NUMERICAL SIMULATION OF THE INTERNAL BOUNDARY LAYER AT THE LAUNCHING CENTER OF ALCANTARA - CLA

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Abstract. *This work presents a numerical study of the Internal Boundary Layer (IBL) formed by a reverse step flow. So, the flow over the coastal cliff site located in the region of the Alcantara Space Center Facilities – CLA (2° 19' S; 44° 22' W) is simulated. This cliff has a height of 50 m and in its neighborhood a rockets launching pad is located. A two-dimensional flow program was used for this study. The governing equations were written using the vorticity-velocity formulation. High order compact finite differences schemes were used for the spatial derivatives. The time integration was performed with a 4th order Runge-Kutta scheme. The step was specified through the immersed boundary method. On the other hand, observational data (ECLICA experiment) showed, through an analysis of (I) the peaks of the wind gusts,(ii) the instantaneous amplitude of the wind gusts and (iii) the turbulent intensity measured with anemometers located in towers in the continent (B – 50 m and C - 100 m away from the cliff, with heights of 10 and 15 m, respectively), that the IBL height is well defined at the site. It was also noted that the top of the IBL stays between the heights of the 4.5 and 9 m anemometers of towerB, and that it is higher than 15 m at the tower C. Finally, the numerical results showed the formation of the IBL with a good agreement with the observational data. Also, through this method one may determine the values of the IBL at any distance from the cliff (discontinuity point), and other numerical studies may be carried out to find under which conditions the undesirable effects of the IBL are minimized, especially during the launching of rockets.*

Keywords*: Alcantara Space Center Facilities, Internal Boundary Layer, Compact Schemes of high order finite differences, method of immersed boundary.*

1. INTRODUCTION

The Launching Center of Alcântara (CLA) is located on the coast of Maranhão, at the latitude 2° 19' S and the longitude 44° 22' W, and 50 m above sea-level, distant 30 km from São Luiz. In this place the Brazilian rockets, such as the Satellite Launching Vehicle (VLS) and the Sounding Rockets (SONDA II, SONDA III, VS30 and VS40), are launched.

The launchpad area of the CLA presents special characteristics, because it is located on a plateau, 150 m away from a 50 m high near vertical coastal cliff, as shown in Fig. 1. Thus, its micrometeorology suffers the influence of an abrupt roughness change due to the passage from the smooth sea surface to the rough continental surface, which is covered by shrubbery vegetation with an average height of 3 m. The wind, which is initially in balance with the oceanic surface, interacts with the surface of the site, with the consequent onset of a stronger turbulence and changes in its profile and shearing properties, including the onset of an internal boundary layer; all these occurences affect the vertical displacement of a rocket during its critical launching phase (Fisch, 1999).

These natural characteristics also complicate the collection of data at the site, such as the ones obtained with captive balloons, which usualy operate with winds of up to 5 to 6 m/s; however, during the dry season, the average velocity of the wind remains around 7 to 8 m/s, with peaks of 12 m/s. On the other hand, the collection of altitude data is effected using radiosoundings launched from a site located 7 km away from the launchpad; so, these data must be corrected to be representative of the atmospheric boundary layer near the launchpad.Thus, due to the problems mentioned, wind tunnel experiments and numerical modeling constitute strong tools to study the micrometeorological behavior of the CLA site (Fisch, 1999).

Figure 1. Alcântara coastal cliff

To analyze the situation at CLA, this work presents a numerical study of the Internal Boundary Layer (IBL) formed after the wind crosses the coastal cliff mentioned above. It should be noted that an IBL is the response of the atmosphere to sudden changes of the surface, such as its roughness, temperature or humidity, or the uneveness of a cliff (Jegede e Foken, 1998).

The influence of the new surface on the flow depends not only on its characteristics, but also on the ones of the previous surface, over which the flow was in balance. So, a new equilibrium layer is formed, whose vertical thickness increases with the distance from the discontinuity point. Above this new layer the wind profile remains in balance with the previous surface, while in its inside, the wind profile is adjusted to the new surface (Stull, 1988).

The first studies aimed the problem of the neutral flow after a step change of a rough surface. The main interest was the development of the modified wind profile, the response of the turbulent field and the growth of the IBL. Later the attentions focused on the effects of the thermal stratification on the flow, the growth and the structure of the IBL related to the surface step changes (Garratt, 1989).

The height of the IBL may be estimated through several methods, as the Table 1 of Savelyev and Taylor (2005) summarizes for a neutral (adiabatic) atmosphere and their item 5 shows for diabatic flows. Figure 2 shows a schematic representation of the development of the IBL and of the wind profile over a change of the surface height, such as is the case at the CLA cliff.

In the present study, simulations of the flow around a coastal cliff were made using the immersed boundary technique, which was proposed by Peskin (1972). This method presents characteristics different from the ones commonly found in computational fluid dynamics: instead of using numerical meshes that adjust to the shape of the solid that serves as an obstacle to the flow, it uses the governing equations expressed in cartesian coordinates, adding a forcing term to them when a body is immersed in the flow. This force is determined by the body configuration. Here the Navier-Stokes equations are expressed in the vorticity-velocity formulation. The spatial derivatives are calculated with a 6th order compact finite differences scheme while the time integration is carried out through a 4th order Runge-Kutta scheme. The simulations were performed for high Reynolds numbers ($Re = 10^5$, 10^6 and 10^7), and the results are compared with previous ones of Pires *et al*. (2006) to verify the numerical code.

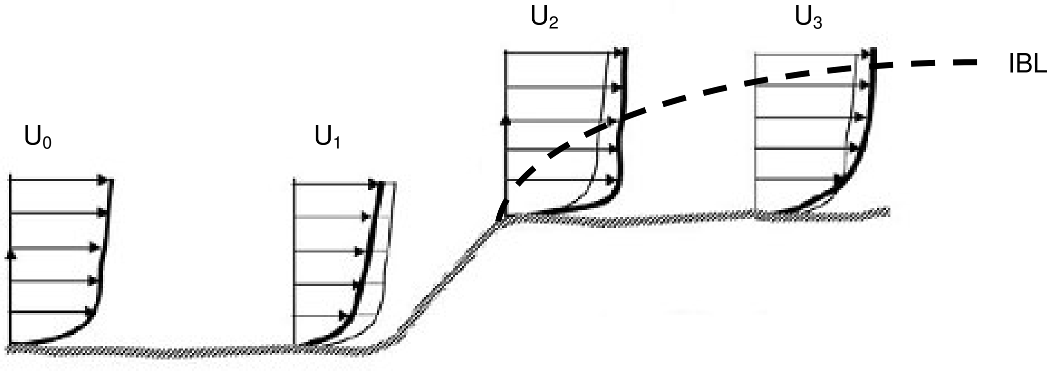


Figure 2. Schematic representation of the development of the IBL and the wind profile

2. FORMULATION

The governing equations are the incompressible, unsteady 2D Navier-Stokes equations with constant density and viscosity, with the streamwise direction (x) velocity component u, and the vertical direction (y) component v (Góis e Souza, 2007):

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{\partial P}{\partial x}+\frac{1}{\mathrm{Re}}\nabla^2 u+F_x, \quad (1)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{\partial P}{\partial y}+\frac{1}{\mathrm{Re}}\nabla^2 v+F_y, \quad (2)$$

and the continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (3)$$

where P is the pressure and

$$\nabla^2=\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right). \quad (4)$$

The variables used are dimensionless, and they are related to the dimensional ones by:

$$x=\frac{\overline{x}}{\overline{L}},\ y=\frac{\overline{y}}{\overline{L}},\ u=\frac{\overline{u}}{\overline{U}_\infty},\ v=\frac{\overline{v}}{\overline{U}_\infty},\ t=\frac{\overline{t}\,\overline{U}_\infty}{\overline{L}},\ \mathrm{Re}=\frac{\overline{U}_\infty\overline{L}}{\overline{\upsilon}}$$

where Re is the Reynolds number, the terms with an over-bar are dimensional terms: $\overline{L}$ is the length of the step, $\overline{U}_\infty$ is the free-stream velocity, $\overline{\upsilon}$ is the kinematic viscosity and F_x and F_y are the forcing terms added to the governing equations to be used by the immersed boundary method.

The vorticity ω is defined as the negative curl of the velocity vector. The vorticity transport equation is obtained by the curl of the momentum equations, Eqs. (1) and (2), thus resulting:

$$\frac{\partial \omega_z}{\partial t}=-u\frac{\partial \omega_z}{\partial x}-v\frac{\partial \omega_z}{\partial y}+\nabla^2\omega_z+\frac{\partial F_x}{\partial y}-\frac{\partial F_y}{\partial x}. \quad (5)$$

Taking the definition of the vorticity and the mass conservation equation, one can obtain a Poisson equation for the v velocity component:

$$\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}=-\frac{\partial \omega_z}{\partial x}\ , \tag{6}$$

The boundary conditions are as follows: at the inflow, the velocity and the vorticity components are specified based on the Blasius boundary layer solution; at the upper boundaries the vorticity disturbances are set to decay exponentially to zero; finally, at the outflow boundary the second derivative of all dependent variables are set to zero. The details are given bellow.

3. NUMERICAL METHOD

As mentioned above, at the inflow boundary of the integration domain (x = x_0), the velocity and the vorticity components are specified, and at the outflow boundary ($x = x_{max}$), the second derivative of the velocity and the vorticity components in the streamwise direction x are set to zero. At the upper boundary ($y = y_{max}$), the derivatives of v in the y direction are set to zero and at the lower one (y = 0), the velocities u and v are set to zero.

Three damping zones were used in the simulations to force the disturbances to gradually decay to zero after the streamwise x domain of interest. The basic idea is to multiply the vorticity components by a ramp function $f_2(x)$ after each step of the integration scheme. This technique has been proved by Kloker (1998) to be very efficient in avoiding reflections that could come from the boundaries when simulating flows with disturbance propagations. Using this technique, the vorticity components are taken as:

$$\omega_Z(x,y)=f_2(x)\omega(x,y,t) \tag{7}$$

where $\omega(x,y,\ t)$ is the vorticity disturbance component that comes out from the time integration scheme, and $f_2(x)$ is a ramp function that varies smoothly from 1 to 0. The implemented function in the x direction was:

$$f_2(x)=f(\in)=1-6\in^5+15\in^4-10\in^3 \tag{8}$$

with $\in=\dfrac{(i-i_3)}{i_4-i_3}$ for $i_3\le i\le i_4$ corresponds to the positions x_3 and x_4 in the streamwise direction, respectively. To ensure a good numerical result, a minimum distance between x_4 and the end of the domain x_{max} should be specified.

The spatial derivatives were calculated using a 6_{th} order compact finite difference scheme (Souza *et al.*,2005). The v-Poisson equation was solved using a Full Approximation Scheme (FAS) multigrid v-cycle working with 4 grids.

The forcing terms were calculated using the following equations:

$$F_x(i,j)=\delta fr(u) \tag{9}$$

$$F_y(i,j)=\delta fr(v) \tag{10}$$

where fr is the relaxation term, here $fr = -Re$, u an v are the velocity components in the streamwise x and vertical y directions, respectively, and $\delta\,(i,\,j)$ = 0 outside the immersed boundary, and $\delta\,(i,\,j)$ = 1 at the boundary and inside the immersed body.

The time integration was performed using a fourth-order Runge-Kutta scheme, and the numerical procedure works as described below; at each step of the Runge-Kutta scheme the following instructions are necessary:

1. Compute the spatial derivatives of the vorticity transport equation.
2. Compute the forcing terms F_x and F_y.
3. Compute the rotational of the forcing terms.
4. Integrate the vorticity transport equation over one step (or sub-step) of the scheme using the values obtained in steps 1 and 3.
5. Apply the buffer domain technique near the outflow.
6. Compute v through the Poisson equation.
7. Compute u through the continuity equation;
8. Verify the values of the velocity components at the immersed boundary; if they are below a predefined value, continue; otherwise, go to step 2

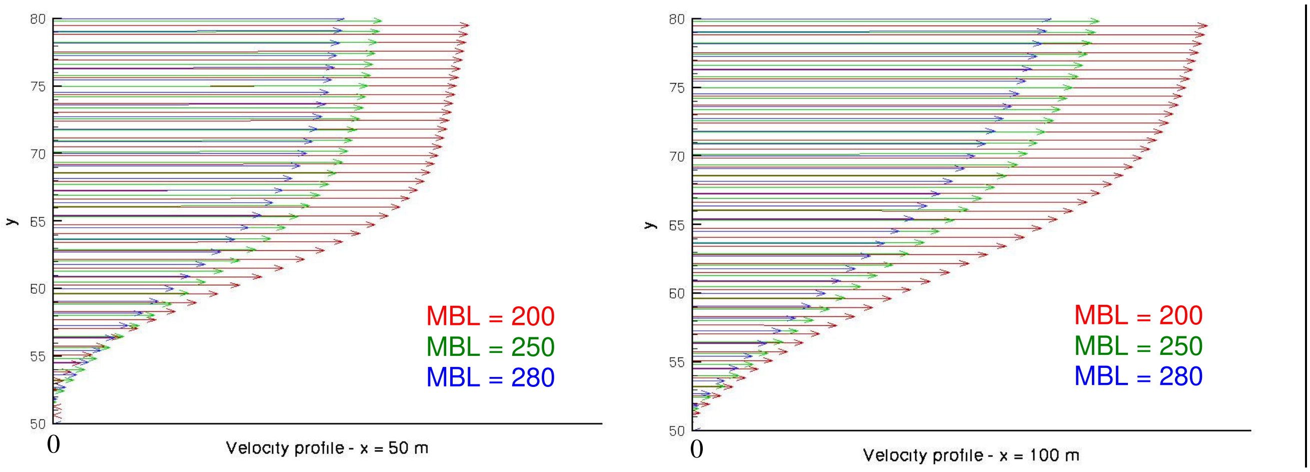
This scheme was repeated until a stable or a time periodic solution was reached.

4.RESULTS

In this work the computational results were compared with the observational data obtained during the ECLICA 2 Campaign (Study of the Internal Boundary Layer in the CLA Region), which took place from October 6 up to 16, 1998, during the transition from the rainy to the dry season (Pires et al., 2006). These observational data, through an analysis of (i) the peaks of the wind gusts, (ii) the instantaneous amplitude of the wind gusts and (iii) the turbulent intensity measured with anemometers located in towers in the continent (points B – 50 m and C - 100 m away from the cliff, with heights of 10 and 15 m, respectively), showed that the IBL height is well defined at the site. It was also noted that the top of the IBL stays between the heights of the 4.5 and the 9 m anemometers of tower B, and that it is higher than 15 m at the tower C.

The atmospheric Re at CLA, based on the height of the cliff (50 m), is of the order of 10^7, a very high value. Thus, the wind profiles numerically computed for the distances of 50 and 100 m downwind of the cliff, with the height of the Marine Boundary Layer (MBL) respectively equal to 200, 250 e 280 m, and Re varying from 10^5 to 10^7, are presented on Figs. 3, 4 and 5.

For Re = 10^5 (Fig. 3), with a MBL height of 200 m, at 50 m downwind from the cliff (tower B), the IBL height is about 18 m; at 100 m downwind (tower C) this height is equal to 20 m. For a MBL height of 250 m, these values become 20 and 22 m, while for 250 m, they are 22 and 24 m. Thus, in this case, the IBL grows proportionally to the growth of the MBL.

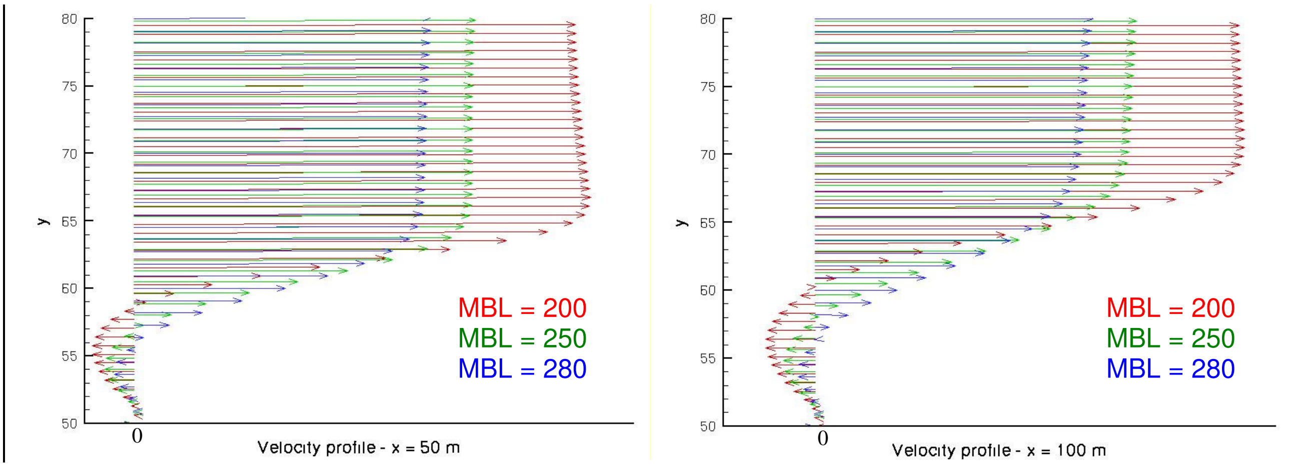


(a) (b)

Figure 3 – Wind profiles at 50 and 100 m downwind of the cliff for Re = 10^5

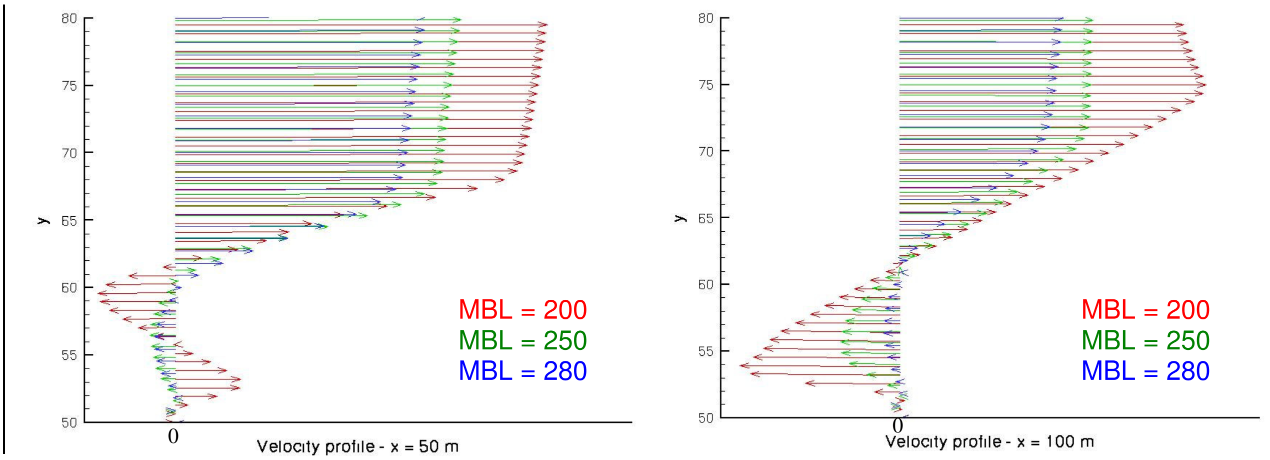
For Re = 10^6 (Fig. 4), there is a recirculation bubble, which is smaller than the one for Re = 10^7 shown on Fig. 5. With a MBL of 200 m, the IBL height at the tower B is about 18 m, while at the tower C it is 20 m. However, with a MBL of 250 m, the IBL decreases to 15 m at point B, and to 16 m at point C. The same does occur with a MBL of 280 m, resulting the values of 12 m for B and 15 m for C. So, the growth of the MBL height causes a decrease of the IBL height; also, observing Figs. 3 and 4, the smaller Re presents a greater recirculation bubble, thus interfering in the height of the IBL.

For Re = 10^7, the results were not stationary, as shown in Fig. 8 (see below), thus presenting varying instantaneous values for the IBL height, such as the ones presented in Fig. 5: for the tower B (50 m), 20 m for both MBL heights of 250 and 280 m, and 22 m for the MBL height of 200 m, while for the tower C (100 m), the IBL height was 24 m for each one of the MBL heights considered.



(a) (b)

Figure 4 - Same as Fig. 3, for Re = 10^6



(a) (b)

Figure 5 – Same as Fig. 3, for Re = 10^7

Figs. 6, 7 e 8 present the iso-vorticity contours, respectively for Re equal to 10^5, 10^6 and 10^7, for a MBL height of 250 m. For Re = 10^7, the flow was non stationary, which was also the case for the other two MBL heights studied (not shown). Notwithstanding, it seems that for higher Re, the differences among their respective IBL heights do decrease, that is, the heights tend to an asymptotic.

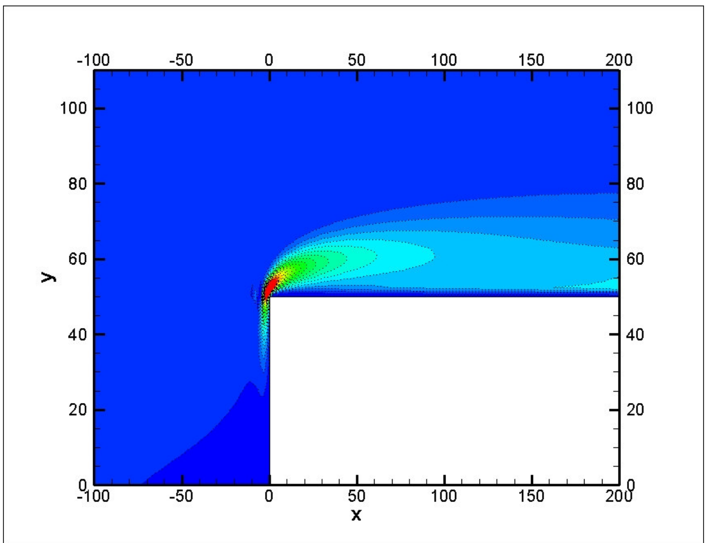


Figure 6 - Vorticity contours for Re = 10^5

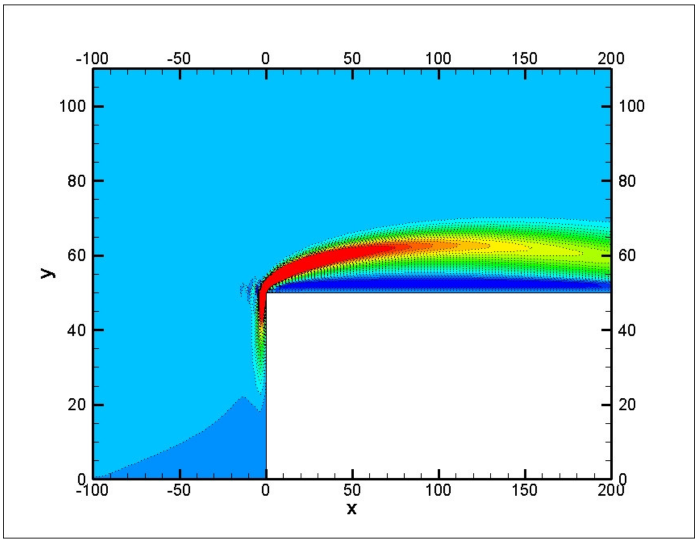


Figure 7 - Vorticity contours for Re = 10^6

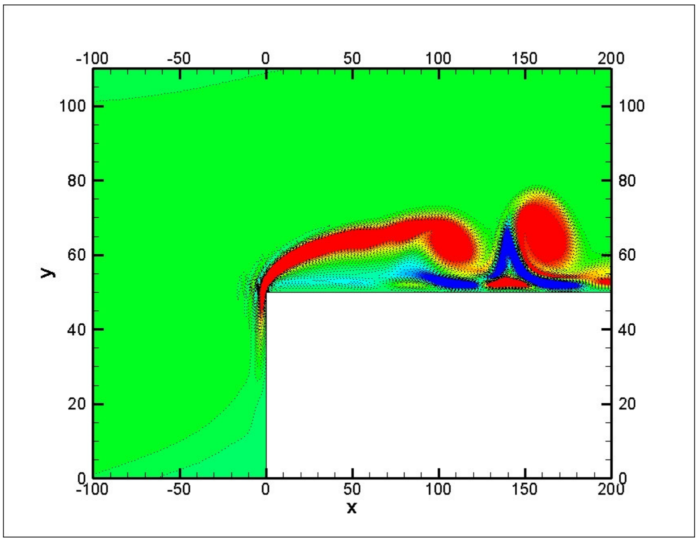


Figure 8 - Vorticity contours for Re = 10^7

5. CONCLUSIONS

The computed IBL heights corresponding to 50 m downwind of the CLA cliff (12 to 22 m) overshoot the measured values of about 9 m, which is probably due to the recirculation bubbles that decrease with the increase of Re near the cliff. On the other hand, the 100 m downwind results (15 to 24 m) agree with the measured ones, which were higher than 15 m. Finally, as the launching pad is located 150 m downwind from the cliff, the IBL does affect the rocket launchings at CLA. The height of the MBL is very important in defining the height of the IBL, as demonstrated by the Figs. 3 up to 5.

6. ACKNOWLEDGEMENTS

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