, viscosity, and thermal conductivity as well as thermophoresis diffusion and Brownian motion coefficients, which are varied with temperature and volume fraction, are solved simultaneously with flow, temperature and volume fraction equations in the whole domain. It is seen that by changing the grid numbers from  $150 \times 150, 180 \times 180$  to  $200 \times 200$ , the variation of nanoparticles local distribution and the average Nusselt number is not significant, thus a uniform grid system of  $180 \times 180$  is used for all simulations.

### 3.1. Effects of inclination angle on temperature field

Fig. 2 shows the isotherm lines at different inclination angles and  $Ra=10^2, 10^3$  and  $10^4$ . Here the average particle volume fraction is equal to  $\varphi_{Ave}=0.02$ . The uniformly distributed isotherms at  $Ra=10^2$  show that heat is primarily transferred by conduction. As shown, at the low  $Ra$  number where the buoyancy-driven flow is weak, with an increase in the inclination angle the isotherms remain unchanged. Nonetheless, in higher  $Ra$  numbers, isotherms are densely packed in the hot and cold walls. Close to the hot and cold



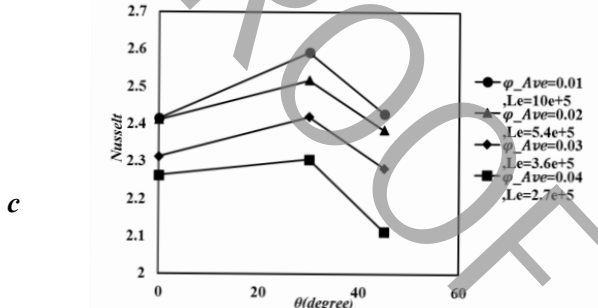
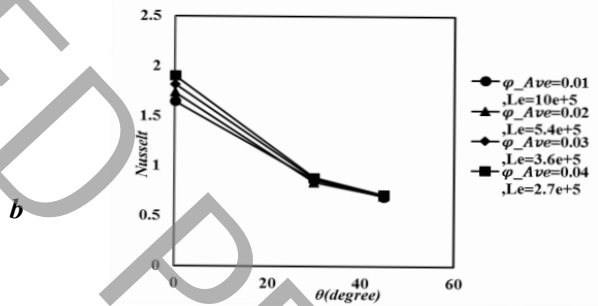
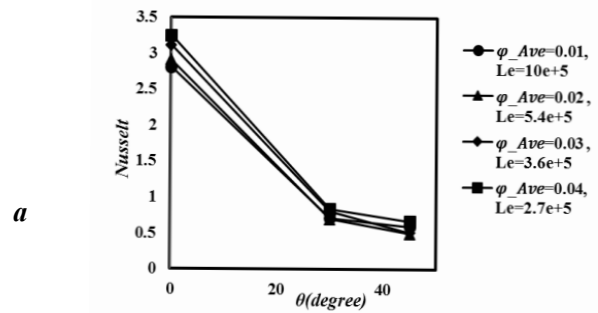
**Fig. 2. Isotherms inside the cavity filled with Al<sub>2</sub>O<sub>3</sub>-water nanofluid with  $\varphi_{Ave}=0.02$  at different inclination angles (a):  $Ra=10^3$  and (b):  $Ra=10^4$ .**

walls, the isotherms are parallel to the walls indicating the dominance of conduction heat transfer, while in the center of the cell; convection is stronger resulting in distortion of the isotherms. With increasing  $Ra$  number from  $10^3$  to  $10^4$  the isotherms attain a more random form. In other words, as the  $Ra$  number increases, the space between the isotherms adjacent to hot and cold walls decreases further which is indicative of an increase in the heat transfer rate due to change of heat transfer mechanism from conduction to convection.

Above this inclination angle, isotherms again tend to become straight. A similar trend can be observed for  $Ra=10^4$  where the inclination angle of  $\theta=45^\circ$  leads to better mixing and higher heat transfer.

### 3.2. Effects of inclination angle on the heat transfer rate

In Fig. 3. the variation of the average Nusselt number versus the particle volume fraction is plotted for various inclination angles and  $Ra$  numbers. The first result of Fig.8 is that with increasing Rayleigh number, the Nusselt number



**Fig. 2. Variation of the average Nu number versus the average particle volume fraction for various inclination angles at (a):  $Ra=10^2$  (b):  $Ra=10^3$  and (c):  $Ra=10^4$ .**

varies for different trapezoidal cavities. This is attributed to increased buoyancy forces, intense advection effects and changing flow patterns from unicellular.

In addition, according to Fig. 3 at  $Ra=10^2$  with increasing the average volume fraction,  $Nu$  number rises continuously. Increasing particle volume fraction causes an enhancement in both viscosity and thermal conductivity of nanofluid. Consequently, with raising the viscosity, the thermal boundary layer grows and hence the temperature gradients near the walls reduce leading to lower heat transfer rates. On the other hand, if nanoparticle volume fraction increases the thermal conductivity of nanofluid will be increased result in higher heat transfer rate. The existence of these two opposing and conflicting effects may lead to having an optimal volume fraction. In contrast, at high Rayleigh numbers, where advection effect is strong, inclination angle affects  $Nu$  number at all volume fractions; with increasing the inclination angle first  $Nu$  number increases and reaches its maximum value and then reduces. It is seen that regardless of particle volume fraction, the maximum  $Nu$  number occurs at about  $30^\circ$ .

#### 4. Conclusions

At high  $Ra$  numbers where advection is strong, the heat transfer was investigated at inclination angles of ( $\theta=0^\circ, 30^\circ$  and  $45^\circ$ ) and the optimal heat transfer was obtained at  $\theta=30^\circ$ .

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