ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

NUMERICAL EROSION PREDICTION IN ELBOWS DUE TO PARTICLES

Gabriel Chucri Pereira
Francisco José de Souza
Federal University of Uberlândia
School of Mechanical Engineering
MFLab - Laboratório de Mecânica dos Fluidos
Av. João Naves de Ávila, 2121, Uberlândia, Minas Gerais, Brazil
gabriel.chucripereira@colorado.edu; fjsouza@mecanica.ufu.br

Abstract. *Erosion in components is one of the major concerns in the oilfield industry. The transport and processing of oil and gas might include the presence of eroding particles, such as sand, generating damage to the parts and components, and by consequence, undesired maintenance operations, leading to unnecessary costs, without mentioning oil spillage, which is hazardous to the environment. The present work is about the investigation of numeric models for predicting erosion, applying them to easily encountered geometries in the oilfield industry; for this case, an elbow pipe with a 90-degree curvature angle, where the wear due to erosion is easily identified. In order to validate the erosion models investigated a knowledge base of experimental data was used. Also in this work, the effect of the number of computational particles was checked, as well as variations in the geometry and three different models for the restitution coefficient. The simulations presented in this work were performed using commercial software Star-CCM+, using Reynolds-Averaged Navier-Stokes (RANS) in order to reduce computational cost without losing accuracy in the results.*

Keywords: *Erosion, Validation, Particles, Flow, CFD*

1. INTRODUCTION

In several engineering applications, a surface is attacked by solid particles contained in a fluid flow, resulting in an undesired superficial wear to the component or piece of a system. This kind of wear is called erosion, and occurs very often on a daily basis, in industrial operations.

The erosion effect can be easily noticed in the oil and gas industry, more specifically in the transport and processing sectors, in which erosion influences directly to the efficiency and safety of the process. Sand particles, generated when extracting oil, act as a threat to the integrity of the transport and processing components of an oil facility, such as piping and particle separators like cyclones, as well as safety valves in the oil lines. The erosion of these systems and components might result in catastrophic consequences, like oil spillage to the environment, as well as a considerable liability to the company. (Stack and Abdulrahman, 2004).

Nowadays, it is of great interest for industries and technology centers to obtain tools to solve this issue with the purpose of saving time, resources and environmental complications due to potential spillage. By obtaining an efficient method to determine erosion is essential for the prediction of component failures. It is also worth noticing that erosion prediction not only allows engineers to estimate service life of a component, but also helps in finding geometry spots in which severe and intense erosion is more likely to occur.

In this context, the main tool to be used is definitely Computational Fluid Dynamics, or CFD, as will be cited further in this paper. Through this tool it is possible to simulate a fluid flow, such as oil or gas through pipes and bends, and finally simulate particles moving embedded in the fluid flow, tracking their trajectories and their interactions with the walls and other particles, in order to estimate erosion in walls.

This paper investigates and validates empirical erosion models applied to easy-to-find geometries in practical engineering applications; in this case, oil and gas transport piping. The chosen geometry was a ninety-degree-elbow, where the erosion effect due to particle impact is very easy to identify in reality. Experimental data collected from Chen *et. al* was used to guide the simulations with geometry dimensions, simulation conditions and erosion profiles, in order to validate the erosion models investigated. Also, investigation on other two important variables was performed; the number of computational particles and the restitution coefficient of the particles. The software Star-CCM+ was used as the CFD solver with the Reynolds-Averaged Navier-Stokes turbulence modeling.

2. THEORETICAL BACKGROUND

2.1 Erosion

Erosion is defined as the wear resulted by the interaction between a solid surface and a fluid flow containing abrasive particles with a certain speed, or the impact of free moving liquid (or solid) particles on a solid surface.(Finnie, 1960). We can divide the understanding of erosion in two major parts, being the first part the determination of the fluid flow conditions of the number, direction, and velocity of the particles striking the surface. The second part may be defined as the calculation of surface material removed, with the data acquired from the first part. It is clear that the first part of the erosion process is characterized as a fluid mechanics problem, with the fluid flow transporting the particles into the surface, which defines the erosion wear.

Erosion wear is dependent of the number of particles striking a surface, as well as the physical quantities associated with it, such as particle velocity and their direction relative to the surface to be struck. It is known that these quantities are noticeably determined by the flow conditions. In other words, any minor change in the flow conditions such as viscous regime or temperature might bring large variations in the erosion rate. For example, in operations where the flow direction changes quickly such as turbine blading, erosion is usually more severe than in a straight run of piping. Other erosion increasing factor is the local turbulence generated from roughened surface or misaligned parts. (Finnie, 1960).

2.2 Mechanisms of Erosion

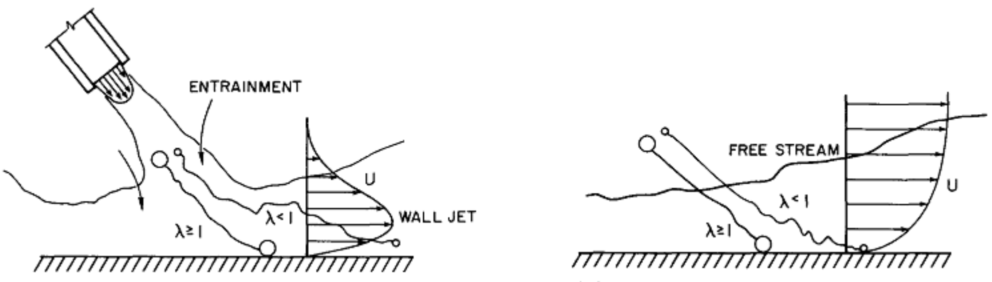
According to the literature, there are several ways to describe the mechanism of erosion, coming from different authors. Therefore, it is difficult to establish only one mechanism as the most reliable and real mechanism. The most used in the literature are the ones proposed by Finnie, Hutchings and Bitter. (Hutchings, 1992).

Finnie and Bitter proposed a mechanism of erosion in which the particle acts as a miniature machine tool in which the surface material is cut, generating a chip. Also, for the erosion of ductile metals, at oblique impact, this mechanism happens irrespective of its shape and size.

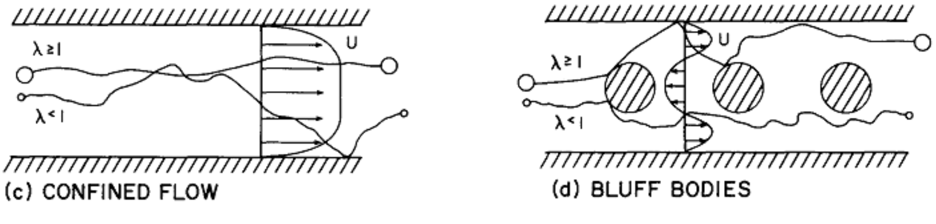
Hutchings proposed a similar mechanism; however, he split the cutting action in three different types, relying on the shape and the orientation of the eroding particle. The first type happens when there's erosion by oblique impact of spherical particles, and the material is removed by a ploughing action, moving materials to the front and side of the particle. The second and third types occur when there is the collision of angular shaped particles, and they differ from each other in the orientation of the erodent particle as it strikes the target surface, as well as the direction of the particle during the contact with the surface; in other words, if the particle rolls forwards or backwards during contact. Type I cutting is defined when the particle rolls forwards during the contact, and material is removed by repeated impacts on a prominent lip formed by the indenting angular particle. Type II cutting is defined when the particle rolls backwards, and the material is removed as if the erosion were a machining operation, with the material being removed as a chip due to the fact that there's a sharp tip of the erodent particle, working as a machining tool. (Hutchings, 1992).

2.3 Flow influence in Erosion

Figure 1 shows four flow configurations commonly found in engineering applications. The first configuration illustrates an impinging jet, as shown in Fig. 1a, in which covers a wide range of application, representing from research applications to abrasion machining; Figure 1b shows the flow configuration found in flows over turbine blades and turbo machinery; Figure 1c shows the flow configuration that occurs in pneumatic transport of solids and in piping; Figure 1d represents the flow configuration found in heat transfers. (Humphrey, 1990).



(a) IMPINGING JET (b) BOUNDARY LAYER



(c) CONFINED FLOW (d) BLUFF BODIES

Figure 1. Examples of flow configurations related to erosion due to impact by solid particles. (Humphrey, 1990).

The dynamic behavior of large and small particles is interpreted briefly in Fig. 1. The hability of a particle to respond to changes imposed by the flow, and therefore, change its trajectory is characterized by the number λ, which is defined by the ratio of two time scales that characterizes the dynamics of both solid and fluid phases, respectively. In Fig. 1, this number simply represents particle dimension; for $\lambda \gg 1$, particles have high momentum and respond slowly to flow changes; on the other hand, for $\lambda \ll 1$, particles tend to follow the flow, being an alternative to flow visualization.

The incident velocity magnitude of a particle depends of interactions between particle and fluid, between particles themselves and between particles and the wall. The behavior of these interactions depends of the flow's viscous regime (laminar or turbulent), as well as the size, shape and density of particles. Interactions between particles are strongly related to particle concentration.

3. MATHEMATICAL MODELING AND NUMERICAL METHOD

In this work, the Eulerian-Lagrangian approach was used. For the Eulerian phase (fluid flow), the Reynolds-Averaged Navier-Stokes turbulence modeling was used, with the standard two-layer k-epsilon model. For the Lagrangian phase, the particles are modeled with equations of motion based on Newton's Second Law. The trajectory and linear momentum conservation equations can be written as:

$$\frac{dx_{pi}}{dt} = u_{pi} \tag{1}$$

$$m_p \frac{du_{pi}}{dt} = m_p \frac{3\rho C_D}{4\rho_p d_p}\left(u_i - u_{pi}\right) + \left(1 - \frac{\rho}{\rho_p}\right) m_p g_i \tag{2}$$

The drag coefficient $C_d$is given by the empirical correlation proposed by Schiller and Naumman (1935):

$$C_D = 24 Re_p^{-1}\left(1 + 0.15 Re_p^{0.687}\right) \;\; if \; Re_p < 1000 \tag{3}$$

$$C_D = 0.44 \;\; se \;\; Re_p > 1000 \tag{4}$$

The erosion rate is defined as the mass of removed material per unit of area per unit of time. It is calculated on the walls and on contact faces accumulating the damage each particle causes when colliding against the face. It is given by:

$$E_f = \frac{1}{A_f} \sum_{\pi(f)} \dot{m}_\pi e_r \tag{5}$$

where A_f is the face area, $\dot{m}_\pi$ is the particle mass flow rate in each parcel that collides with the face and e_r.

There are four empirical models for the calculation of the erosion ratio, in which consists in the ratio of mass of eroded material over mass of erodent material. The first three models shown below are native in Star-CCM+ and the last one was implemented using field functions, in the Software's own environment.

The correlation proposed by Ahlet (1994) is:

$$e_r = K F_s f(\alpha) \left(\frac{u_p}{u_{ref}}\right)^n \tag{6}$$

in which K is a material-dependent constant, F_s is a factor to account for the shape of the particles, $f(\alpha)$ is a function expressing the dependency on the particle incidence angle, u_{ref} is a constant reference velocity and n a constant exponent. The shape coefficient F_s is reported to take the value 1 for angular particles, 0.53 for semi-rounded particles and 0.2 for fully rounded particles.

The angle function $f\,(\alpha)$ is split into two ranges. Below the user-specified transition angle α_0 is a polynomial inα, the incidence angle in radians. Above the transition angle, $f\,(\alpha)$ follows a trigonometric relationship

$$f(\alpha) = x \cos^2 \alpha \sin w\alpha + y \sin^2 \alpha + z \tag{7}$$

The constants w, x and y are user-defined, whereas z is calculated internally by requiring that $f\,(\alpha)$ is continuous atα_0.

The correlation proposed by Neilson and Gilchrist (1968) is:

$$e_r = e_{rC} + e_{rD} \tag{8}$$

in which e_{rC} and e_{rD} represent contributions from cutting and deformation respectively. The cutting erosion is modeled as a function of the incidence angle α.

$$e_{rC} = \begin{cases} \frac{u^2{}_p \cos^2\alpha \sin\frac{\pi\alpha}{2\alpha_0}}{2\varepsilon_C} & \alpha < \alpha_0 \\ \frac{u^2{}_p \cos^2\alpha}{2\varepsilon_C} & \alpha > \alpha_0 \end{cases} \tag{9}$$

with α_0 and ε_C user-specified constants, the transition angle and cutting coefficient respectively. The deformation erosion is similarly

$$e_{rD} = \frac{\max(u_p \sin\alpha - K, 0)^2}{2\varepsilon_D} \tag{10}$$

with ε_D the deformation coefficient and K the cut-off velocity, below which no deformation erosion occurs.

The correlation proposed by Oka et. al. (2005) is:

$$e_r = e_{90} g(\alpha) \left(\frac{u_p}{u_{ref}}\right)^{k_2} \left(\frac{D_p}{D_{ref}}\right)^{k_3} \tag{11}$$

The reference velocity u_{ref} and reference diameter D_{ref}, together with their respective exponents k_2 and k_3, are user-specified. The angle function $g\ (\alpha)$ is defined as:

$$g(\alpha) = (\sin\alpha)^{n_1}(1 + H_V(1 - \sin\alpha))^{n_2} \tag{12}$$

with n_1, n_2 and H_V user-specified constants. The value of the latter is identified by Oka et al as the Vickers hardness of the eroded material in units of GPa. By inspection of Eq. 11 and Eq. 12, e_{90} is revealed to be the reference erosion ratio at $u_p = u_{ref}, D_P = D_{ref}$ and $\alpha = 90^o$.The purported strength of the Oka model is that the coefficients for a particular combination of eroded material and eroding material can be derived from more fundamental coefficients, which are specific to either the eroded material or the eroding material. Hence, for example, the fundamental coefficients for sand can serve as a basis for both sand-steel erosion and sand-aluminum erosion. The fundamental coefficients for the eroding material, in turn, are shown to be derivable from measurable properties of the eroding material such as its Vickers hardness.

The correlation proposed by Zhang et. al. (2007) is:

$$e_r = C(BH)^{-0{,}59} F_s V_p{}^n F(\alpha) \tag{13}$$

$$F(\alpha) = 5{,}4\alpha - 10{,}11\alpha^2 + 10{,}93\alpha^3 - 6{,}33\alpha^4 + 1{,}42\alpha^5 \tag{14}$$

where $C$and n are empirical constants, BH is Brinnell hardness of the eroded material, F_s is the particle shape coefficient, in this case 0.2 for perfectly round particles, V_p is the particle impact velocity and α is the particle incidence angle. Just like the Oka correlation, this is a robust model due to the fact that depends exclusively of flow information and the eroded material properties.

In order to get the accurate prevision of the particles trajectories, it is necessary to select a particle restitution model, or in other words, how they behave after collisions with walls. After the collision, the particle's reflection velocity is smaller than the particle's incident velocity. This effect after the impact is taken into account through the coefficients of restitution. In this work, three different models were used, being all of them experimental. It is worth noticing that the correlations were determined for certain pairs of materials, in which might bring errors when used with different materials. These models were also implemented by the authors through field functions, in the Software's own environment.

The model proposed by Forder et. al. (1998) for the perpendicular and parallel components of the restitution coefficients are:

$$e_{per} = 0{,}988 - 0{,}78\alpha + 0{,}19\alpha^2 - 0{,}024\alpha^3 + 0{,}0027\alpha^4 \tag{15}$$

$$e_{par} = 1 - 0{,}78\alpha + 0{,}84\alpha^2 - 0{,}21\alpha^3 + 0{,}028\alpha^4 - 0{,}022\alpha^5 \tag{16}$$

where α is the particle incidence angle.

Grant and Tabakoff (1975) proposed the following model after treating the particle movement dynamics after collision in a statistical approach. Based on experimental data on aluminum and sand, the equations for the coefficients are:

$$e_{per} = 0{,}993 - 1{,}76\alpha + 1{,}56\alpha^2 - 0{,}49\alpha^3 \tag{17}$$

$$e_{par} = 0{,}998 - 1{,}66\alpha + 2{,}11\alpha^2 - 0{,}67\alpha^3 \tag{18}$$

where α is the particle incidence angle.

Sommerfeld (1999) proposed a model with only the perpendicular component of the coefficient restitution, defining the parallel component as close to unity. The reason for that is the low contribution of the parallel component on the reflection of particles after collision. The correlation for the perpendicular component is:

$$e_{per} = \max(0{,}7, 1 - 0{,}013\alpha) \tag{19}$$

4. PROBLEM DESCRIPTION

The investigation of erosion models performed in this work had as a database an experiment conducted by Chen et. al. (2004), where a test piece (elbow) was fixed at the end of an air line. Sand particles were injected in the line at about four feet from the test piece. The test piece was a ninety-degree-elbow with a diameter of 1 in and a curvature radius of 1.5 in., with a four feet long duct before the inlet, in order to replicate more correctly the particles trajectory. This duct is also present in the experiment. The simulation was conducted attempting to pursue the same conditions the experiment was operated, shown in Tab. 1.

Table 1. Flow Conditions Summary

Temperature	298 K
Fluid	Air
Fluid Velocity	45.72 m/s
Particle Diameter	1.5e-4 m
Particle Mass Flow Rate	2.08e-4 Kg/s
Particle Volume Concentration	0.0042%
Test Piece Material	Aluminum

The mesh used in the simulation was generated using hexahedra elements (cubes), in which guarantee more stability to the solver, generating less diffusivity in the model. Other benefits of using this kind of element in the mesh are the regularity and the uniformity of the mesh when applied to the geometry, as well as angle distribution and anisotropy. This element was also chosen because the precision of the numeric resolution close to the walls, where we can notice greater velocity gradients and boundary layer effects.

The mesh generated for the simulation has approximately 1,700,000 elements, and is shown in details in Fig. 2.

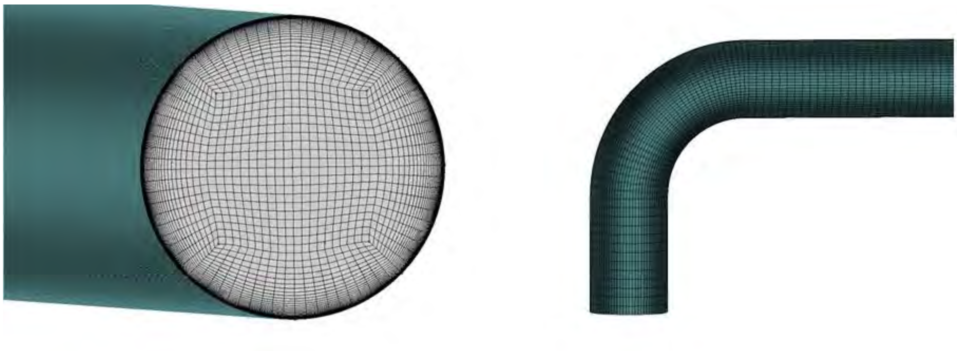


Figure 2. Computational mesh used in the simulation

5. RESULTS AND ANALYSIS

In order to perform a more accurate and without the need of simulating all the possible combinations of situations between restitution coefficient models and erosion models, as well as other variables, pre tests were conducted, with simpler geometry and rough mesh, around 200 000 elements, as a first approach, with low computational cost. Analyzing these results, it was possible to identify an erosion model in which approximates best from the experiment, and from that benchmark, other variables were investigated, such as particle number influence and restitution coefficient influence in erosion, as well as the influence of the more realistic geometry.

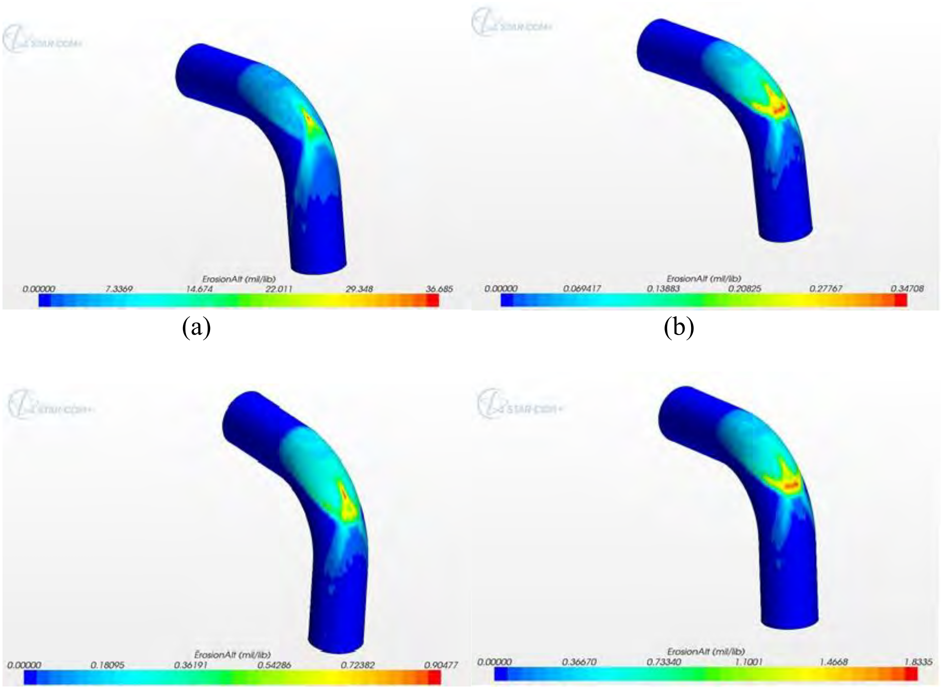
It is important to cite that other model combinations might arise, however, in this situation, taking into account the computational cost and the post-processing work volume, the choice of only one erosion model for the investigation of other variables is justified.

Another important topic in this analysis is the Erosion Rate unit. In the software Star-CCM+, this value is given in units of removed wall mass per face area per second. However, for comparison manners, the same unit used in the experimental data was used here, which is called the Penetration Ratio, translated by the ratio of the wall penetration (in millimeters) and the mass of sand (in pounds). This conversion was implemented with a field function in the Software's own environment, in which simply divides the original unit by the wall material density and also by the sand mass flow rate, as shown in Tab. 1.

5.1 Pre tests

Pre tests were conducted using the simpler geometry, with a rougher mesh. The simulation conditions and the models tested were the same, and the only variable in this simulation was the Erosion Model, in which the four models were tested. For this test, a minimal number of computational particles was injected in the domain (3000 particles), in order to reduce computational cost and simulation time. The restitution coefficient model used in this simulation was the one proposed by Grant and Tabakoff (1975), due to the fact that this model relates the interaction between sand and aluminum.

The erosion profiles for the four Erosion Models tested are shown below.



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

Figure 3. Erosion profiles for: Ahlet (a), Neilson-Gilchrist (b), Oka (c), Zhang (d).

Thanks to the reference experimental data, it was also possible to compare the erosion profile as a function of the curvature angle, in the back of the elbow, being 0 degrees parallel to the flow inlet and 90 degrees perpendicular to the flow inlet. Figure 4 shows the erosion profile for the four simulated models, as well as the experimental data.

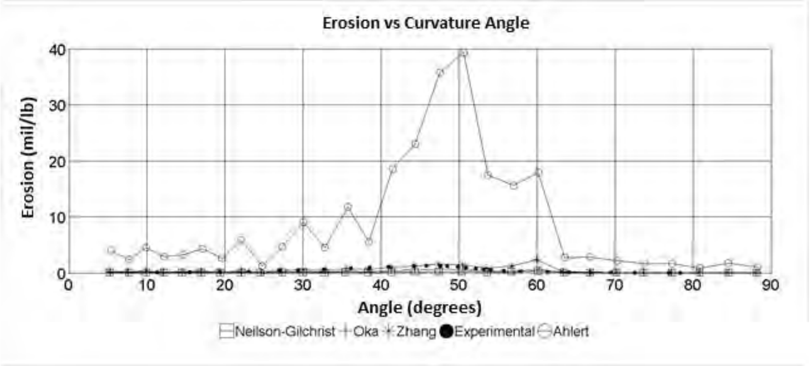


Figure 4. Erosion vs Curvature angle for the four erosion models in comparison with experimental data.

It can be noticed that the Ahlet correlation resulted in very high values when compared to the experimental results, as well as the other three correlations showed closer values to the experimental data. Excluding the Ahlet correlation of the analysis, and plotting once more the relation between the erosion and the curvature angle, we have:

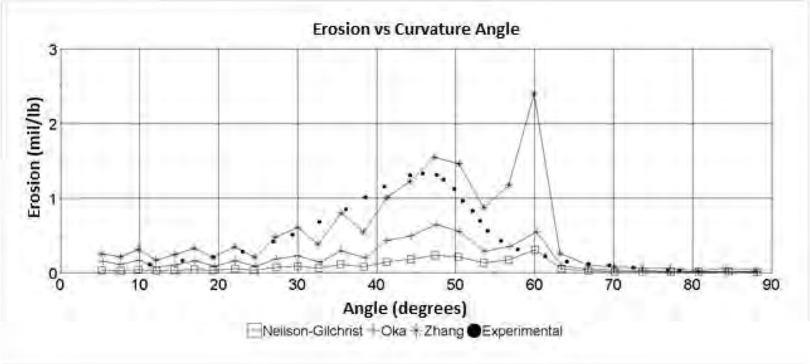


Figure 5. Erosion vs Curvature Angle for the three models in comparison with experimental data.

Analyzing Fig. 5, it is noticeable that the correlation proposed by Zhang et. al. (2007) was the closest to the results obtained in the experiment, represented in the plot with simple dots. That can be attributed due to the fact that this correlation uses as an input information from the eroded material (Brinell Hardness), differently from the other correlations, in which depend on pairs of materials they were based on. The correlation proposed by Oka et. al. (2004) also showed satisfactory results, however, in a lower magnitude when compared with the Zhang correlation. The correlation proposed by Neilson and Gilchrist (1968) showed the worst results when compared with the experimental results. This might be explained due to the dependence of the model of empirical constants that are associated to only one erosion situation, and using this model to other situations might bring results that are not satisfactory, just like this case. In order to save time and reduce computational cost, the analysis was emphasized in the Zhang correlation, due to the fact that this correlation showed the best results among the four models of Erosion Ratio tested.

5.2 Influence of the Number of Computational Particles

The number of particles injected into the flow plays a merely computational role, due to the fact that the number of computational particle does not affect the mass flow rate of particles. What occurs in the software is a division of the number of particles injected in each parcel, located in each cell in the inlet. Since the particles' trajectory is calculated stochasticly, the increase of samples tends to increase the accuracy of the simulation, as well as reduce random errors originated from a reduced number of samples in the simulation.

However, it can be found in the literature that the increase of the number of particles has a limited gain when a certain number of particles is reached, which makes the constant increase of the number of particles unfeasible, since the computational cost increases as well, but there is no gain in such action.

In order to investigate the influence of the number of particles in erosion, three cases were tested, using only one erosion correlation (Zhang) and one restitution coefficient model (Grant and Tabakoff). 3000, 100 000 and 200 000 particles were injected into the domain for further investigation.

It is worth noticing that the change in the number of computational particles did not alter significantly the qualitative erosion profiles, and thus, their presentation is not justified in this section.

Figure 6 shows erosion behavior as a function of the curvature angle.

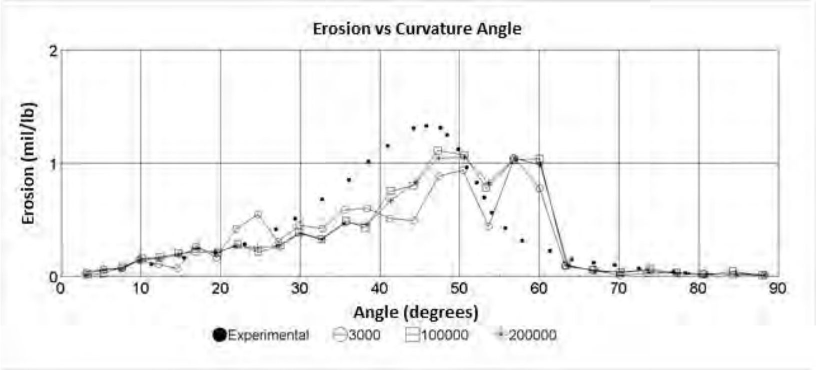


Figure 6. Influence of the Number of Particles in erosion behavior.

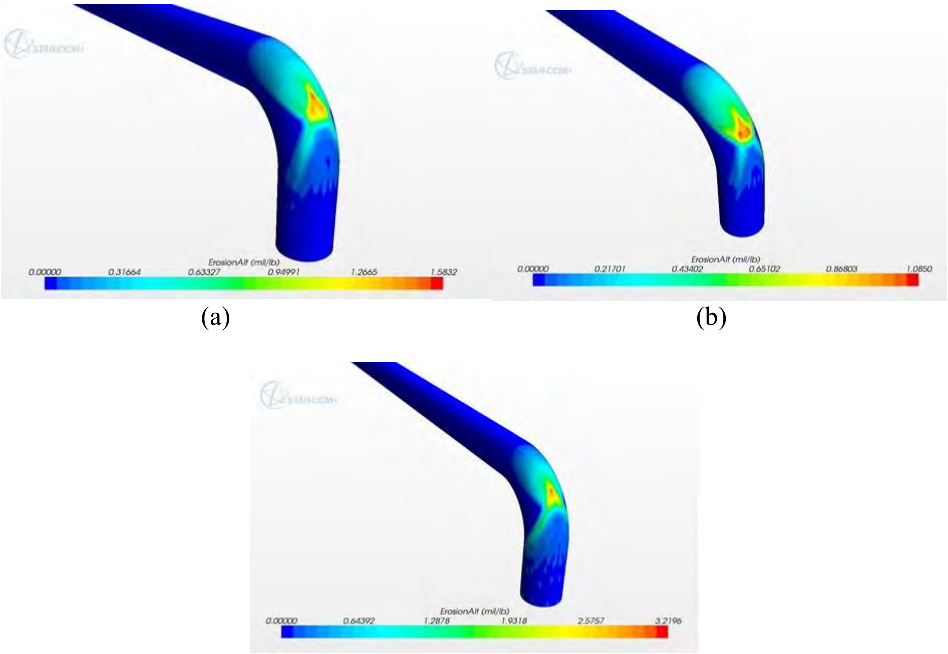
Figure 6 shows that there is no much of a difference between the result obtained with 100 000 particles and with 200 000, which indicates that a reduced number of particles can be used, with a reduced computational cost, without jeopardizing the results.

However, when comparing the results obtained with 3 000 particles with 100 000 particles, a great difference is noticed in the behavior of the plot, as well as the magnitude of the erosion, justifying the use of more particles in the simulation.

5.3 Influence of the Restitution Coefficient Models

The analysis of the influence of the restitution coefficient models was performed using the three models cited in section 4. As previously stated, the models attempt to predict particles' behavior after the collision with the walls, or in other words, what the particles' reflected velocity will be, as well as other characteristics as rotation and position.

The erosion profiles are shown below.



(a) (b)

(c)

Figure 7. Erosion profiles for: (a) Forder, (b) Grant and Tabakoff, (c) Sommerfeld

Figure 8 shows the plot of erosion as a function of the curvature angle for the three restitution coefficient models.

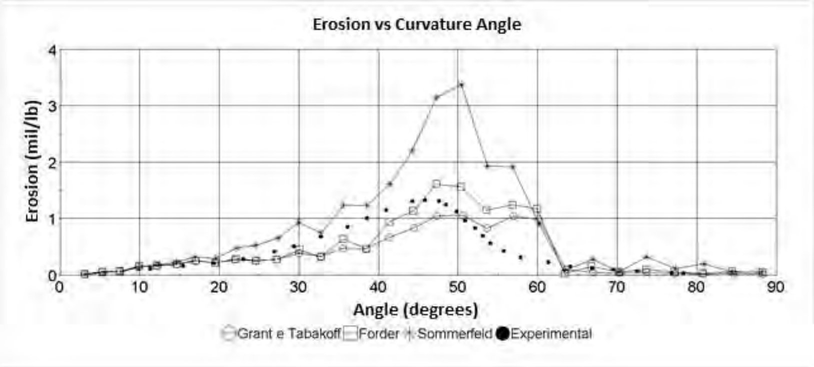


Figure 8. Influence of the Models of Restitution Coefficients in erosion behavior.

Analyzing the plot above, it can be noticed that the model proposed by Sommerfeld (1999) resulted in higher values of erosion, when compared with experimental results. The model proposed by Forder (1998) exceeded a little bit in magnitude while the model proposed by Grant and Tabakoff was a little bit lower, when both are compared with experimental results.

6. CONCLUSIONS

Through this paper, it was possible to evaluate the behavior of erosion prediction models using Computational Fluid Dynamics (CFD), as well as key factors of great influence in erosion prediction, such as the restitution coefficient models and the number of computational particles.

Reynolds Averaged Navier-Stokes turbulence modeling was used due to good performance and low computational cost, as well as the reduced number of elements in the mesh and the simplified geometry, which do not require more robust methodologies.

By analyzing the results and taking into account all simulated conditions, it can be concluded that the combination of the models proposed by Zhang et. al. (2007) for the erosion ratio and Forder et. al. (1998) for the restitution coefficient are the most trusted for the erosion prediction for this case (elbow with sand particles), due to the fact that, not only the values were close to the obtained in the experiment but also was a little bit higher than the experimental results. The combination Zhang- Grant and Tabakoff also obtained very good results; however, since the magnitude was lower than the obtained in the experiment, it cannot be trusted at the point of eliminating further experiments.

With these models in mind, there are high expectations in applying them in future simulations with complex geometries of great use in industry and obtaining satisfactory results, especially in Particle Separators such as Cyclones, due to the fact the particles' behavior is similar to the elbow, in the inlet and after the initial collision with the wall, in the upper part of the system. It is believed that erosion prediction can be done in these systems without the great distrust erosion prediction had in previous work, where the erosion models ore outdated and did not include eroded material data, such as hardness, and depended exclusively of empirical data extracted of a pair of eroded and eroding materials.

7. ACKNOWLEDGEMENTS

The authors would like to thank Petrobras S.A for the financial support, as well as MFLab for the infrastructure and equipment to perform this work.

8. REFERENCES

Ahlet ,K., 1994. *Effects of particle impingement angle and surface wetting on solid particle erosion of AISI 1018 steel*. MS Thesis, University of Tulsa, USA

Chen, X., McLaury, B.S., Shirazi, S., 2004. *Application and experimental validation of a computational fluid dynamics (CFD) – based erosion prediction model in elbows and plugged tees.* University of Tulsa, 2004.

Finnie, I., 1960. "Erosion of Surfaces by Solid Particles" . *Wear,* Elsevier.

Forder, A., Thew, M., Harrison, D., 1998. "Numerical investigation of solid particle erosion experienced within oilfield control valves". *Wear*, 216:184-93.

Grant, T., Tabakoff, W., 1975. "Erosion prediction in turbomachinery resulting from environmental solid particles". *J Aircraft,* 12:471-547

Humphrey, J.A.C., 1990 "Fundamentals of fluid motion in erosion by solid particle impact". *Int. J. Heat and Fluid Flow, Vol. 11*, No.3, pp173-195

Hutchings, I.M, 1992. *Tribology, Friction and Wear of Engineering Materials.* Elsevier Limited, 1st edition.
Neilson, J.H, Gilchrist, A., 1968. "Erosion by a stream of solid particles"., *Wear,* 11, pp.111-122.
Oka, Y.I., Okamura, K., Yoshida, T., 2005. "Practical estimation of erosion damage caused by solid particle impact". *Wear, 269*, pp102-109.
Schiller, L., Naumann, A., 1933., "Ueber die grundlegenden Berechnungen bei der Schwerkraftaufbereintung", *VDI Zeits, 77 (12)* , pp. 318-320.
Sommerfeld, M., Huber, N., 1999 "Experimental analysis and modeling of particle-wall collision". *Int. J. Multiphase Flow 25,* 1457-1489.
Stack, M.M., Abdulrahman, G.H., 2004. "*Mapping erosion-corrosion of carbon steel in oil exploration conditions: Some new approaches to characterizing mechanisms and synergies*", Ph.D. thesis, Strathclyde University.
Zhang, Y., Reuterfors, E.P., McLaury, B.S, Shirazi, S.A., Rybicki, E.R., 2007. "Comparison of computed and measured particle velocities and erosion in water and air flows". *Wear, Vol. 263,* pp. 330-338.

9. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.