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INFLUENCE OF A BUBBLE'S PRESENCE IN THERMAL TRANSFER OF 3D NUMERICAL SIMULATIONS IN CAVITIES

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Abstract. Literature presents several works where the thermal transfer rate at heated surfaces is enhanced by the inclusion of bubbles in flow. Previous works have reported even almost 60% of Nusselt number increasement by the addition of bubbles in single-phase flows. The goal of this work is the understanding of the influence of a bubble's presence in wall-to-fluid thermal transfer in two-phase flow using a volume of fluid (VOF) approach. In order to comprehend how the presence of a bubble affects thermal transfer, 3D numerical simulations in cavities with and without a bubble were presented. Validation cases were performed in 3D simulations using adaptive mesh refinement. Results show good agreeement with Nusselt number calculations and bubble evolution with previous works, demonstrating the validity of the present model. Nusselt number calculation and the modification of the angles of the isotherms with the vertical axis component revealed the impact of the bubble's presence in the proximity of the heated walls. Numerical results shows the modfication of the thermal boundary layer by the bubble's passage near the heated walls.

Keywords: Nusselt number, thermal transfer, CFD, Oberbeck-Boussinesq approximation

1. INTRODUCTION

The present work reports an investigation of the influence of a dispersed phase in thermal transfer rate in non-isothermal problems. The main objective was to evaluate qualitatively and quantitatively the effects of the inclusion of a dispersed phase in single-phase flows according to thermal transfer rate variations.

Thermal exchange is an important phenomena in nature and in a wide range of industrial applications such as evaporators, reactors and condensers (Bukhari et al., 2007). Most part of these phenomena consists of multiphase flows and a significant number of them involve natural convection (Bukhari et al., 2007; Kizildag et al., 2014; Wan et al., 2001). In natural convection, specific mass differences produces an additional force, commonly known as the buoyancy force. Most of the scientific studies focused on natural convection for single-phase fluids. Natural convection plays a fundamental role in nature and in many technological applications (Horvat et al., 2001). This type of convection is generated by specific mass differences in the fluid and it takes place due to temperature gradients (Padilla et al., 2013). In order to understand the influence and the effects of a bubble's presence in natural convection problems, numerical simulations were performed and thermal transfer was evaluated.

Literature have some experimental and numerical studies demonstrating that the presence of bubbles in flows affects thermal transfer. According to Deen and Kuipers (2013), it's generally agreed in the literature that the introduction of a gas into a liquid enhances the turbulence in the medium and thus increases the heat transfer rate to immersed surfaces. Deen and kuipers (2013) additionally defend that higher gas velocities enhances even more thermal transfer. Deckwer (1980) suggested that the presence of bubbles can increase the heat transfer in a gas-liquid bubble column by more than one order of magnitude. Oresta et al. (2007) studied the thermal transfer mechanism in Rayleigh-Bénard convection in a liquid with vapor bubbles. The authors concluded that the presence of bubbles have a profound effect on the flow structure and on the Nusselt number. Deen and Kuipers (2013) found that the passage of a bubble in a vertical chanel increases the local thermal transfer from a hot wall. Tamari and Nishikawa (1976) reported that the presence of bubbles increases convection due the addition of bouyancy force. Dabiri and Tryggvason (2015) studied turbulent bubbly flow and reported that the presence of bubbles increases the mixing and reduces the temperature difference between the hot wall and the bulk of the flow. The latter work presents that Nusselt number increases 60% when bubbles (3% of volume fraction) were included in the domain. According to Dabiri and Tryggvason (2015), the presence of moving bubbles generally increases the local thermal transfer.

The present work comprises the validation of the numerical model employed and then the investigation of the influence of a bubble in flow on thermal transfer rate is conducted by 3D simulations with a Volume of Fluid (VOF) approach to track interface position.

2. MATHEMATICAL MODEL

Oberbeck-Boussinesq approximation (OB) was included in the present work in order to model thermal effects on specific mass variations. OB has been used for most of what is known about natural convection (Gray, 1976); nonetheless, OB is restricted to single-phase flows or two-phase flows with the same specific mass as seen in (Qiu et al., 2013) and it may be inappropriate to employ this mathematical approximation in applications where large effects of specific mass variations occurs (Harish et al., 2016). Since the two-phase flow simulations were performed considering the same specific mass between the two phases, OB was employed. Therefore, the continuity equation is given by the following expression:

$$\vec{\nabla} . \vec{v} = 0 \tag{1}$$

The momentum equation is given in eq. (2):

$$\rho_0 \frac{D\vec{v}}{Dt} = -\vec{\nabla}p + \vec{\nabla} . \left[\mu \left(\vec{\nabla}\vec{v} + \left(\vec{\nabla}\vec{v} \right)^T \right) \right] + (\rho - \rho_0)\vec{g} \tag{2}$$

Finally, the energy equation is given by eq. (3):

$$\frac{DT}{Dt} = \alpha \nabla^2 T \tag{3}$$

Equation (4) expresses the thermodynamic relation employed in the momentum equation to compute variable specific mass effects as a temperature function:

$$(\rho - \rho_0)\vec{g} = -\rho_0 \beta (T - T_0)\vec{g} \tag{4}$$

3. COMPUTATIONAL PROCEDURE

Simulations were performed using a three-dimensional cubic cavity with flow subjected to gravity acceleration action which is shown in Fig. 1.
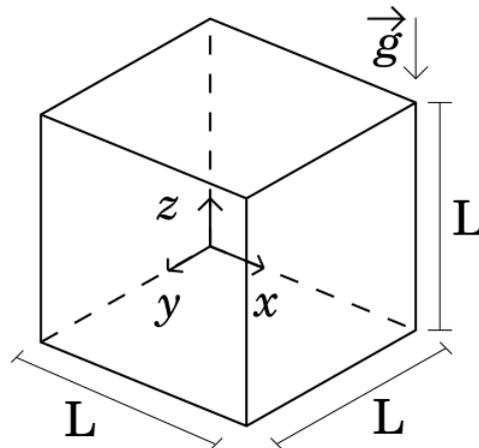

Figure 1. Physical model employed in the present paper

Domain boundaries were named according to geographic orientation which is illustrated in Fig. 2. The east and west walls have, respectively, a uniform high and low temperature. The south, north, bottom and top walls are adiabatic.
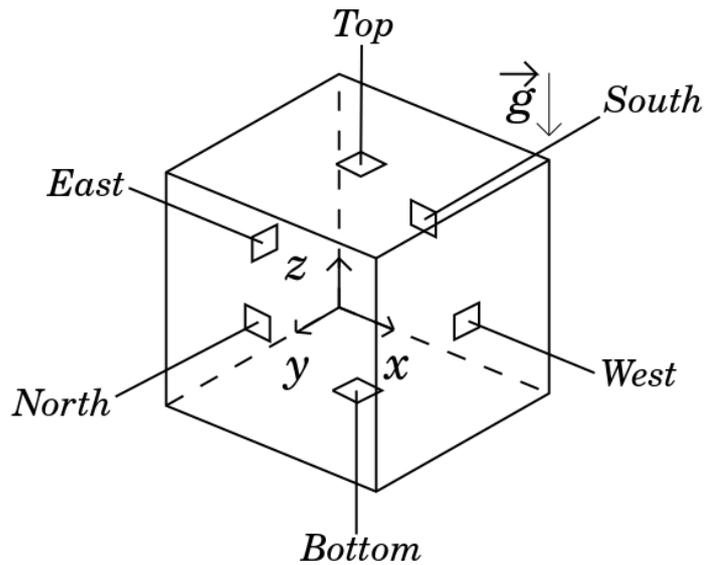
Figure 2. Domain boundaries names according to geographic orientation

Null velocities and null pressure gradient were imposed over all domain faces. East and west walls have, respectively, a uniform high and low temperature. The south, north, bottom and top walls are adiabatic. Simulations were carried out using a structured and uniform three-dimensional cartesian grid. Velocity-pressure coupling was accomplished using a two-step projection method with an explicit treatment for advection terms and an implicit treatment for pressure and diffusion terms. Pressure and energy equations were solved implicitly using multigrid-multilevel solver. MFSim code was used, which has being developed in the last 10 years in cooperation with a large research group and Petrobras scientifical support. All the simulations were performed in parallel ambient in the fluid mechanics laboratory at the Federal University of Uberlândia, Brazil.

4. RESULTS AND DISCUSSION

First, the numerical model was validated with literature according to thermal transfer rate and isotherms behavior. Then, simulations with a bubble were performed and the impact of the presence of the dispersed phase was evaluated.

4.1 Numerical model validation

In order to validate the numerical model employed, natural convection in one-phase flow was examined using Oberbeck-Boussinesq approximation. Computational simulations were performed considering Prandtl number of 0.71 and a range of Rayleigh numbers were tested; namely, from Ra= 10^3 to Ra=10 . Figure 3 presents the isotherms obtained from the present work.
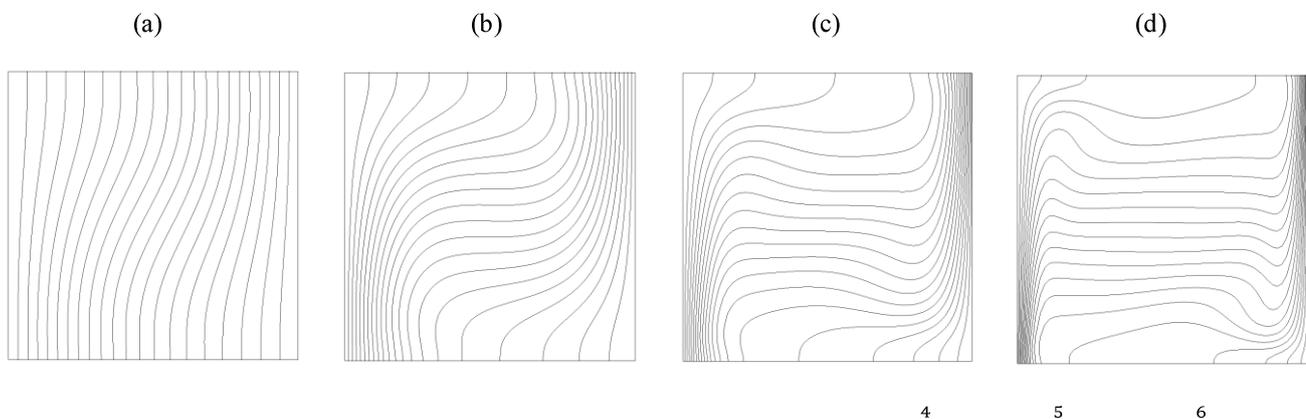
| (a) | (b) | (c) | (d) |

Figure 3. Isotherms from the present work with (a) Ra=10^3 ; (b) Ra=10 ; (c) Ra=10 ; (d) Ra=10

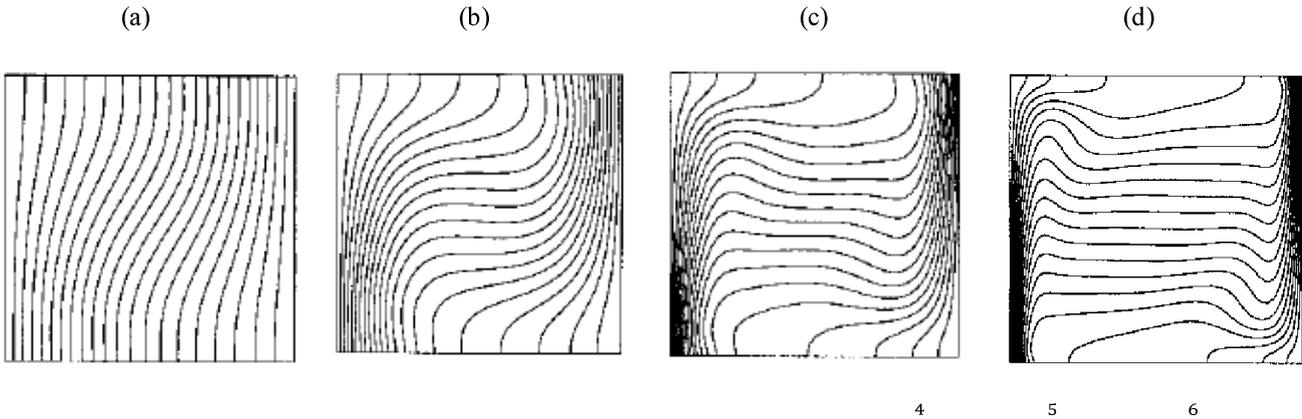Figure 4 presents isotherms from Wan et al. (2001) for a range of Rayleigh numbers tested.

(a)   (b)   (c)   (d)

Figure 4. Isotherms from Wan et al. (2001) with (a) Ra=10³ ; (b) Ra=10 ; (c) Ra=10 ; (d) Ra=10

Isotherms were compared to Wan et al. (2001) and good agreement was found between the isotherms behavior for all the range of Rayleigh numbers tested. Nusselt number was calculated at the east wall and then compared to literature. Good agreement was found between the present work and literature as shown in Tab. 1.

Table 1 – Nusselt number at east wall

Reference	Ra = 10³	Ra = 10⁴	Ra = 10	Ra = 10
Present work	1.071	2.061	4.390	8.901
Padilla et al. (2013)	1.072	2.068	4.427	8.805

Acording to the numerical results found, the numerical model was correctly validated with literature. In the next subsection, simulations were performed to evaluate the influence on thermal transfer by the addition of a dispersed phase from the continuos phase.

4.2 Effects of the presence of a bubble

Natural convection in two-phase flow was simulated with Prandtl number of 0.71 and Rayleigh number of 10^4 for the dispersed phase and 10^3 for the continuos phase. Since Oberbeck-Boussinesq approximation was used, the two fluids presented the same specific mass, as similarly seen in Qiu et al. (2013). The dispersed phase consisted of a bubble in the center of the cavity and bubble's initial radius was set as 0.32L, which represented approximately 13 % from the total volume of the cavity. Figure 5 presents the cavity with the bubble in simulation's final time.
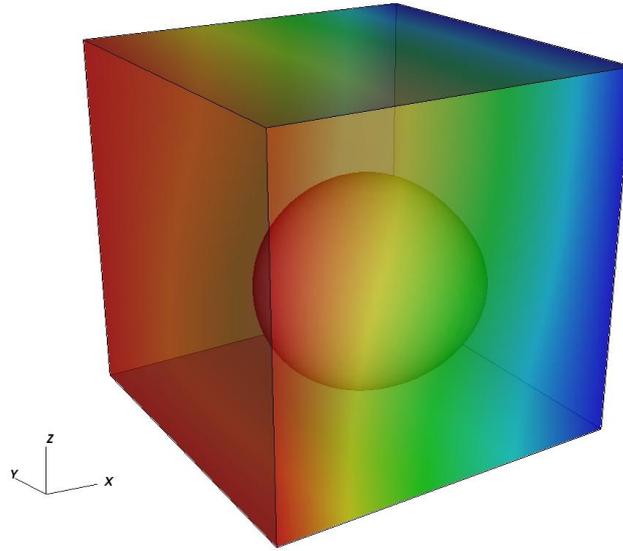
Figure 5. Three-dimensional view of temperature field with the interface between the two fluids.

The dispersed phase presented a rotational and translation movement inside the cavity. A clockwise displacement of the dispersed phase was evident in time due to the temperature gradient inside the computational domain. Thermal transfer rate at the heated wall presented severely high variations in time due to the dispersed phase position. The closer the dispersed phase was from the heated wall, higher was mean Nusselt number computed. When the dispersed phase was far away from the heated wall, thermal transfer rate was few affected in comparison to the single-phase flow case. Figure 6 shows mean Nusselt number computed at east all in time.
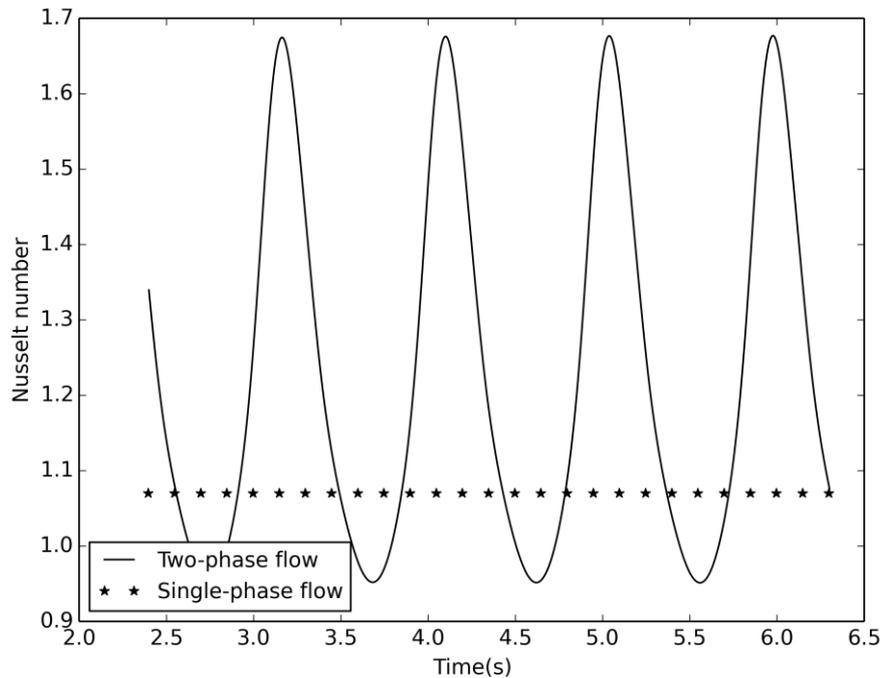

Figure 6. Mean Nusselt number evolution in time

Fgure 7 shows the interface contour and isotherms behavior inside the cavity in the moment when the dispersed phase was far away from the heated wall where Nusselt number was computed.
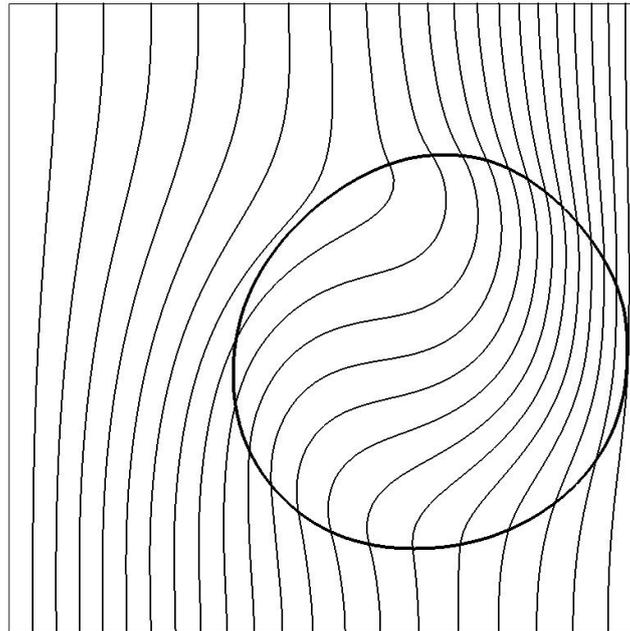
Figure 7. Slice of xz-central plane with isotherms and interface contour

Isotherms were deeply modified by the presence of a bubble as Fig. 7 shows. Isotherms inside the dispersed phase assumed a horizontal inclination which is similar to the isotherms behavior of Ra=10⁴ seen in Fig. 3-b. On the other hand, Fig. 8 shows the moment when Nusselt number is significantly impacted by the presence of the dispersed phase.
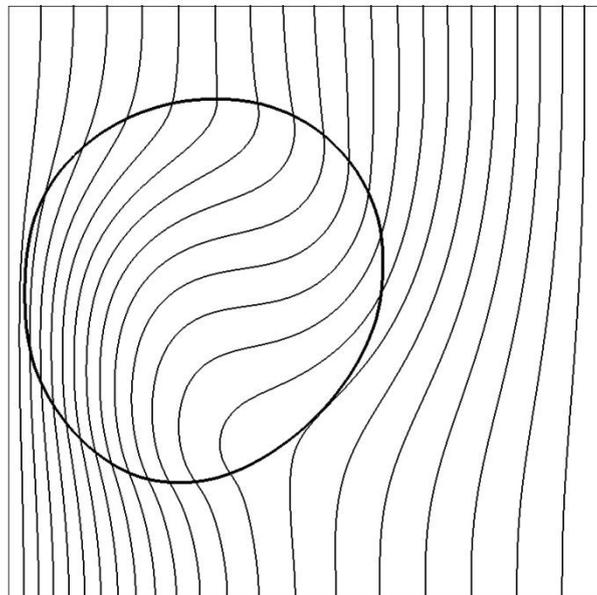

Figure 8. Slice of xz-central plane with isotherms and interface contour

Figure 8 presented the moment when Nusselt number increased almost 57% compared to the single-phase flow case. The present work found numerical results that corroborates previous works in literature, as Deen and Kuipers (2013) and Dabiri and Tryggvason (2015) which presented that Nusselt number increased when bubbles were included in the domain. Therefore, as literature previously described, the presence of a bubble increases thermal transfer in natural convection problems.

The dispersed phase presence affected isotherms inclination due to the reduction of the thermal boundary layer. Although the thermal transfer rate was mostly affected by the passage of the dispersed phase, the mean Nusselt number

in time presented close to 20% of mean augmentation. Therefore, the inclusion of bubbles in single-phase flows may increase the thermal transfer rate by the reduction of the thermal boundary layer at the heated wall.

5. CONCLUSIONS

According to the numerical results obtanied from the simulations of natural convection, thermal transfer rate was directly affected by the proximity of a dispersed phase. The inclusion of a bubble promoted the modification of isotherms angles and the reduction of thermal boundary layer close to the heated wall.

The presence of a bubble in a cubic cavity enhanced Nusselt number up to 57%. This information can be useful for industrial processes to improve equipment design and optimization of chemical processes.

6. ACKNOWLEDGEMENTS

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