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PROVE THE CYCLOIDAL SLOTTED ANODE EFFICIENCY BY MODELING THE BUBBLE FLOW

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Abstract. *The electric energy consumption has a strong impact on production costs of an aluminum smelter. On the alumina reduction reaction process gas bubbles are generated what create a resistance layer at the anode/electrolyte interface what leads to an increase on energy consumption. Slotted anodes have been used in order to reduce gas bubble resistance. However, that is not consensus in aluminum industry about what is the best slot shape. The main objective of this study is to present a new slot shape: the cycloidal slotted anode and by using a CFD model of the bubble driven flow, to prove its better efficiency when compared with the traditional slotted anode shapes. We consider the multiphase flow as a continuous liquid/dispersed gas pair, turbulent and steady state. A comparison with measurements found in the literature is made. The simulations were done using the commercial code ANSYS CFD 14.0.*

Keywords: *aluminum smelter, gas bubbles, slotted anode, CFD model, multiphase flow.*

1. INTRODUCTION

In the Hall-Héroult process many gases are generated inside the pots. The gas (mainly carbon dioxide) creates a layer below the anode surface (see Fig. 1).

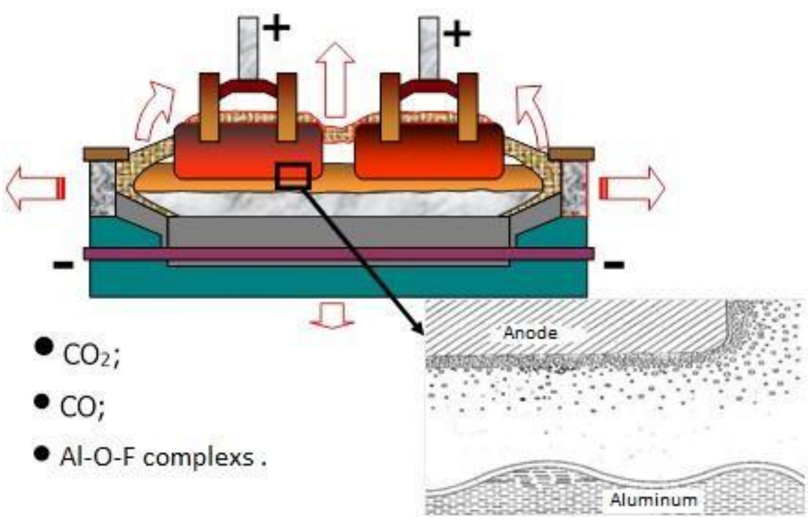


Figure 1. Shows a resistive layer made by the bubbles generated at anode bottom.

This layer contributes to the bath flow that is responsible for the alumina dissolution and its transport into the interpolar space. However, the bubble layer increases the voltage drop and electric noise (voltage fluctuation) of the cell (Chen, 2001). Also, the gas induces bath flow and bath turbulence which influence the current efficiency (Haarberg, 1998) and (Richards, 2003).

It is well known that slots in the anodes are effective in reducing the voltage drop and noise due to bubbles. This happens because the slots allow a better elimination of the gas from the anode bottom surface (Chen, 2001). Improvements in current efficiency are expected too (Tandon, 2005).

Well, the CO_2 and other gases flow from the anode bottom through the bath moved by the difference between gas density and bath density. When the anode has slots the gases flow more easily. Naturally, if a good slot design was made at anode bottom the speed that these gases flow can be improved (Severo, 2007).

The main objective of this work is, by using a CFD model, to prove that the cycloidal slotted anodes have a better performance than the traditional ones (straight slotted anodes).

2. THE PHYSICAL PROBLEM

To study the physical phenomena really happens inside an aluminum pot line is very complex. There are several phenomena happen simultaneously influenced by: the magnetic field, the heat transfer between substances, the pot surfaces and the environment, chemical reactions, and so on. Besides, both the gases and the bath are a mix of many substances. Naturally, if no simplifications were made will be impossible to advance on any study about it (Grjotheim, 1993).

First, the problem can be simplified by considering CO_2 all the gases that are generate on anode bottom. This is in fact a kind of reasonable consideration. Doing this is not so difficult to estimate the mass of CO_2 that is generate at the electrolytic reaction. This reaction can be simplified by (Fischer, 1995):

$$2\,Al_2O_3 + 3\,C \rightarrow 4\,Al + 3\,CO_2 \tag{1}$$

Knowing the net carbon consumption, that means, the mass of carbon need to produce 1000 kg of aluminum, the aluminum production and the quantity of pots in operation and the quantity of anodes per pot is possible to calculate the CO_2 mass flow rate at the bottom of one anode. With the CO_2 mass flow rate and the slot geometry is possible estimate the CO_2 speed inside the slot if the bath properties were known.

Well, thinking with the same logic as was made to the CO_2, maybe could be considerate that the bath is made a 100% of cryolite (in fact, about 80% of the bath is really cryolite). But, the problem is how to find all the properties needed on the mathematical model. Even if all the properties of the cryolite at 960°C were know, it will be wrong to considerate that 100% of the bath is cryolite. On a real pot line, the bath chemistry and the pot temperature are controlled by adding more or less fluorite on the pot. The fluorite changes the bath viscosity and the temperature with the reaction occurs. Besides that, the fluorite addition logic control changes according the control technology used by the aluminum smelter. Thus, determinate the bath properties still a problem.

Happily, knowing fluid mechanics there is a solution for that. Considering an incompressible flow, the original problem can be study by dynamic similarity: “The dynamic similarity exists when the model and the prototype Reynolds number are equal” (White, 2003). That means, as soon as, the dynamic similarity exists , it is possible to create a model in which the gas bobble are 100% CO_2 and the liquid is 100% water and collect valuable information from it.

The Reynolds number is defined by:

$$Re = \frac{VL}{\nu} \tag{2}$$

where,

V: CO_2 speed
L: slot length
ν: CO_2 kinematic viscosity

In reality the CO_2 flows in the bath. But, at the model the CO_2 flows in water. As soon as, the water viscosity is lower them the bath viscosity the speed must be greater to maintain the Reynolds number constant.

To reach this work goal, that is to compare the cycloidal slot and the straight slot efficiencies, is enough to estimate a Reynolds number and a CO_2 mass flow rate in water to run the proposed biphasic mathematical model.

3. THE CYCLOIDE CURVE

The cycloid is the curve that connecting two points along which a particle falling from rest and under the influence of gravity goes from the highest point to the lowest point in the shortest time. This was proved by Johann Bernoulli on a work named "The Brachistochrone Problem" (Øbaule, 1958). At this work it was analytically demonstrated and the particule falling time is also calculated. The Figure 2 show a schematic drawing of an apparatus used to measure the falling time of a particle by the cycloid curve and by a straight plan.

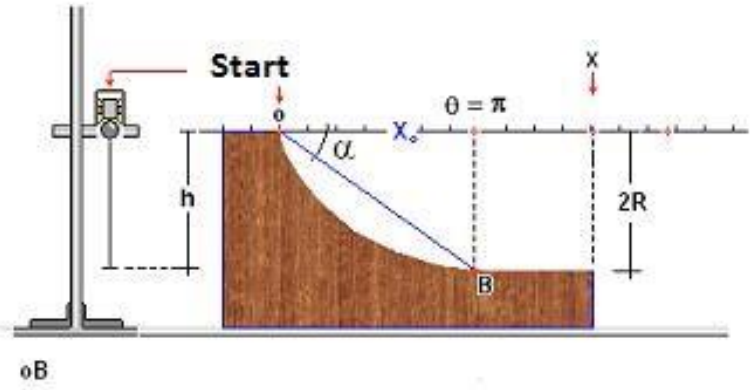


Figure 2. Schematic drawing of an apparatus used to measure the falling time of a particle by the straight plan (t_1) and by the cycloid curve (t_2)

The falling time of a particle on a plan (t_1) is:

$$t_1 = \sqrt{\frac{2h}{a}} = \sqrt{\frac{2h}{g\ sen\alpha}} \tag{3}$$

The minimum falling time of a particle (t_2) which is the falling time on a cycloid can be determined by:

$$\boldsymbol{t_2 = \int_{x_1}^{x_2} \frac{\sqrt{1+\left(\frac{dy}{dx}\right)^2}}{2gy}.dx = \pi\sqrt{\frac{h}{2g}}} \tag{4}$$

Then the falling time of a particle on an inclined plan is:

$$t_1 = \pi\sqrt{\frac{h}{2g}}\sqrt{1+\left(\frac{2}{\pi}\right)^2} \tag{5}$$

Now, comparing t_1 obtained on equation (3) with t_2 obtained on equation (5) and dividing t_2 per t_1:

$$\frac{t_2}{t_1} = \frac{\pi\sqrt{\frac{h}{2g}}}{t_1 = \pi\sqrt{\frac{h}{2g}}\sqrt{1+\left(\frac{2}{\pi}\right)^2}} = \frac{1}{t_1 = \sqrt{1+\left(\frac{2}{\pi}\right)^2}} = 0{,}84356 \tag{6}$$

In another words, we can say that the particle falling time by the cycloid is about 84% of the time that the same particle falling by an inclined plan.

4. THE MATHEMATICAL MODEL

The commercial CFD software package ANSYS CFX solves the hydrodynamics equations (Navier-Stokes and mass conservation) by the Finite Volume Method. This software has several options for multiphase inhomogeneous flow. On those model is crucial to predict with accuracy the mechanical, thermal and chemical interactions between phases (CFX 14.0 User Manual).

The multiphase flow is widely classified as segregated or disperses. At the segregated flows, the phases are circulated through the domain. At the disperse flows, at least one of the phase is a little drop, bobble or particle. In the case of this article, one gaseous phase was used.

The Volume of Fluid Method (VOF) was originally introduced by Hirt and Nichols (Hirt and Nichols, 1981) and can be applied in problems with several fluids with different densities and thus, is considered appropriate to predict the free surface movement. The main idea of the VOF method is introduce a function φ with the value is φ = 1 at any point occupied by one fluid and φ = 0 in case of do not be occupied by any fluid. The φ average in one cell represents the cell volume fraction occupied by the fluid. In particular φ = 1 corresponds to a cell full of fluid, φ = 0 corresponds to an empty cell and 0 < φ < 1 corresponds to a cell that contains the free surface.

4.1 Domain Discretization

At a CFD simulation, the volume in turn of one anode is divided in a mesh composed by "small" volumes, to which are realized calculations of mass and momentum conservation.

At this work a mesh composed by tetrahedra in the major part of the domain and by prismatic cells next to the solid borders. The evaluation quality method used to build the mesh was the average Skewness, that evaluate how much one cell of the mesh was distorted in comparison with a reference cell (See Fig. 3).

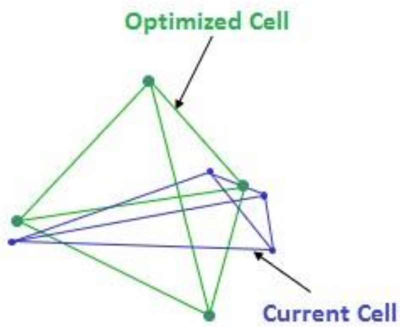


Figure 3. Comparison between a distorted cell (current cell) and a reference cell (optimized cell)

The average Skewness is given by:

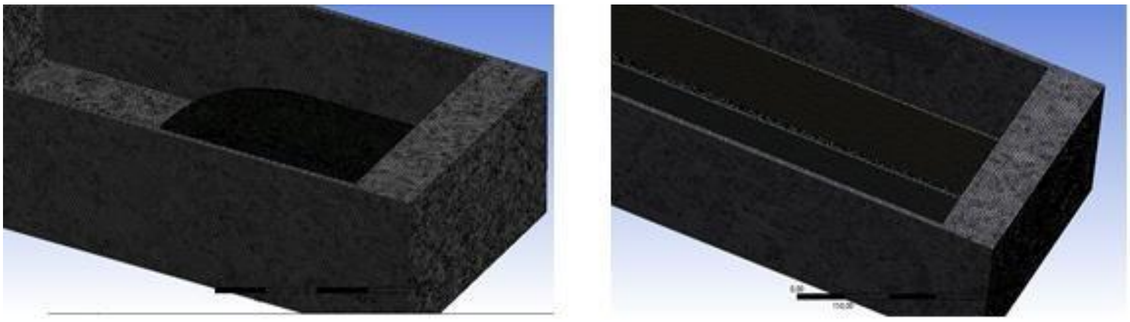
$$Skewness = \frac{Optimized\ cell\ size - Current\ cell\ size}{Optimized\ cell\ size}$$
(3)

When skewness=0 the cell is good and when skewness=1 the cell is bad. See on table 1 the data with the mesh used at the simulations

Table 1: Data with the mesh used at the simulations

	SLOT TYPE	
	CYCLOIDAL	STRAIGHT
nodes number	427315	620782
Elements number	2176652	2893605
Average Skewness	0.23	0.22

The domain used at the simulation is show at Fig. 4: (a) Cycloidal slotted anode and (b) Straight slotted anode



(a) (b)

Figure 4. The domain used at the simulation: (a) Cycloidal slotted anode and (b) Straight slotted anode.

4.2 Turbulence Model

The most usual approach at CFD simulations is the use of conservation equations simplified by a technique known as RANS (Reynolds-averaged Navier-Stokes). RANS calculate the average flow without in fact “solve” the turbulence, which the effect on the flow are described in a simplified way, by using one of turbulence models or closing models. Theoretically, the second order closing models, like the Reynolds Stress Model, go more in-depth on description of the turbulence statistical properties, because it permits considerate the anisotropic aspect of the flow.

At this work, a first order closing model (standard Kϵ-), on which the turbulence effects in the average flow are described by two equations:

(a) One for the kinetics turbulent energy (k); (b)
Other for the rate of turbulence dissipation (ϵ).

The standard K-ϵ method was chosen because it has a good balance between the results quality and the little processing capacity needed. The use of alternatives approaches to the RANS, like LES or DES, gives known benefits to the calculations, but still restricted to the academic use because of the high processing capacity needed (Nozu et al., 2008).

5. RESULTS AND DISCUSSION

The results presented here were obtained from the proposed mathematical model which solves the hydrodynamics equations (Navier-Stokes and mass conservation) for a multiphase inhomogeneous flow by the Finite Volume Method.

Two models were made, one to the straight slotted anode and other to the cycloidal slotted anode. As was explained before as biphasic flow of CO_2 bubbles inside water was used to run the mathematical model at the same conditions.

5.1 Cycloidal Slotted Anode Results

According the model there are two longitudinal cycloidal slots per anode. The cycloidal slots lead the CO_2 flow from the anode bottom just to one side of the anode (Face A). When the anodes were putted on the pot the anode Face A must be set to the pot central channel. The idea is that the gas flow going to the pot central channel helps to mixing the alumina with the bath. The geometric characteristics of the cycloidal slots are showed at the Table 2.

Table 2 – Geometrical characteristics of the cycloidal slot

Cycloidal Slot	value	unit
Slot thickness	0.01	m
Maximum slot depth	0.30	m
Minimum slot depth	0.00	m

The Figure 5 shows the cycloidal slotted anode placed on the domain used at the mathematical model. Note the slot shape and how they are disposal at the anode. The anode is inside a bath of water.

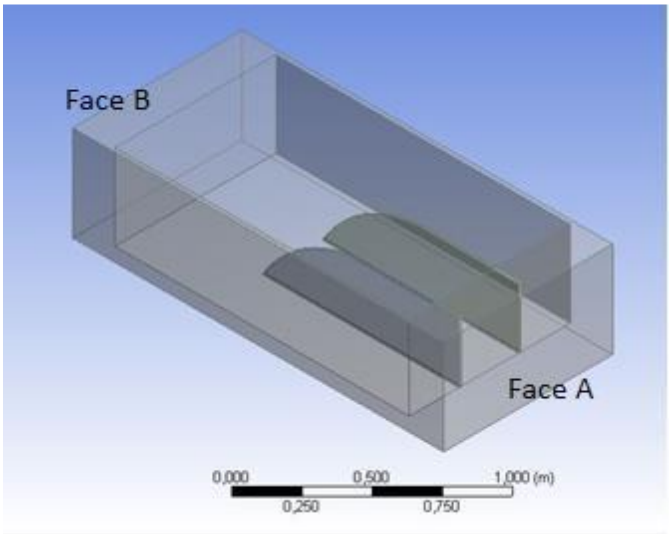


Figure 5. The cycloidal slotted anode placed on the domain used at the mathematical model

The Figure 6 shows the CO_2 flow speed at the outside of the cycloidal slot according the slot deep. Note that the CO_2 speed increases according the slot deep until to be about 3 mm from the slot maximum depth (on anode wall) when a little decrease on that speed happened.

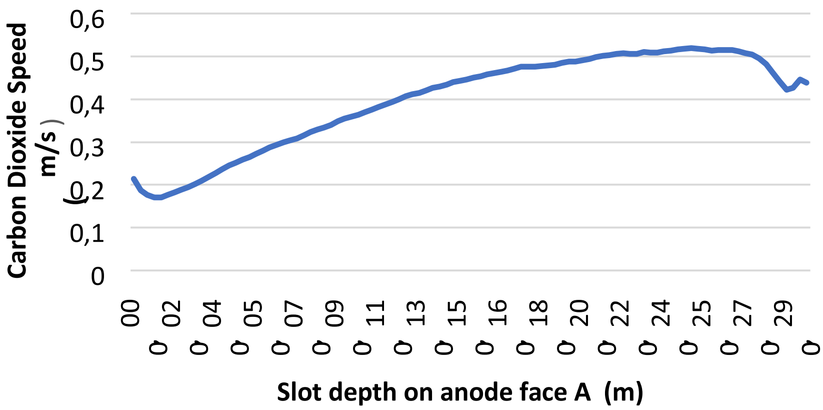


Figure 6. The CO_2 flow speed at the cycloidal slot outside at Face A

The Figure 7 shows map of the CO_2 flow speed on a center plan of one of the slots. Note that the CO_2 speed increases according the flow become next to be cycloid curve and also when the flow be close to the anode edge (the slot outside on Face A). The cycloid seams to accelerate the flow.

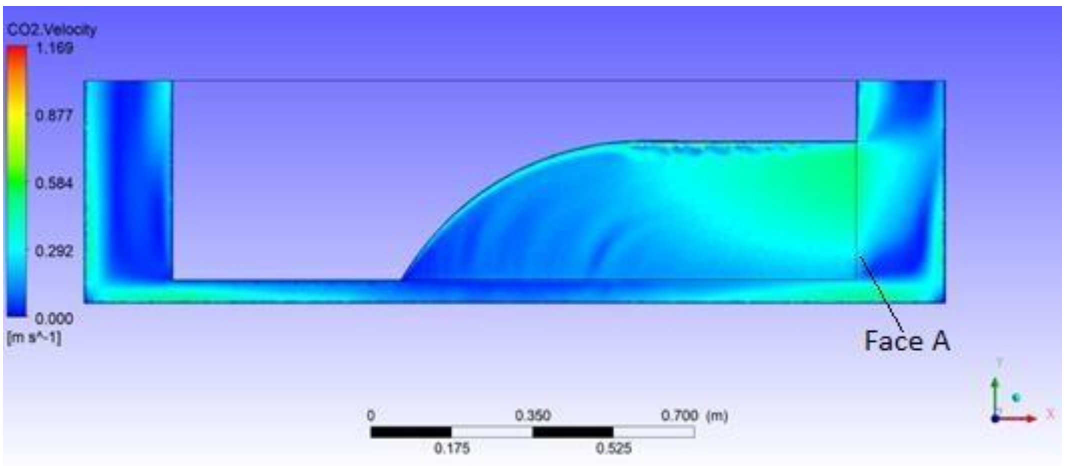


Figure 7. The map of the CO_2 flow speed on a center plan of one cycloidal slotted anode

5.2 Straight Slotted Anode Results

According the model there are two longitudinal straight slots per anode. The straight slots have 280 mm deep at anode Face B and 300 mm deep at anode Face A. When the anodes were putted on the pot the anode Face A must be set to the pot central channel. When the anodes where putted on the pot the anode Face A must be set to the pot central channel. The geometric characteristics of the straight slots are showed at the Tab. 3.

Table 3. Geometrical characteristics of the straight slot

Cycloidal Slot	value	unit
Slot thickness	0.01	m
Maximum slot depth	0.30	m
Minimum slot depth	0.28	m

The Figure 8 shows the straight slotted anode placed on the domain used at the mathematical model. Note the slot shape and how they are disposal at the anode. The anode is inside a bath of water.

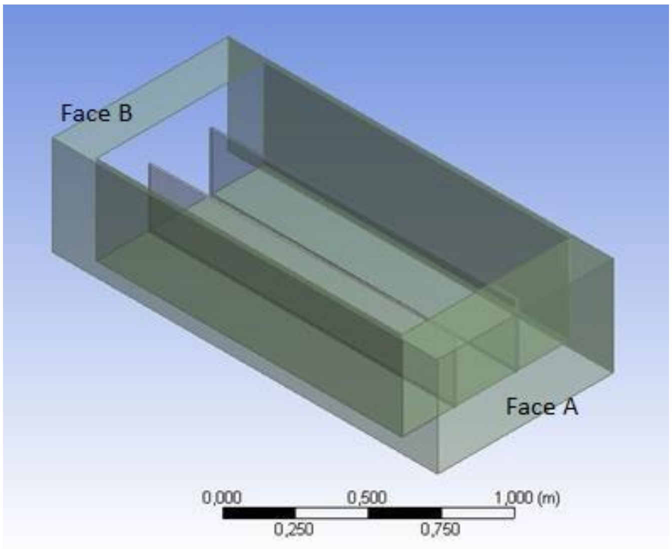


Figure 8. The straight slotted anode placed on the domain used at the mathematical model

The Figure 9 and Figure 10 shows the CO_2 flow speed at the outside of the straight slot according the slot depth. The maximum depth at anode Face A is 300 mm and at anode Face B it is 280 mm. The CO_2 speed increases according the slot depth until to be next from the anode outside (at Face A or at Face B). At these areas next to the anode outside the speed of the flow oscillates decreasing and increasing again next the anode border.

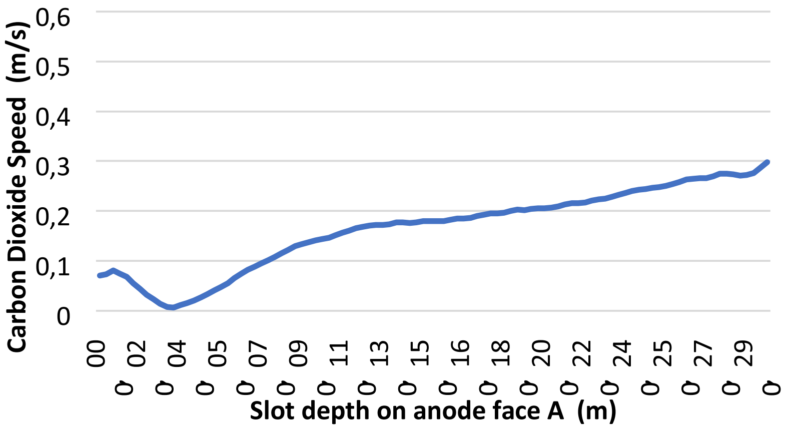


Figure 9. The CO_2 flow speed at the straight slot outside on Face A

Note that the CO_2 speed obtained with the straight slot at the both anode faces (A and B) are slow than the speed of the cycloidal slotted anode observed on Fig. 8.

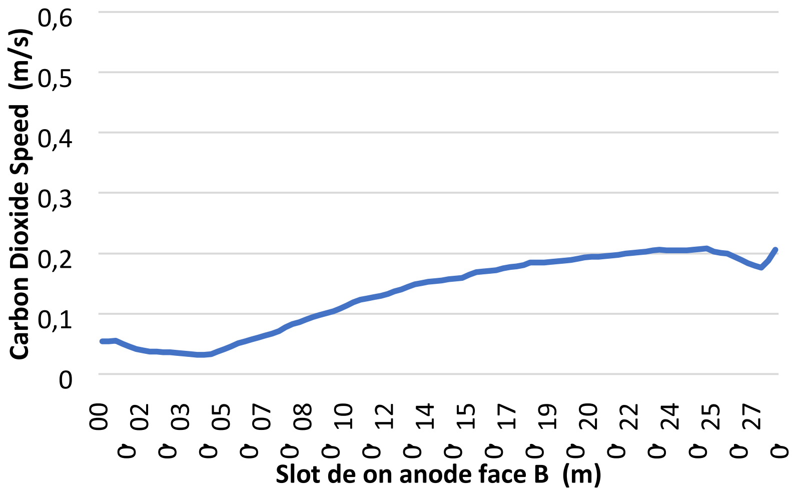


Figure 10. The CO_2 flow speed at the straight slot outside on Face B

The Figure 11 shows map of the CO_2 flow speed on a center plan of one of the slots at a straight slotted anode. Note that the CO_2 speed is low at the center and increases according the flow be next to the borders (on Faces A or B).

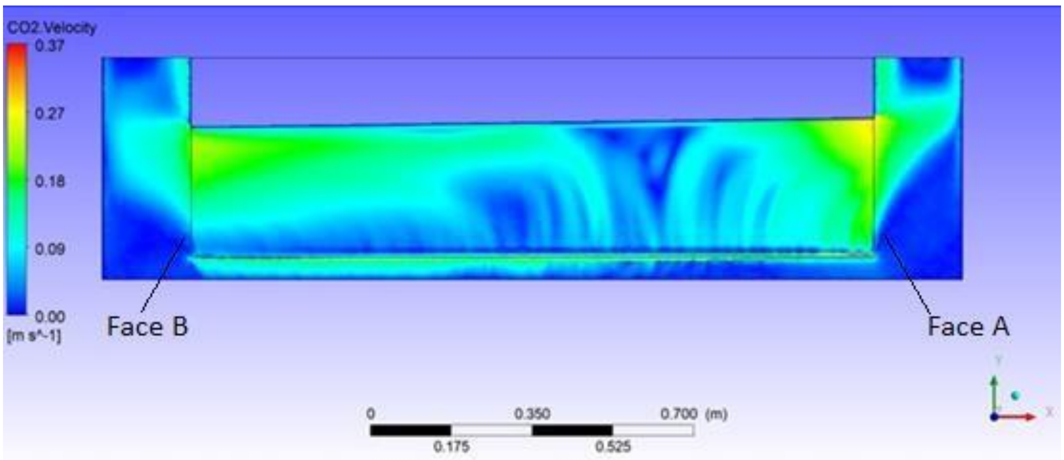


Figure 11. The map of the CO_2 flow speed on a center plan of one straight slotted anode

5.3 Straight Slot Versus Cycloidal Slot

To better compare the CO_2 map speed results of the cycloidal slotted anode (see Fig. 7) with the CO_2 map speed results of the straight slotted anode (see Fig. 11) is very important to observe that the graphics have different scales. The maximum speed at Fig. 7 is 1.169 m/s and at Fig. 11, it is 0.37 m/s. Besides that, note that the CO_2 speed obtained with the straight slot at anode outside at the both faces A and B (see Fig.s 9 and 10) are slow than the CO_2 speed at the outside of the cycloidal slotted anode observed on Fig. 8.

This fact confirms the great advantage of the cycloidal slots. The CO_2 flows from the anode bottom with higher speeds at the cycloidal slotted anode that at the straight slotted anode. At Table 4 is shown a comparison between the flow speed on straight and cycloidal slots.

Table 4. Comparison between the bubble speed on straight and cycloidal slots.

Bubble average speed (m/s)	value
Cycloidal slotted anode	0.40
Straight slotted anode	0.15
Straight slotted anode at Face A	0.17
Straight slotted anode at Face B	0.13

In fact, the total CO_2 mass flow rate is the same for any type slot (cycloidal, straight or not slotted anode). The important thing here is to optimize the quantity of CO_2 that flows through the slots. The average speed that the CO_2 bubbles going out from anode bottom by the slots is very important. If we give an easy way to the bubbles a big part of them follow this way. That means that the mass flow rate increase in the slots and decrease at anode borders maintaining the mass flow rate constant. Knowing that the mass flow rate is equal the volumetric flow rate multiplied by the substance density, we can take many conclusions comparing volumetric flow rates. At Table 5 is shown a comparison between the CO_2 volumetric flow rate on straight and cycloidal slots.

Table 5. Comparison the CO_2 volumetric flow rate on straight and cycloidal slots.

Flow rate (m^3/s)	value
Cycloidal slotted anode	0.001196
Straight slotted anode	0.000870
Straight slotted anode at Face A	0.000495
Straight slotted anode at Face B	0.000375

Observing the Table 5, is possible to calculate that the volumetric flow rate is 0.00326 m^3/s (or 27%) bigger at the cycloidal slotted anode than at the straight slotted anode.

Dias and Moura (Dias and Moura, 2005) made measurements at Albras smelter in other to compare the performance of the straight slotted anodes with not slotted anodes. It was observed a decrease in pot resistance of 0.10 □□ and noise by 0.04 □□ could be explained by the decrease in the volume of gas below the anode in 17% from 5.895 L to 4.876 L.

Naturally, the only way to know the decrease in pot resistance, noise and the gas volume below the anode that the cycloidal slotted anodes can give is made similar measurements at Albras pots. However, this will be another step. First, we must prove that the cycloidal slotted anode has a great potential. So, the smelter can invest in produce them in order to perform a test in situ. But, with basis on our studies we should expected an increase of about 27% on the mass flow rate that the gases scape from anode bottom with the use of cycloidal slotted anodes. If we considered that can reduce at least in 8% the volume of gas below the anode, this volume can decrease from 4.876L to 4.514L what will represent a great impact on pots performance, reducing significantly the noise and the energy consumption at the aluminum electrolytic cells. See at Table 6 a study with a comparative performance between: Not slotted, Straight slotted and Cycloidal slotted anodes.

Table 6. Comparative performance study between:
Not slotted, Straight slotted anodes and Cycloidal slotted anodes

	Gas volume under the anodes (L)	Resistance Decrease ($\mu\Omega$)	Energy save in one cell (kWh)
Not slotted anodes	5.895	-	-
Straight slotted anodes	4.876	0,10	2,97
Cycloidal slotted anodes	4.514	0,09	3,21

6. CONCLUSION

The CFD multiphase model of the bubble driven flow presented at this work was detailed enough to differentiate the effects of different anode and slot geometries. A full pot model is necessary in order to observe all the significant phenomena that occur including better information about the electrolytic bath properties.

Anyway, the results obtained indicate that we can expect an improvement of 160% on the average speed and of around 27% in the mass flow rate at which the gases will come out from the cycloidal slotted anodes bottom than compared with the straight slotted ones. This can reduce the volume of gas below the anode what represents a great impact on pots performance, reducing significantly the noise and the energy consumption at the aluminum electrolytic cells. Thus, to reduce in some millions of dollar per year the aluminum production costs.

7. ACKNOWLEDGMENTS

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8. REFERENCES

CFX 14.0 User Manual, "Solver Modeling, Multiphase Flow Modeling".

Chen J. J., Qian, K.X. and Zhao, J.C., 2001." "Resistance Due to the Presence of Bubbles in an Electrolytic Cell with a Grooved Anode", *Chemical Engineering Research & Design*, 79(A4), p. 383-388.

Dias, H. P. and Moura, R. R., 2005. "The use of transversal slot anodes at Albras smelter" *Light Metals*, p. 341- 344.

Fischer, W. F., et al., 1995. "Anodes for Aluminum Industry", *R&D Carbon Ltd*., Switzerland, p. 30-50.

Grjotheim K., and Kvande, H., 1993, "Introduction to Aluminium Electrolysis", *Aluminium-Verlag*, 2nd edition, Düsseldorf, p. 15-30.

Haarberg, T., Solheim, A., and Johansen,S. T., 1998. "Effect of anodic gas release on current efficiency in HallHéroult cells", *Light Metals*, p. 475-481.

Hirt, C.W. and Nichols, B. D., 1981. "Volume of fluid (VOF) method for the dynamics of free boundaries". *Journal of Computational Physics*, vol. 39, p. 201–225.

Nozu, T. *et al*., 2008. "LES of the flow and building wall pressures in the center of Tokyo". *Journal of Wind Engineering and Industrial Aerodynamics*, v. 96, n. 1, p. 1762-1773.

Øbaule B., 1958. "Die Mathematik des NaturForchers und Ingenieurs", teil 5, *Variationsrechnung*, 3. auflage, Leipzig, Hirzel, Germany.

Richards, N. et al., 2003. "Characterization of the fluctuation in anode current density and bubble events in industrial reduction cells", *Light Metals*, p. 315-322.

Tandon S.C. and Prasad R.N., 2005. "Energy saving in Hindalco´s aluminium smelter", *Light Metals*, p. 303-309.

Severo D. S., Gusberti V., Pinto E. C. V. and Moura, R. R., 2007. "Modeling the bubble driven flow in the electrolyte as a tool for slotted anode design improvement", *Light Metals*, p. 465-470.

Tandon S.C. and Prasad R.N., 2005. "Energy saving in Hindalco´s aluminium smelter", *Light Metals*, p. 303-309.

White, F., 2003."Fluid Mechanics", *McGraw Hill*, U.S.A, p. 279-281.

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