NUMERIC-EXPERIMENTAL ANALYSIS OF THE DISTRIBUTION OF TEMPERATURE IN A TANK OF OIL WITHOUT THERMAL INSULATION

Rejane De Césaro Oliveski
Universidade do Vale do Rio dos Sinos – UNISINOS
Cetro de Ciências Exatas e Tecnológicas
Av. Unisinos, 950 - São Leopoldo – RS -CEP: 93022-000
decesaro@euler.unisinos.br

Jacqueline Biancon Copetti
Universidade do Vale do Rio dos Sinos – UNISINOS
Cetro de Ciências Exatas e Tecnológicas
Av. Unisinos, 950 - São Leopoldo – RS -CEP: 93022-000
copetti@euler.unisinos.br

Mario Henrique Macagnan
Universidade do Vale do Rio dos Sinos – UNISINOS
Cetro de Ciências Exatas e Tecnológicas
Av. Unisinos, 950 - São Leopoldo – RS -CEP: 93022-000
mhmac@euler.unisinos.br

Abstract. *This work presents a numeric and experimental analysis of the thermal stratification inside a tank containing thermal oil. Starting from an initial condition of uniform temperature, the tank is submitted to a cooling regime through the natural convection provoked by the thermal losses to the environment. The numeric analysis is accomplished with a two-dimensional model in cylindrical coordinates through the Finite Volumes method. The program is fed with polynomials originated from experimental tests, in function of the height of the tank and time, prescribing the tank sidewall temperature. The bottom and the top of the tank were thermally insulated. The temperatures of the tank sidewall and centerline are measured with copper-constantan thermocouples. Results of the temperature variation at the centerline along the time for several heights are presented. A dynamic analysis of the problem is presented through velocity fields. The numeric results show an good agreement with the experimental results.*

Keywords*. natural convection, oil, tank experimental, Finite Volumes*

1. Introduction

Many activities in engineering have storage tanks as a basic component. Typical examples are liquid heating systems, food and petrochemical industry. In the case of thermal storage tanks, the objective is to store the working fluid at the project temperature. In order to reach this goal in an optimized way, besides the mechanical project, a thermal project of the tank must be considered. This study should be able to emulate the physical phenomena that happen in real systems. It can be made from an experimental approach (using tanks with different configurations) or by using numeric simulation, which can save a lot of time and effort with the advantage of permitting a detailed analysis of the system under study. Nevertheless, the computational program responsible for the generation of the simulated data must be experimentally validated in order to obtain reliable results. This fact explains the need and the importance of producing experimental data.

The literature presents many experimental (Gross, 1982, Zurigat *et al.*, 1991, and Murthy *et al.*, 1992, Nelson, Balakrishnan and Murthi, 1999, Oliveski, 2000) and numeric simulation (Barakat and Clark, 1966, Reindl, Beckman and Mitchell, 1992, Cotter and Charles, 1992, Kimura and Bejan, 1996, Oliveski *et al.* 2001 and 2003) works on thermal storage, most of them using water as working fluid. Water is a natural choice because it is a cheap, non toxic and easy handling fluid. On the other hand the use of water as a working fluid brings some limitations concerning the project temperature. More recently, Oliveski (2000) and Oliveski *et al.* (2001 and 2003) analyzed thermal storage water tanks from both numeric and experimental approaches. The latter two works presented partial results from the doctoral thesis of Oliveski (2000).

A fluid stored at a high temperature (that is, higher than the environment temperature) loses heat to the environment. As a consequence, the natural convection provokes the distribution of the fluid in different temperature layers, the so called thermal stratification. According to Gross (1982), Zurigat *et al.* (1991) and Murthy *et al.* (1992), among others, the thermal stratification is influenced by: a) internal natural convection caused by the thermal losses to the environment; b) natural convection caused by the heat transfer from hotter to colder layers through highly conductive walls, and c) thermal diffusion between layers of different temperatures.

The degradation of the thermal stratification is as important as its formation. Jaluria and Gupta (1982), Shyu *et al.* (1989) and Nelson *et al.* (1999) studied this effect and concluded that walls with high thermal conductivity increase the axial heat transport through them, resulting in a relative heating of the cold layers at the bottom and a cooling of the fluid at the tank top. In other words, highly conductive walls contribute to the degradation of the thermal stratification.

Oliveski *et al.* (2001) compared numeric and experimental results of the thermal stratification formation and degradation in hot water tanks. The hydrodynamic development of these problems was also presented. The experimental validation of the numeric simulation was presented with first and third kind boundary condition. Correlations of the Nusselt number as a function of the thermal losses to the environment, aspect ratio and tank volume is presented by Oliveski *et al.* (2003).

As mentioned before, the existing literature has focused considerable attention on the thermal stratification in thermal water storage tanks. A few studies having oil as the working fluid are reported (Cotter and Michael, Poujol *et al.*, 2000 and Vardar 2003). Cotter and Michael analyzed the cooling of a cylindrical vertical petroleum tank, presenting the transient average Nusselt number with several values of oil viscosity. Poujol *et al*. analyzed numerical and experimentally the natural convection in a square tank submitted to a growing heat flow through the east sidewall. The natural convection is obtained from the temperature difference between this and the opposite walls, whose temperature was kept constant.

The objective of this work is to obtain, in a numeric and experimental approach, the temperature profile inside a vertical cylindrical tank containing thermal oil. The thermal stratification development and its degradation during the cooling regime were also analyzed.

2. Experimental apparatus

The experimental assembly was constituted by a vertical cylindrical stainless steel tank, temperature sensors (thermocouples and PT100), glass wool as thermal insulation and a wooden structure to hold the thermocouples inside the tank. The working fluid used was thermal oil.

The tank is 57 cm height, with a 21 cm radius. The walls are 1 mm thick. The tank top and bottom were insulated with 12 cm thick sheets of glass wool. The sidewall was submitted to the environment temperature. An electric resistance of 500 W, used to heat the oil, is installed at the bottom of the tank. The oil surface was covered with a floating plastic sheet and expanded polystyrene wrapped with impermeable material in order to minimize losses by evaporation. After the oil was heated the tank was submitted to the cooling regime.

One PT100 and 26 copper-constantan (0.1 mm diameter wires) thermocouples were used to sense the system temperatures. Their signals were registered by a HP75000 data acquisition system, equipped with a 5 ½ digits multimeter, communicating to a microcomputer through GPIB. The data were acquired and recorded at a once in a minute rate. The data from the sensors was transformed to temperature through calibration curves.

The PT100 was used to sense the environment temperature. Thirteen thermocouples registered the tank external sidewall temperatures and the remaining thirteen registered the tank center temperatures in different heights, as can be seen in Fig. (1).

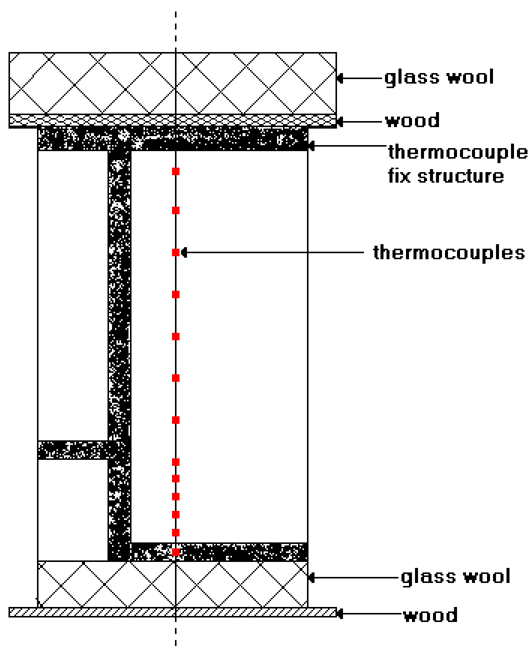

Fig. 1- Storage tank.

Table 1 shows the distance in relation to the tank bottom of the thermocouples at the centerline (TP1-TP13) and at the tank sidewall (TP14-TP26). The environment temperature was used as the reference temperature for the thermocouples.

Table 1 - Thermocouples and respective height from the tank bottom.

Thermocouples (TC)	1	2	3	4	5	6	7	8	9	10	11	12	13
	14	15	16	17	18	19	20	21	22	23	24	25	26
Height (cm)	1.0	3.5	6.0	8.5	11.0	13.5	18.0	23.0	29.5	35.5	42.0	48.0	53.0

As demonstrated by Oliveski (2000), errors in the temperature measurements can be induced by the different thermal resistances associated to the different methods of sensor fixing in the metallic wall. In this work was adopted the fixation method proposed by the mentioned author.

The oil physical properties were calculated considering the average between the oil initial temperature and the environment temperature.

3. Numerical approach

The experiments were simulated with the equations of mass conservation, momentum in axial and radial directions, and energy. These are represented in Eq. (1)-(4), respectively,

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial z}+\frac{1}{r}\frac{\partial(\rho r v)}{\partial r}=0 \tag{1}$$

$$\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho u u)}{\partial z}+\frac{\partial(\rho v u)}{\partial r}=-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 u}{\partial z^2}+\frac{1}{r}\frac{\partial u}{\partial r}+\frac{\partial^2 u}{\partial r^2}\right)+\rho g \tag{2}$$

$$\frac{\partial(\rho v)}{\partial t}+\frac{\partial(\rho u v)}{\partial z}+\frac{\partial(\rho v v)}{\partial r}=-\frac{\partial p}{\partial r}+\mu\left(\frac{\partial^2 v}{\partial z^2}+\frac{1}{r}\frac{\partial v}{\partial r}+\frac{\partial^2 v}{\partial r^2}-\frac{v}{r^2}\right) \tag{3}$$

$$c_p\left[\frac{\partial(\rho T)}{\partial t}+\frac{\partial(\rho u T)}{\partial z}+\frac{\partial(\rho v T)}{\partial r}\right]=k\left[\frac{\partial^2 T}{\partial z^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial r^2}\right] \tag{4}$$

where ρ is the density, μ is the dynamic viscosity, k is the thermal conductivity, c_p is the specific heat at constant pressure, u is the axial velocity, v is the radial velocity, T is the temperature and p is the pressure.

3.1 Initial conditions

Null velocity hypothesis is used as initial condition to the hydrodynamic problem. The initial condition of the thermal problem inside the tank is of isothermal temperatures field, also experimentally obtained. These conditions are shown below.

$$u(z,r,0) = 0 \tag{5}$$

$$v(z,r,0) = 0 \tag{6}$$

$$T(z,r,0) = T_{in} \tag{7}$$

where T_{in} is the oil initial temperature.

3.2 Boundary conditions

The boundary conditions used for momentum equations are impermeability and non-slip on every tank walls, including the symmetry line (where the thermocouples are located). Thus:

$$u(0,r,t) = u(Z, r, t) = 0 \tag{8}$$

$$u(z,0,t) = u(z, R, t) = 0 \tag{9}$$

$$v(0,r,t) = v(Z, r, t) = 0 \tag{10}$$

$$v(z,0,t) = v(z, R, t) = 0 \tag{11}$$

The boundary conditions for the energy equation are: perfect insulation at top and bottom (see Fig. 2), no heat flow at the symmetry line and prescribed temperature at the tank sidewall. The boundary condition of first kind at the external sidewall is prescribed by thirteen polynomials having the tank height and time as variables. Thus:

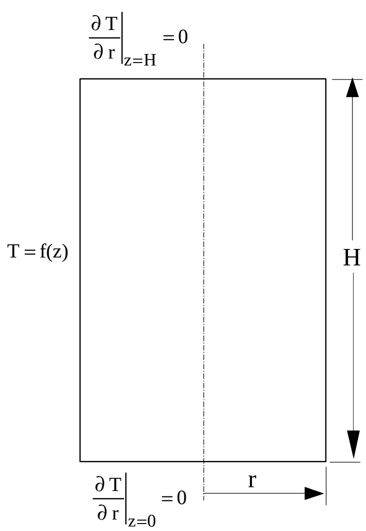

Fig. 2 – Tank representation with the insulated surfaces of the top and bottom.

3.3 Methodology

The numerical solution was obtained from the discretization in Finite Volumes of Eq. (1-4), as described by Patankar (1980). Pressure-velocity coupling was obtained by the SIMPLEC method of Van Doormaal and Raithby (1984). The Power Law scheme was used for the interpolation of volume control faces. The resulting equation systems were solved with the TDMA method. The convergence criterion used was a mass conservation residue established as 10^{-4}. In order to increase the convergence, a block correction was used to calculate velocity and temperature components, diffusing the influence of the boundary conditions to the inside of the domain.

A grid of 40 volume elements in the radial direction and 60 volume elements in the axial direction with refinement at the side, top and bottom walls of the tank was used. In order to observe the influence of the grid, the experiments were simulated with grids of 20x30, 40x60 and 60x90 volume elements in the axial and radial directions respectively. The results obtained with the grids of 40x60 and 60x90 volume elements were very similar. Those obtained with the grid of 20x30 volume elements were shown to be unsatisfactory when compared to the experimental data. Thus, a grid of 40x60 volume elements was adopted in this work.

The vertical space z_i of the i-mesh in the grid was determined through Eq. (12), presented by Davidson, 1990.

$$z_i = H\left\{-0.5\tanh\left[\alpha\left(2\frac{i-2}{n-2}-1\right)\right]/\tanh\left(-\alpha\right)+0.5\right\} \tag{12}$$

Equation (12) is valid for $2 \leq i \leq n$, where n is the number of volume elements in the axial direction, H is the height of the tank and α is the grid refinement coefficient in the axial direction. Similar equation was used for the radial direction. The grid refinement coefficients used in axial and radial directions were 2.0 and 2.4, respectively. Figure 3 represents the employed grid.

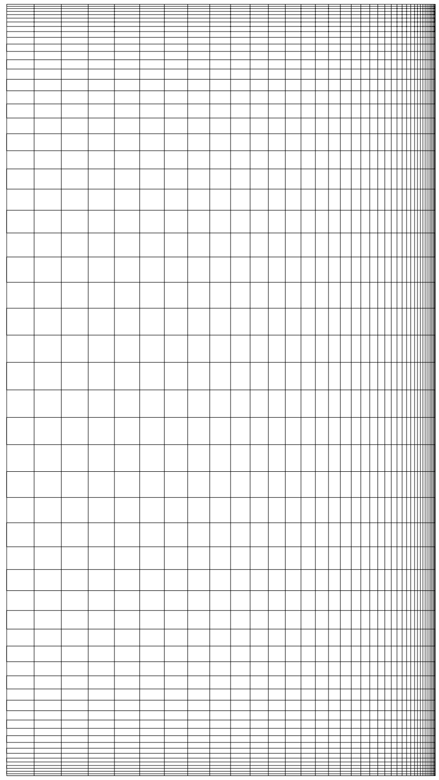

Figure 3 – Representation of the grid obtained with Eq. 12.

4. Results

Several tests with initial condition of uniform temperature were carried out. The first cooling results were obtained with an initial temperature field of 51 ^{o}C. The other tests were conducted with higher initial temperatures, with increase steps of approximately 10 ^{o}C. All the tests were performed with cooling times of 15 hours.

The comparisons between experimental and numerical results are shown in Fig. 4 and 5, where the stratification formation during the cooling process is indicated by the temperature profile at the center of the tank. These figures show that, even after 15 hours, the numerical simulation is able to reproduce the experimental results with good accuracy. At the bottom region, we can also observe an evident increase of the thermal gradient in the vertical direction. The same behavior was observed by Abdoly and Rapp (1982) and Oliveski (2000), where the authors suggested that this sudden drop in temperature was due to conductive losses through the metallic columns of the tank.

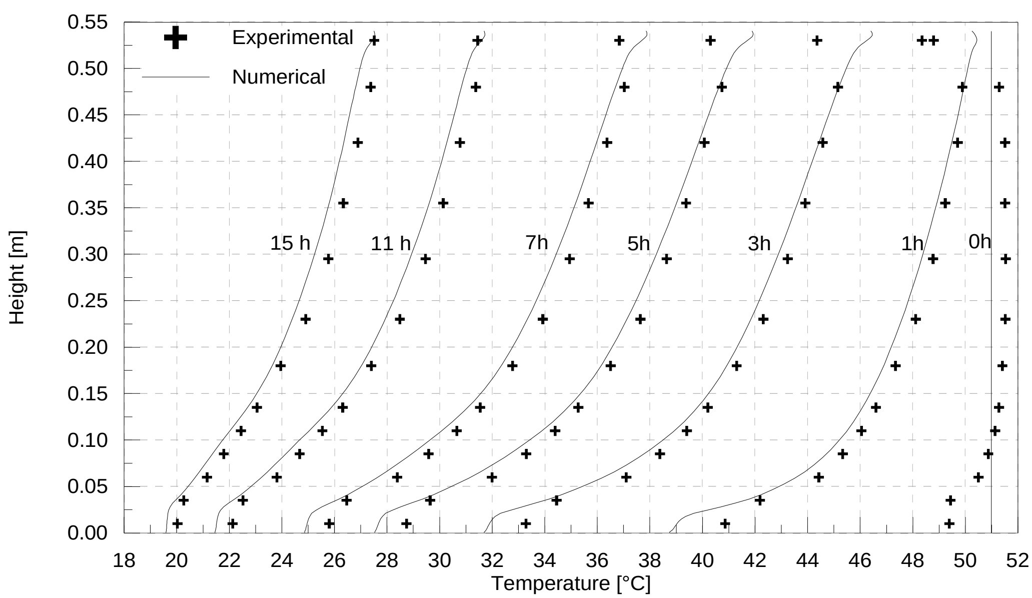

Fig. 4 - Temperature profile along the height of the tank, obtained with experimental and numeric analysis and with initial temperature of 51 ^{o}C.

One can observe in these experiments that the development of thermal stratification occurred until about 3 hours of cooling, when temperatures differences between top and bottom of approximately 14 °C in Fig. 5a and 18 °C in Fig. 6a. From then the stratification began to deteriorate and after 15 hours of cooling the temperatures differences dropped to 8 °C and 10 °C.

The electric heater was installed at approximately three centimeters from the tank bottom. While the oil was being heated tthe natural convection process happened due to density variation, homogenizing the temperature of the oil above the electric resistance. Meanwhile, the oil amount located below this resistance was heated only by thermal conduction. Therefore a crescent thermocline was observed in this area while the oil was being heated, as can be observed from the experimental results at zero hour, shown in Fig. 4.

In the attempt of obtaining experimental results with an uniform profile of initial temperature, as that presented in Fig. 5, the electric resistance was turned off after the oil have reached the wanted temperature and the temperature homogenization process began. This manual homogenization process was done in slow movements, in order to avoid damages to the sensor fixation structure. In addition, an abrupt agitation would provoke spilling of the oil, with the consequent loss of a certain amount of mass.

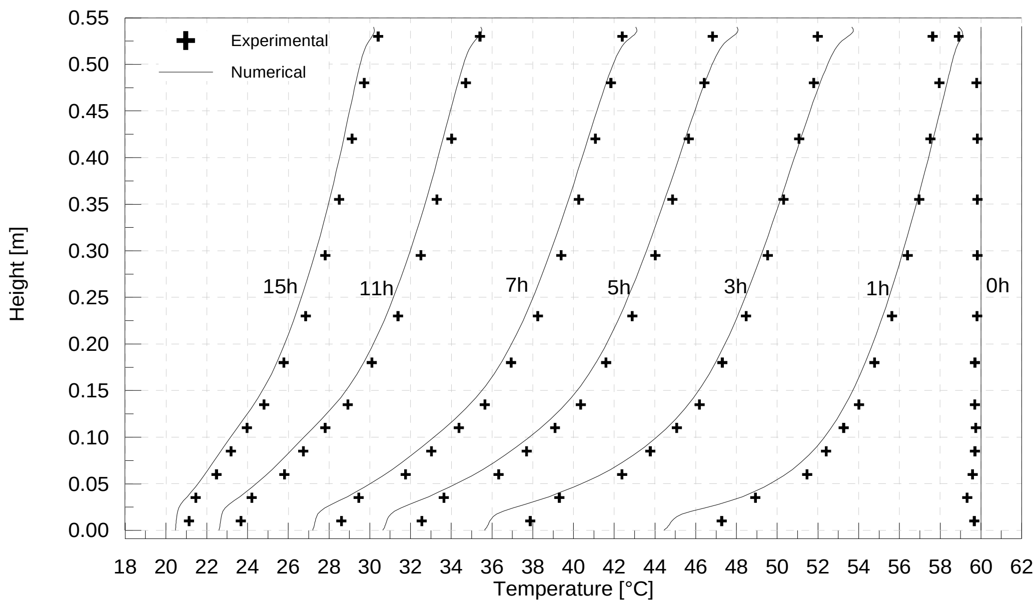

Fig. 5 - Temperature profile along the height of the tank, obtained in an experimental and numeric analysis, with initial temperature of 60 ^{o}C.

The use of first kind boundary condition obtained from experimental data (as is the case of this work) does not ensure by itself the agreement of results presented in Fig. 4 and 5 by itself. In the areas of larger thermal and hydrodynamic gradients a refined grid should be used. In the problem in study these gradients are located at the top of the tank and along its sidewall.

When the oil is losing heat through the tank sidewall its density increases with the temperature decrease. This process causes downwards displacement of mass. Thus, besides the thermal boundary layer, one can observe the presence of the hydrodynamic boundary layer. Figure 6 shows the velocity profile inside the hydrodynamic boundary layer after 3 hours of cooling. It can be observed that, close to the sidewall (radius = 0.21 m), the hydrodynamic boundary is totally inside a limit of 1 cm. It is possible to verify also, from the number of vectors, that the velocity profile was obtained with approximately 12 volume elements unevenly spaced.

Being this experiment a process of mass conservation, the equivalent amount of mass that descends close the tank sidewall has to arise at the tank central region but with a lower velocity than those found in the vertical hydrodynamic boundary layer, as it can be seen in Fig. 6. Observing these two mass flows, descendent and ascendant, it can be identified the shear layer, which also demands a grid refinement.

The grid refinement also is important near the top region because we also verified there the formation of a hydrodynamic boundary layer, as a consequence of the mass conservation, as it can be seen in Fig. (7). The velocity profile at this region is similar to the one verified at the sidewall. It could not be different, because during the tests, a plastic sheet aiming the implementation of the impermeability and no slip boundary condition during the numeric simulation covered the oil surface free. It can be observed in this figure three different directions of mass flow: the ascendant, with very low velocities and occupying almost the totality of the tank volume; the horizontal, with a thickness of approximately two centimeters; and one descendent, with an initial hydrodynamic boundary layer thickness of approximately 5 mm.

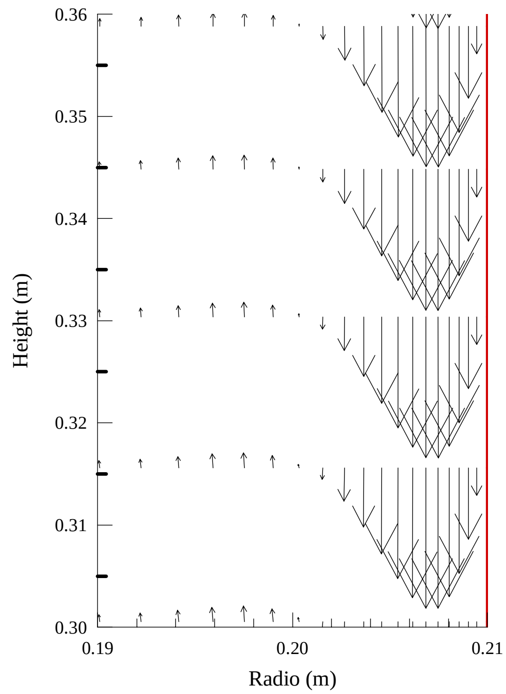

Figure 6 - Velocity profile at the tank sidewall after three hours of cooling.

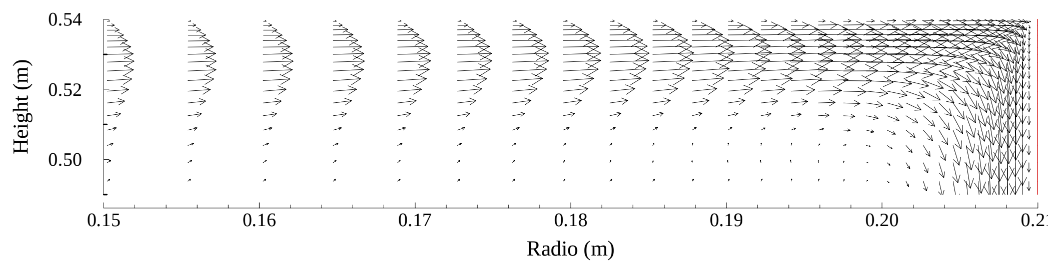

Fig. 7 - Velocity profile at the tank top after three hours of cooling.

5. Conclusions

The numerical and experimental results showed that, as time passes, the oil volume is divided in two regions: a stratified region (at the bottom) and another at a uniform temperature (at the top). The interface between these two regions advances towards the top.

It was numerically verified that the tank under natural convection regime, in terms of convective flow direction, has two different regions. The region of descending flow has a ring shape along the sidewall, represented by the hydrodynamic boundary layer. The other one is the central region, with a very slow ascending flow, occupying almost the totality of the tank volume. The thermal gradients have their maximum values close the sidewall and are null at the centerline of the tank.

It was verified a good consistency between the numerical and experimental results, ensuring the validation of the employed numerical model. It was demonstrated that the model was able to describe in detail the phenomena that occur inside thermal tanks subjected to natural convection regime.

6. Acknowledgements

The author is grateful to the FAPERGS and UNISINOS for the financial support to this work and the Solar Energy Laboratory of UFRGS for the support on the experimental phase.

7. References

Abdoly, M. A. and Rapp, D., 1982, “Theoretical and Experimental Studies of Stratified Thermocline Storage of Hot Water”, Energy Convers. Mgmt., Vol. 22, pp. 275-285.

Barakat, H. Z. and Clark, J. A., 1966, “Analytical and Experimental Study of the Transient Laminar Natural Convection Flows in Partially Filled Liquid Containers”, AIChE International Heat Transfer Conference, Vol. 3, Chicago, EEUU, pp. 152-162.

Cotter, M. A. and Charles, 1992, “Transient Cooling of Petroleum by Natural Convection in Cylindrical Storage Tanks -II. Effect of Heat Transfer Coefficient, aspect ratio and Temperature - Dependent Viscosity”, International Journal of Heat Mass Transfer, Vol. 36, pp. 2175-2182.

Davidson, L., 1990, “Calculation of the turbulence buoyancy-driven flow in a rectangular cavity using an efficient solver and two different low Reynolds number κ-ε turbulence models”, Numerical Heat Transfer, Vol. 18, pp.129-147.

Gross, R. J., 1982, “An Experimental Study of Single Medium Thermocline Termed Energy Storage”, ASME Report 82-HT-53, pp. 1-8.

Jaluria, Y. and Gupta, S. K., 1982, “Decay of Thermal Stratification in a Water Body for Solar Energy Storage”, Solar Energy, Vol. 28, pp. 137-143.

Kimura, S. and Bejan, A., 1996, “Natural convection in a differentially heated corner region”, Physics Fluids, Vol. 28, pp.2980-2989.

Murthy, S.S., Nelson, J.E.B. and Rao, L. S., 1992, “Effect of Wall Conductivity on Thermal Stratification”, Solar Energy, Vol.49, pp. 273-277.

Nelson, J. E. B., Balakrishnan, A. R. and Murthy, S. S., 1999, “Experiments on Stratified Chilled-Water Tanks”, International Journal of Refrigeration, Vol. 22, pp. 216-234.

Oliveski, R. De C., 2000, “Análise Numérica Experimental dos Campos de Temperatura e Velocidade em Armazenadores Térmicos”, Doctoral Thesis, Universidade Federal do Rio Grande do Sul, PROMEC, Brazil.

Oliveski, R. De C., Krenzinger, A., Vielmo, H. A. and Prieb, C. W. M., 2001, “Experimental na Numerical Analysis of a Thermal Storage Tank”, 5Th World Conference on Experimental and Heat Transfer, Fluids Mechanics and Thermodynamics, Thessaloniki.

Oliveski, R. De C., Krenzinger, A and Vielmo, H. A., 2003, “Cooling of Cylindrical Vertical Tank Submitted to Natural Internal Convection”, International Journal of Heat and Mass Transfer, V. 46, pp. 2015-2026.

Patankar, V., 1980, “Numerical Heat Transfer and Fluid Flow”, McGraw-Hill.

Poujol, F. T., “Natural convection of a High Prandtl number fluid in cavity”. Int. Comm. Heat Mass Transfer, vol. 27, pp.109-118, 2000.

Reindl, D. T., Beckman, W. A. and Mitchell, J. W., 1992, “Transient natural convection in enclosures with application to solar thermal storage tanks”, Solar Engineering, Vol. 2, pp. 1143-1148.

Shyu, R-J, Lin, J-Y and Fang, L-J., 1989, “Thermal Analysis of Stratified Storage Tanks”, Journal of Solar Energy Engineering**,** Vol. 111, pp. 54-61.

Van Doormaal, J. P. and Raithby, G. D., 1991, “Enhancements of the simple method for predicting incompressible fluid flow”, Numerical Heat Transfer, Vol. 7, pp. 147-163.

Vardar, N., 2003, “Numerical analysis of the transient turbulent flow in a fluel oil storage tank”, ”, International Journal of Heat Mass Transfer, Vol. 46, pp. 3429-3440.

Zurigat, Y. H., Liche, P. R. and Ghajar, A. J., 1991. “Influence of Inlet Geometry on Mixing in Thermocline Thermal Energy Storage”, International Journal of Heat Mass Transfer, Vol. 34, pp. 115-125.