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COMPUTACIONAL SIMULATION OF NATURAL CONVECTION IN A SEMI-CIRCULAR CAVITY WITH A HEAT GENERATING FLUID

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Abstract. Based on the importance of natural convection for heat transfer analysis in a molten core, Computational Fluid Dynamics (CFD) simulations may provide a better understanding of the phenomena occurring within the corium oxide layer after a severe accident. This work presents two-dimensional numerical simulations of natural convection in a semi-circular cavity containing a fluid with a uniform internal heat generation, with the objective to investigate the heat transfer with internal heat generation in the cavity in order to guarantee the physical integrity of the reactor pressure vessel. The simulations were performed in laminar regime, using the commercial software ANSYS FLUENT v.18.2, for a fluid whose Prandtl number is 7.0 and five Rayleigh numbers were simulated ranging from 10^9 to 10^{13} . Two cases were simulated. In the first case, the Boussinesq approximation was applied to the Buoyancy term. In the second case, the Boussinesq approximation was not applied in order to make a comparison and analyze the importance of the model to the problem. The results showed that average Nusselt numbers on the top surface of the semicircular cavity were in agreement with the correlations of Mayinger et al (1976) and Kulacki and Emara (1975) with $Ra = 10^{10}$ in both cases (with and without Boussinesq) and the average Nusselt number on the bottom surface of the semicircular cavity was in excellent agreement with Mayinger et al. (1976) correlation with $Ra = 10^{10}$.

Keywords: heat transfer, severe accident, natural convection, Rayleigh number, molten core.

1. INTRODUCTION

Since the first nuclear reactor, the attention has been focused on the safety of nuclear power plants to prevent accidents. A nuclear power plant has a control and protection system, that keeps the state variables within allowed limits such as the position of the control rods, the temperature of the pressurizer water, the coolant flow of the core and the flow of the steam generator. When these state variables violates the protection limits, the reactor protection system is activated, turning off the reactor by inserting the shutdown bars.

According to IAEA (2008), nuclear reactors are vulnerable to the occurrence of project bases accidents, that are caused by safety valve failures, loss of power from cooling pumps and loss of reactor coolant, also known as LOCA, among others, and severe accident which exceeds project bases accidents, making core cooling impossible, resulting in melting partial or total reactor core, generating failures in the protection barriers and in the safety system.

After the reactor shutdown, the residual heat of the fission products must be removed to avoid melting the fuel rods, making it is impossible to release radioactive materials into the atmosphere. In case of non-operation of the heat pump, there will be an increase of the, temperature in the core, compromising the core geometry leading a severe accident. During a severe accident, a pool of the molten core material will be formed inside the lower plenum of the pressure vessel. The fluidized core melt with high temperature will attack the reactor pressure vessel wall, which is the last barrier against the release of the radioactivity to the containment. The phenomenon that results from the temperature gradient inside the core is called natural convection. If the corium can be retained inside the reactor pressure vessel, the progression of the accident can be detained. However, the whole scenario depends of the heat removal capacity of the reactor pressure vessel wall.

Natural convection has been studied in several areas and its advance has increased in nuclear engineering due to the prevention of a severe accident in a nuclear power plant, since the heat transfer by natural convection determines the thermal loads on the pressure vessel wall. Bernaz et al. (2001)

In general, the physical phenomenon of the natural convection of a heat-generating fluid in a cavity is studied by two dimensionless parameters, the Prandtl number and the internal Rayleigh number, defined respectively by:

$$Pr = \frac{\nu}{\alpha} \quad \text{and} \quad Ra_i = \frac{g\beta q_v H^5}{\nu\alpha\kappa} \quad (1)$$

where g is the gravity, β the coefficient of thermal expansion, q_v the volumetric heat source, H the height, ν is the kinematic viscosity, α the thermal diffusivity and κ the thermal conductivity.

This phenomenon depends heavily on the geometry, boundary conditions, and thermo-physical properties of the fluid. The spatial and temporal variation of the heat flux in the walls of the natural convection system depends on the flow pattern, which, depending on the combination of Pr and Ra_i , can be laminar or turbulent, whose characteristics are completely different.

In order to evaluate the local and average heat transfer rates, the Nusselt number, a dimensionless parameter, is used, which is defined as:

$$Nu = \frac{hL}{k} \quad (2)$$

where h is convective heat transfer coefficient, L is representative dimension and k is the thermal conductivity of the fluid. Nusselt number is a measure of the ratio between heat transfer by convection (h) and heat transfer by conduction alone (k/L).

Some authors also use the Grashof number (Gr), which is related to the Prandtl (Pr) and Rayleigh (Ra_i) numbers as follows:

$$Gr = \frac{Ra_i}{Pr} \quad (3)$$

These dimensions are widely applied as parameters for the analysis of the behavior of flow regimes, facilitating the simplified identification of laminar, transient and turbulent regions of fluids in natural convection.

Experimental and numerical studies on natural convection heat transfer of a heat generating fluid have been carried out in the last two decades. The experimental studies are important to generate validation data of numerical models to stop programming softwares such as MELCOR and RELAP, as well as simulation software as dynamic computational fluid to investigate the natural convection in the reactor core.

Bonnet and Seiler (1999) built a facility at BALI, located in CEA (Grenoble-France), in a cavity with its geometry was half a semicircle, with the objective of studying the focus effect for a metal barrier on the molten oxidized material, the high internal number of Ra_i (10^{15} and 10^{17}) using simulant fluid (water) as it fluid, for reasons of safety, for standard processing from the datasheet, from the numbers numbers from Rayleigh. The validation on the basic data base was done by DNS code in the future or by code having their own sub-grid model.

Liaqat and Baytas (2001) performed a numerical study of conjugated and unconjugated heat transfer in a semicircular cavity, using the algorithm SIMPLER, the fluid had the number of $Pr = 7.0$ and the Rayleigh number was between 10^6 and 10^{11} . Aiming to validate the numerical method used, Liaqat and Baytas (2013) did a study with the same conditions and compared with the literature, concluding that there is a good agreement between the data.

Fukasawa *et al.* (2008) reviewed and analyzed the heat transfer of the inversely stratified molten corium in the lower vessel, which was experimentally demonstrated in the MASCA project. For the oxide layer, turbulent models of the k-e and the large eddy simulation were examined through the CEA BALI test analysis. An analysis under an inversely stratified configuration of a lower power density condition shows that the peak heat flux from the corium does not exceed the critical heat flux of the flooded vessel.

Vieira and Su (2011) performed an investigation of the natural convection in fluids with volumetric heat generation, performing simulations in square and semicircular two-dimensional cavities, with fluids with numbers of Pr of 0,03, 0,71 and 7,0 to 8,52, using the software ANSYS CFX 12.0 and comparing its numerical results with other computational results available in the literature. In order to investigate turbulent natural convection in fluids with volumetric heat generation, performed cavity simulations whose geometry was square and half of a fluidic semicircle varying the number of Pr from 0.6 to 8.52 and the number of Ra_i in the range of 10^6 and 10^{16} , using OpenFOAM.

Taylor *et al.* (2012) reported results from the Mini-SIGMA (Simulation of Internal Gravity-driven Melt Accumulation) tests with Rayleigh numbers up to 10^{10} . The test section was two-dimensional slice with 250 mm diameter, 125 mm height and 50 mm thickness. They concluded that the heat flux profile along the lower wall and average upward heat transfer with the Ra ranged from 10^7 to 10^{10} were in agreement with the data obtained from other numerical and experimental studies reported in the literature.

There are also several studies using the Boussinesq approach in the buoyancy-driven flow field, that is, the density variation driven by small temperature variations as stated by Mahony *et al.* (1986) who carried out a numerical finite difference investigation and concluded that the Boussinesq approximation was valid in a narrow range with a temperature difference ratio not greater than 0.2. However, relevant studies on non-Boussinesq effects when a large temperature difference ratio is imposed are quite limited. Considering the above, it is crucial to discuss which the behavior of vessel pressure under severe accident condition can be modeled by Boussinesq approximation or not.

2. PHYSICAL PROBLEM, GOVERNING EQUATIONS AND SIMULATION PROCEDURE

The geometry under consideration is a two-dimensional semicircular cavity, shown in Fig.1. The walls are kept at a constant temperature. Two cases are analyzed. One case has been performed by assuming fluid as incompressible and model of approximation Boussinesq, while the second has been performed case by only assuming fluid as incompressible without the use of the model.

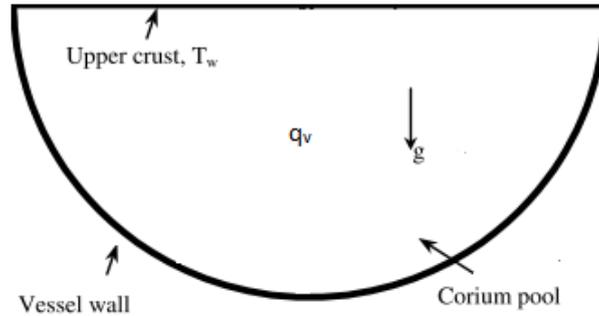


Figure 1. Schematic diagram of the semicircular cavity.

The basic equations that govern the physical problem of natural convection are the Navier-Stokes equations (conservation of mass, momentum and energy). They can be solved depending on the conditions of the fluid, flow, considering or not the buoyancy treatment of the moment equations, and they may be written a dimensionless form as demonstrated in equations (Eqs. 4, 5, 6 and 7). It is worth pointing out, in all the other terms, except the buoyancy one, that the density was considered constant as well as the specific heat, thermal conductivity and viscosity and considering an uniform volumetric heat generation.

The continuity equation

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0; \quad (4)$$

The momentum equation

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} = \left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2} \right) - \frac{\partial P}{\partial X}; \quad (5)$$

$$\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial X} + V \frac{\partial V}{\partial Y} = \frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2} - \frac{\partial P}{\partial Y} + \frac{R_{ai}}{Pr} \theta; \quad (6)$$

The energy equation

$$\frac{\partial \theta}{\partial t} + U \frac{\partial \theta}{\partial X} + V \frac{\partial \theta}{\partial Y} = \frac{1}{Pr} \left(\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2} \right) + \frac{1}{Pr}. \quad (7)$$

where the dimensionless variables are defined as:

$$X = \frac{x}{H} \quad Y = \frac{y}{H} \quad U = \frac{u}{(\nu/H)} \quad V = \frac{v}{(\nu/H)}$$

$$\tau = \frac{t}{(H^2/\nu)} \quad P = \frac{\rho d}{\rho(\nu/H)^2} \quad \theta = \frac{T - T_0}{q_v \frac{H^2}{k}}$$

The mathematical model was solved numerically using the commercial CFD ANSYS FLUENT v.18.2 package, which uses finite volume techniques to solve problems in uniform or non-uniform, unstructured and hybrid structured meshes. Therefore, it is possible to obtain a numerical solution of discretized momentum and mass balance equations.

3. RESULTS AND DISCUSSION

An analysis of mesh independence was carried out prior to the obtainment of results. The heat transfer in the studied cavity was analyzed for four meshes. Table 1 shows the statistics of the meshes used in the mesh sensitivity procedure performed for $Pr = 7.0$ and $Ra_i = 10^{10}$, considering the following boundary conditions $T_{w_{top}} = 300K$, $T_{w_{bottom}} = 293K$, $P = 1$ atm, in order to observe if the numerical solutions obtained in each mesh are similar, that is, if convergence occurs.

From the mesh analysis we studied two cases, being the first case with boussinesq and the second case without boussinesq in order to analyze the behavior of the model in the previously mentioned cases.

Table 1. Mesh independence analyzes.

	Number of nodes	Number of elements
Mesh 1	14213	14438
Mesh 2	41603	41988
Mesh 3	118370	119018
Mesh 4	200498	201342

By obtaining the values of the heat flux along the wall, one can find the Nusselt number and the average temperature (for each mesh), making a comparison to the visualization of which best workout to be used in the study. According to the table 2 and Figure 2 are observed as solutions being in the asymptotic range of convergence.

Table 2. Average Nusselt number around the bottom of the semicircular cavity and T_{av} for $Pr = 7$ and $Ra_i = 10^{10}$

	Nusselt number	Average Temperature
Mesh 1	36.1	386.74
Mesh 2	39.7	400.15
Mesh 3	38.2	401.2
Mesh 4	41.6	401.6

The local heat transfer around the bottom is shown in Fig. 2 in which the local distribution of wall-average Nusselt numbers are presented.

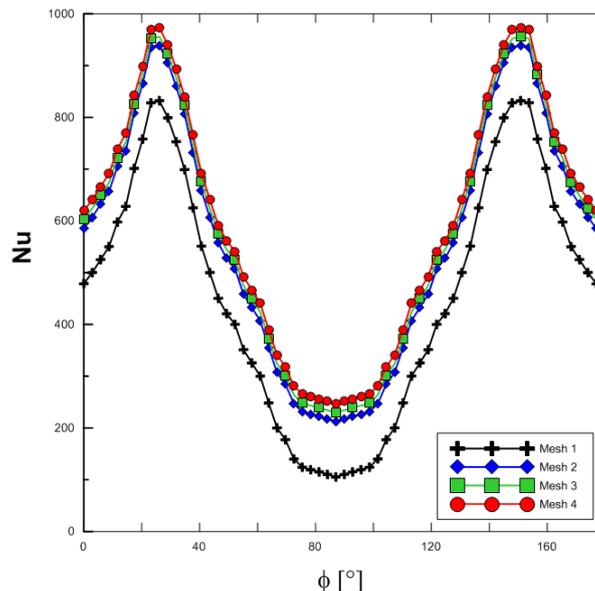


Figure 2. Distribution of Nusselt number around the bottom of the semi-circular cavity

The mesh used in the numerical simulations was the mesh 3, since it is a fine mesh and does not require too much computational effort as mesh 4.

As can be seen in Figure 3, the Nusselt numbers on the top surface and bottom surface obtained by the present simulation are in excellent agreement with the empirical correlation proposed by Mayinger et al. (1976) that fitted their experimental data with $Pr = 7,0$ and Rayleigh number ranging from 10^7 to 5×10^{10} . For the case without the Boussinesq model, it can be seen that for low numbers of rayleigh (10^9 and 10^{10}) in the interval studied, there was a little divergence, after Rayleigh 10^{11} there was a better agreement between the correlations and the cases studied.

It is also observed that by increasing the number of rayleigh to a better agreement of the cases with the correlations studied indicating that Mayinger et al. (1976) and Kulacki and Emara (1975), developed for larger Rayleigh numbers, may not be applicable for rayleigh numbers less than 10^9 .

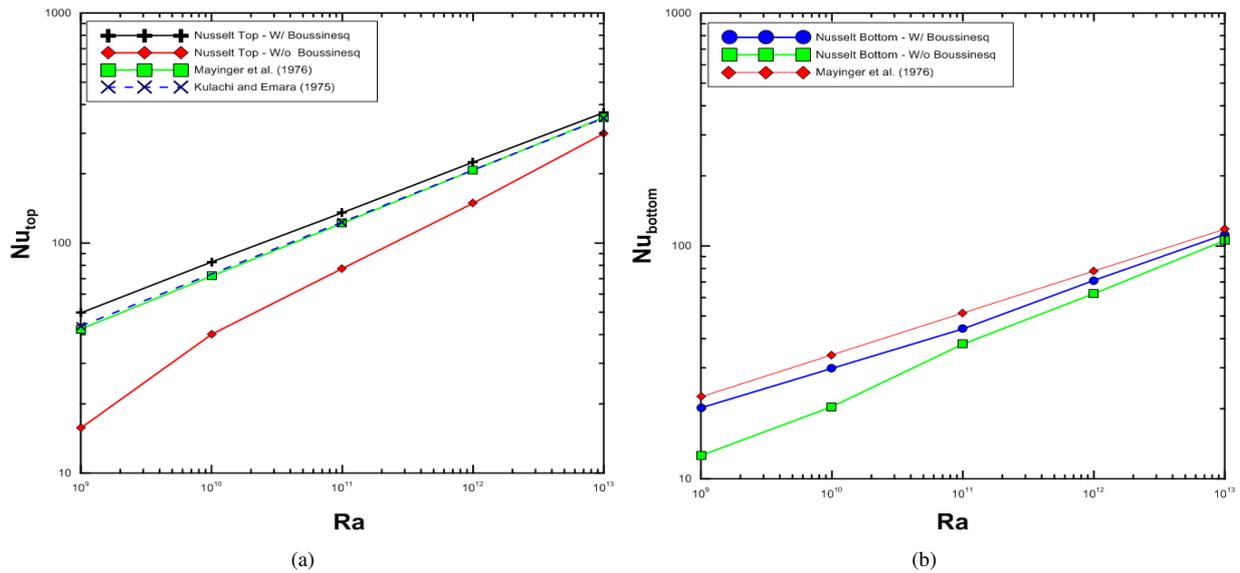


Figure 3. Nusselt numbers as a function of Rayleigh number: (a) Top; (b) Bottom average.

The temperature profiles of the studied cases obtained by the simulations, performed for $Pr = 7.0$ and Rayleigh ranging from 10^9 to 10^{10} , are shown in figures (4 to 8) for case comparison. It can be observed that, at a constant stratification in the lower part of the semicircular cavity for smaller numbers of rayleigh, which is getting smaller with the increase of the number of rayleigh, the homogenization of the temperature in the cavity can be explained by the growing mixture in the cavity, with the increase of the number of rayleigh to an approximation between cases, where the phenomena defined by Dinh and Nourgaliev (1997) can be seen in figures 7 and 8.

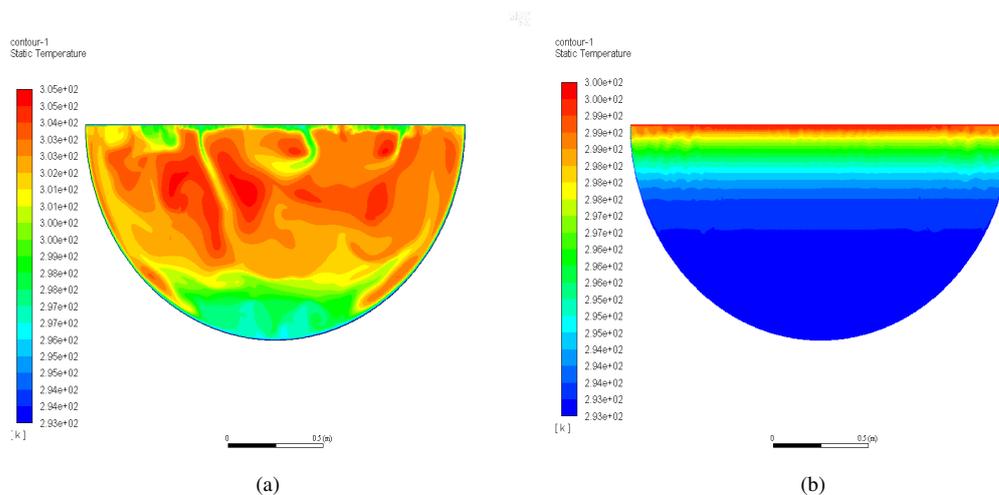


Figure 4. Temperature fields for $Ra_i = 10^9$: (a) With Boussinesq model; (b) Without Boussinesq model..

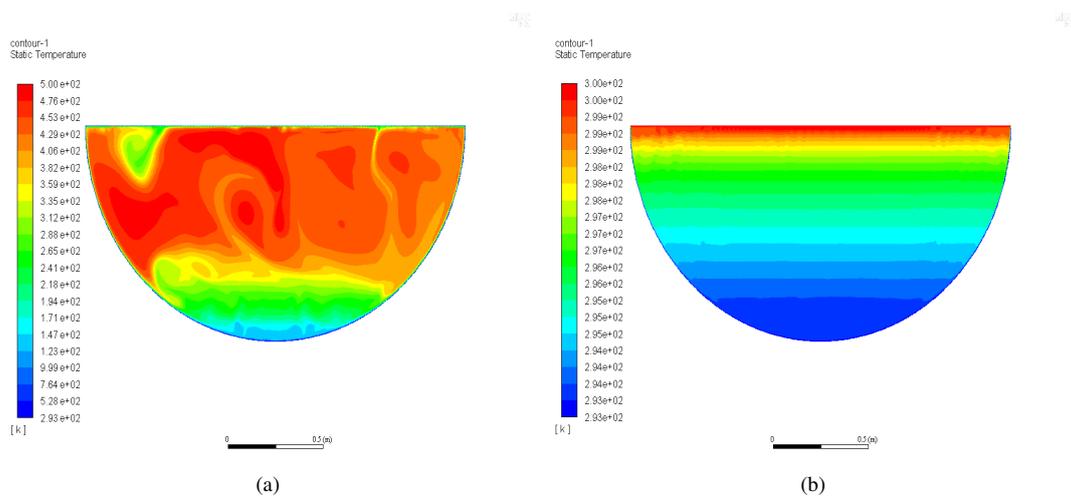


Figure 5. Temperature fields for $Ra_i = 10^{10}$: (a) With Boussinesq model; (b) Without Boussinesq model..

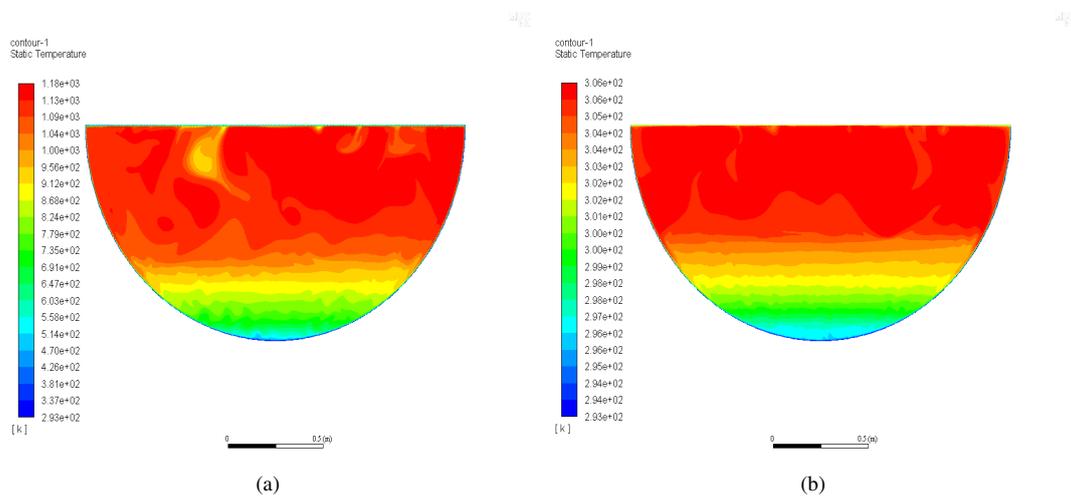


Figure 6. Temperature fields for $Ra_i = 10^{11}$: (a) With Boussinesq model; (b) Without Boussinesq model..

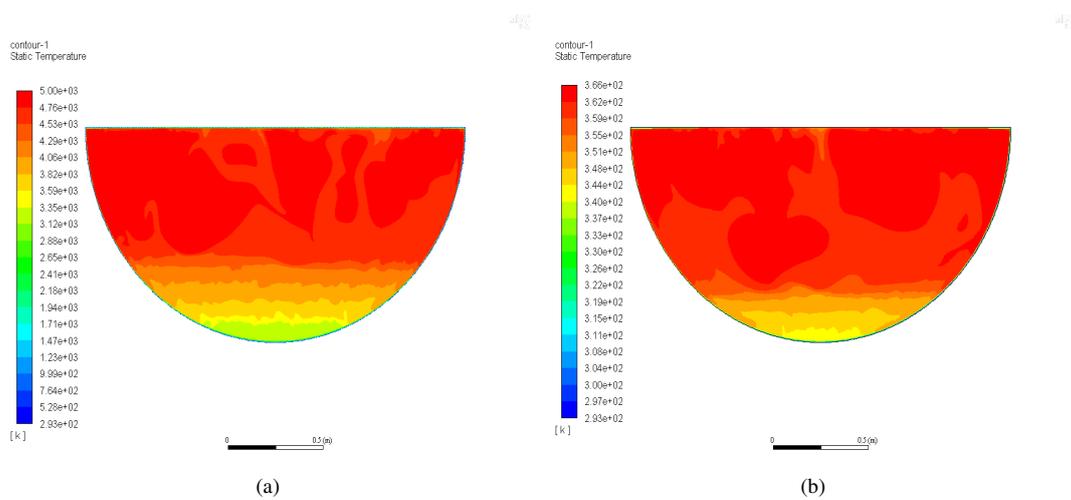


Figure 7. Temperature fields for $Ra_i = 10^{12}$: (a) With Boussinesq model; (b) Without Boussinesq model..

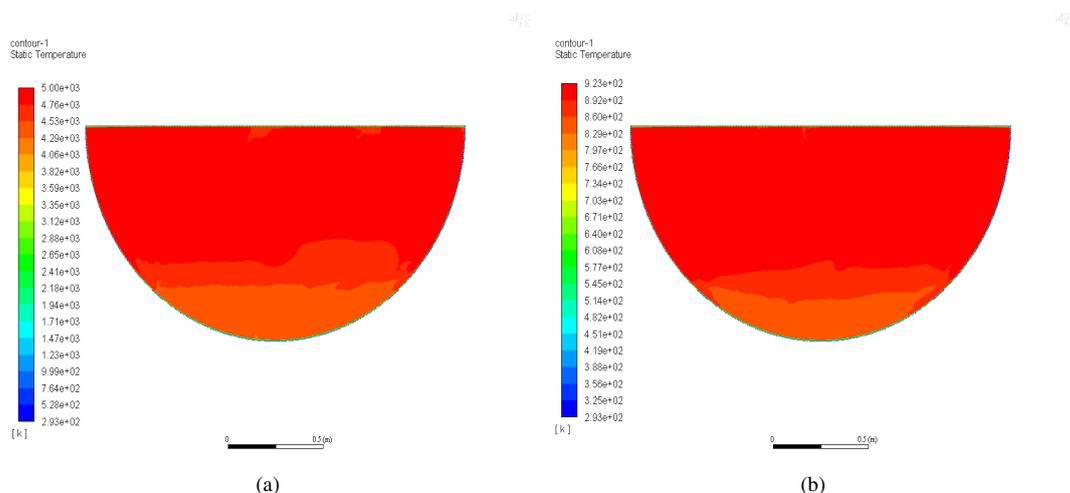


Figure 8. Temperature fields for $Ra_i = 10^{13}$: (a) With Boussinesq model; (b) Without Boussinesq model..

4. CONCLUSIONS

The average Nusselt numbers on the top and bottom surfaces, calculated by the computational simulations, were in excellent agreement with the correlations of Mayinger et al. (1976) and Kulacki and Emara (1975) only for Rayleigh higher than 10^{10} . For lower Rayleigh numbers, the calculated Nusselt numbers were systematically lower than the values given by the empirical correlations. Comparing the results, we can see that the case that does not use the Boussinesq approach has a small divergence in relation to the case that uses the Boussinesq approach and the correlations studied. The numerical results of the temperature field show the phenomena defined by Dinh and Nourgaliev (1997) which can be clearly visualized in figures (7 and 8) where the descending fluids penetrate, at the peripheral regions, into the stably stratified layers, concluding, that with increasing Rayleigh numbers, the temperature distribution in the cavity becomes more uniform.

5. ACKNOWLEDGEMENTS

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