

EVALUATION OF THE PERFORMANCE OF DIFFERENT TURBULENCE MODELS IN THE PREDICTION OF PRESSURE DROP AND COLLECTION EFFICIENCY OF CYCLONE DUST SEPARATORS WITH DIVERSE GEOMETRIES

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Abstract. *CFD simulations of six cyclones with different geometries were made using the software Fluent 6.3.26. All the cyclones had the same main diameter (0.245 m), the same outlet diameter (0.098 m) and the same total height (0.875 m), but the length of the conical section varied from 0.725 m to 0.235 m and the vortex finder height varied from 0.122 m to 0.395 m. Two different turbulence models were used in the simulations: RNG* κ–ε *and RSM. The predicted overall pressure drop and collection efficiency was very much influenced by the turbulence model used. The RSM model performed better than the RNG* k–ε *model in predicting pressure drop, although it over predicted the pressure drop. As for collection efficiency,none of the models performed well, with the RSM over predicting the efficiency for most cases while the RNG* k–ε *model under predicting.*

Keywords*: cyclone separator, CFD, pressure drop, collection efficiency, turbulence models*.

1. INTRODUCTION

Cyclone separators are widely used gas cleaning industrial devices. Its main advantages are the low maintenance and operational costs, absence of moving parts and possibility of use with high pressure and temperature. The low collection efficiency for particles below 5 μm is its main disadvantage. Notwithstanding the simplicity of design and construction, its hydrodynamic behavior is far from simple. Phenomena such as vortexes, recirculation zones, flow reversal, high turbulence, among other are all present in a cyclone separator (Boysan et al., 1982; Dirgo and Leith, 1985; Fraser et al., 1997; Meier, 1998; Salcedo and Pinho, 2003). In such cases, computational fluid dynamic (CFD) studies can help us understand better some of the more complex flow phenomena (Hoffmann and Stein, 2008).

The high swirling and anisotropic turbulent gas flow in a cyclone is difficult to model. The most common approach to turbulence modeling consists in the time averaging of the Navier-Stokes equations. As a result of this operation, new terms, known as Reynolds stresses, appear in the equations, as shown in Eq.(1), where U stands for the average fluid velocity, u' for the velocity fluctuation, t for time, x for space coordinates, P for average pressure, ρ for density and ν for kinematic viscosity. The subscripts i and j indicate direction in a Cartesian coordinate system. The specific Reynolds stresses are represented by the last term on the right hand side of Eq.(1).

$$\frac{\partial(U_i)}{\partial t}+\frac{\partial(U_iU_j)}{\partial x_j}=-\frac{1}{\rho}\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left[v\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)\right]-\overline{u_i'u_j'} \quad (1)$$

Because of these new variables which appear in the Reynolds Averaged Navier-Stokes (RANS) equations, new closing equations are needed in order to solve the system of equations. The turbulence models based on the RANS approach differ from one another mainly due to using different closing equations. The most common of these is the k–ε model. The symbol k stands for kinetic energy per unit mass due to the fluctuation velocities, and is defined by Eq.(2) and ε stands for the dissipation of this energy per unit mass, defined by Eq.(3).

$$k=\frac{1}{2}\overline{u_i'u_i'}=\frac{1}{2}\left(\overline{u'^2}+\overline{v'^2}+\overline{w'^2}\right) \quad (2)$$

$$\epsilon=\nu\overline{\frac{\partial u_i'}{\partial x_k}\frac{\partial u_i'}{\partial x_k}} \quad (3)$$

The k-ε model assumes that the Boussinesq approximation is valid, and therefore computes (Eq.(4)) the specific Reynolds stress (τ_{ij}^T) as a function of an eddy viscosity (ν_T) multiplied by the mean strain-rate tensor (S_{ij}, see Eq.(5)), in analogy to the laminar shear stress tensor. The symbol δ in Eq.(4) is Kronecker's delta.

$$-\overline{u_i' u_j'} = \tau_{ij}^T = 2\nu_T S_{ij} - \frac{2}{3} k\delta_{ij} \tag{4}$$

$$S_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) \tag{5}$$

In the standard k-ε model, the eddy viscosity is written in terms of k and ε, which then become the only two new variables apart from the time averaged pressure and velocity. Two partial differential equations, one for k and one for ε, close the system. In deriving these two equations, some simplifying hypothesis and approximations are made. In contrast to the standard version, the RNG version of the k-ε model utilizes the more rigorous renormalization group statistical technique when deriving the transport equations for k and ε. As a result of this, the RNG version (Yakhot and Orszag, 1986) has improvements over the standard version, such as an additional term in the ε equation that significantly improves the accuracy for rapid strained flows and analytical formulas for terms which are considered constants in the standard version. These features improve the performance of the model for many flows of practical engineering interest, one example being the highly swirling flow present in cyclone separators. The drawback is an increase in computational time.

A disadvantage of all k-ε versions is their isotropic representation of the turbulence, which is intrinsic in the Boussinesq approximation. The Reynolds Stress Model (RSM) abandons the Boussinesq hypothesis, therefore making it possible to model the anisotropic turbulence which is present cyclones, for instance. By taking moments of the Navier-Stokes equations, it is possible to derive transport equations for each of the Reynolds stress components (Launder et al., 1975), thus eliminating the need for Boussinesq approximation. This means an addition of seven partial differential equations to be solved for each computational cell in the domain, which makes the RSM model much more expensive computationally, and also much more difficult to converge.

Being able to account both for swirling and anisotropic turbulence, the RSM model is certainly better suited to describe the flow in cyclones than the RNG k-ε model (Hoffmann and Stein, 2008). One should ask, however, if the gain in performance is justified in view of the increased computational difficulties.

The purpose of this paper is to compare the performance of both of these turbulence models, the RSM and the RNG k-ε, in predicting the total pressure drop and the collection efficiency of eight different cyclones.

2. MATERIALS AND METHODS

All the cyclones had the same body diameter of 0.245 m and total length of 0.875 m, but the ratio of the cylindrical to the conical section as well as the lid position varied. The geometry of the cyclones is presented in Fig. 1 and Tab. 1.

Table 1. Dimensions (in meters) of the cyclones studied.

Dimension[(1)]	C1	C2	C3	C4	C5	C6
Dc	0.245	0.245	0.245	0.245	0.245	0.245
De	0.098	0.098	0.098	0.098	0.098	0.098
L	0.122	0.367	0.122	0.367	0.112	0.367
h	0.150	0.150	0.395	0.395	0.640	0.640
H	0.875	0.875	0.875	0.875	0.875	0.875
S	0.090	0.090	0.090	0.090	0.090	0.090
A	0.098	0.098	0.098	0.098	0.098	0.098
B	0.051	0.051	0.051	0.051	0.051	0.051

[(1)] : For the meaning of the symbols, please refer to Fig. 1.

The fluid was air at ambient conditions. As São Carlos is located 800 m above sea level, and the average inlet air temperature during the experiments was 25 ^{o}C, the air density was considered equal to 1.09 kg/m^3 and the viscosity 1.84e-5 kg/m.s. Inlet air velocity was maintained at 10.2 m/s in all experiments. The mono-dispersed particles used had a density of 3030 kg/m^3 and diameter of 1.33e-6 m. Inlet dust concentration was 0.003 kg/ m^3.Experimental pressure drop and collection efficiency data for these cyclones are available in the literature (Scarpa, 2000).

The commercial software Fluent was used in the simulations. The computational grid contained approximately 220,000 hexahedral cells. The semi implicit linked equations (SIMPLEC) algorithm was used for the pressure-velocity coupling. A pressure staggering option (PRESTO!) discretization scheme was used for the pressure and a first order scheme for the Reynolds stress equations. All the other variables were calculated using a second order scheme. The gaseous phase flow was considered to be unaffected by the particulate phase, which is reasonable if the dust concentration is low.

A Lagrangian approach was chosen to describe particle motion, using Fluent's Discrete Random Walk Model. The entrance of the cyclone was divided into 90 equal area elements, and 30 particles of a given size were released from each element, totaling 2700 particle trajectories of each diameter that needed to be computed in each simulation. According to Shi and Bayless (2007), this number of particles is sufficient to ensure a good representation of the collection efficiency for single diameters in a random model such as the one used. For the boundary condition for particles hitting walls it was considered that all particles hitting the walls of the external cylinder, cone and hopper were trapped immediately. Particles hitting other walls were reflected, returning to the flow. Griffiths and Boysan (1996) implemented a similar condition, except that for those authors, the particles hitting the cylinder were also reflected.

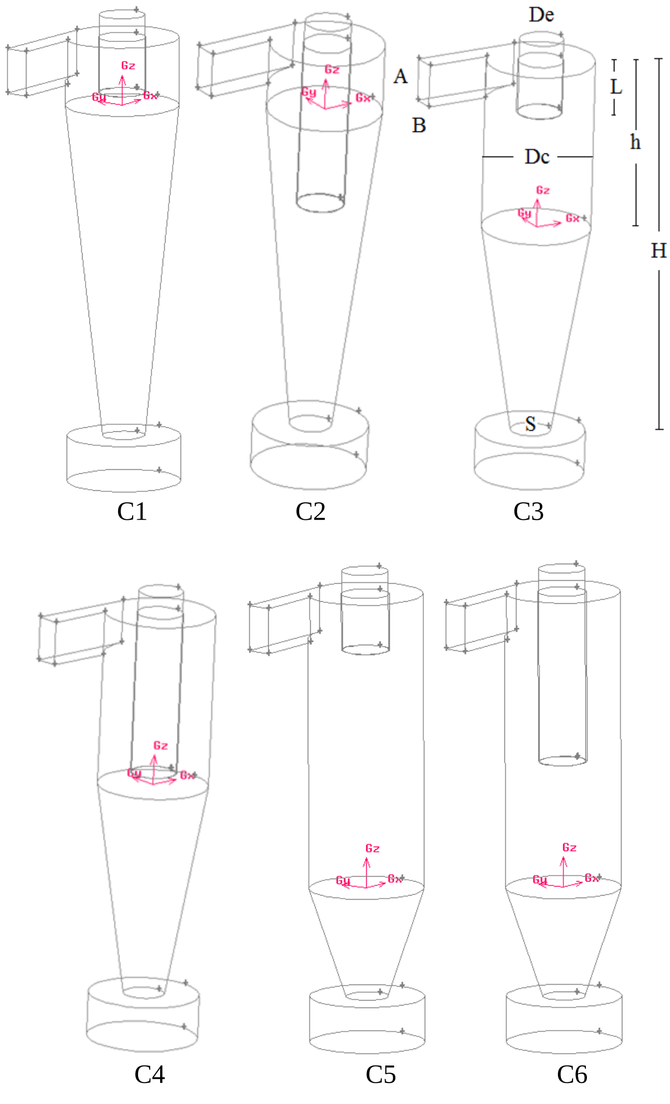

Figure 1. Drawings of the six cyclones studied.

3. RESULTS AND DISCUSSION

The RSM model was more difficult to converge than the RNG k-ε model, often requiring the use of lower values for the under relaxation factors to achieve stability. The demanded computational time was also a major difference between the two models. While the RNG k-ε model converged typically in less than one hour in a machine powered with a quad-core Xeon 5435 processor, the RSM model usually demanded an overnight work.

The pressure drop predicted by each turbulence model is presented in Fig. 2. The RSM model performed better than the k-ε RNG, with predictions within 10% of the experimental value. However, the RSM model over predicted the pressure drop in all cases.

The pressure profiles inside the cyclones are presented in Fig. 3 for the RNG k-ε model and Fig. 4 for the RSM turbulence model. Both models predicted significant negative pressures in the centerline of the cyclones, although in the RSM model the negative pressures extend from the center of the outlet to the bottom of the hooper. This tendency was also found by other authors (Fraser et al., 1997; Salcedo and Pinho, 2003; Hoffmann and Stein, 2008). The fact that

RSM model can account for both swirling and anisotropy can explain its better performance when compared to the k-ε model.

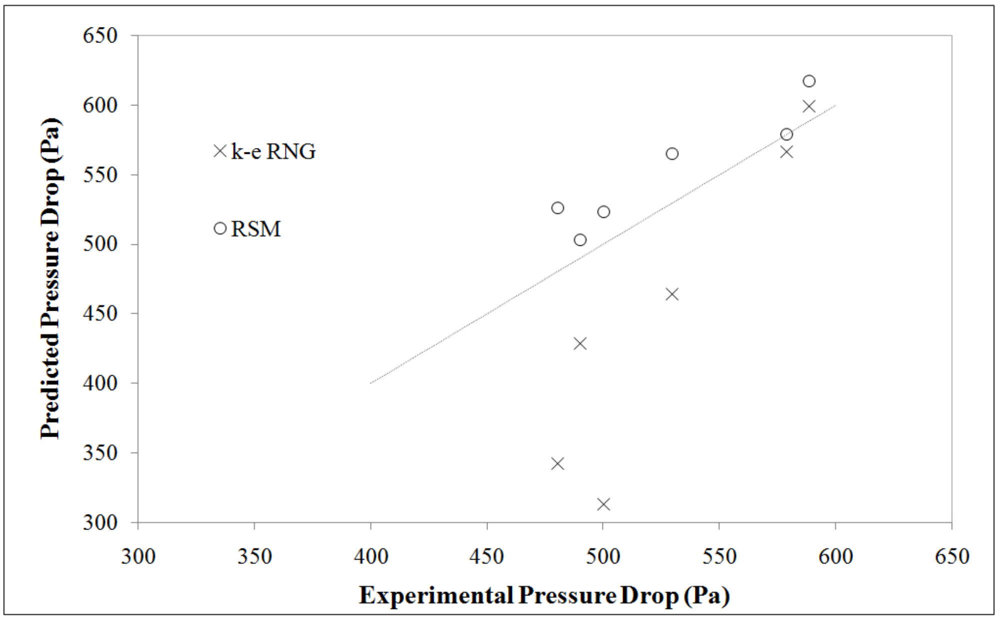

Figure 2. Pressure drop predicted by the two turbulence models used.

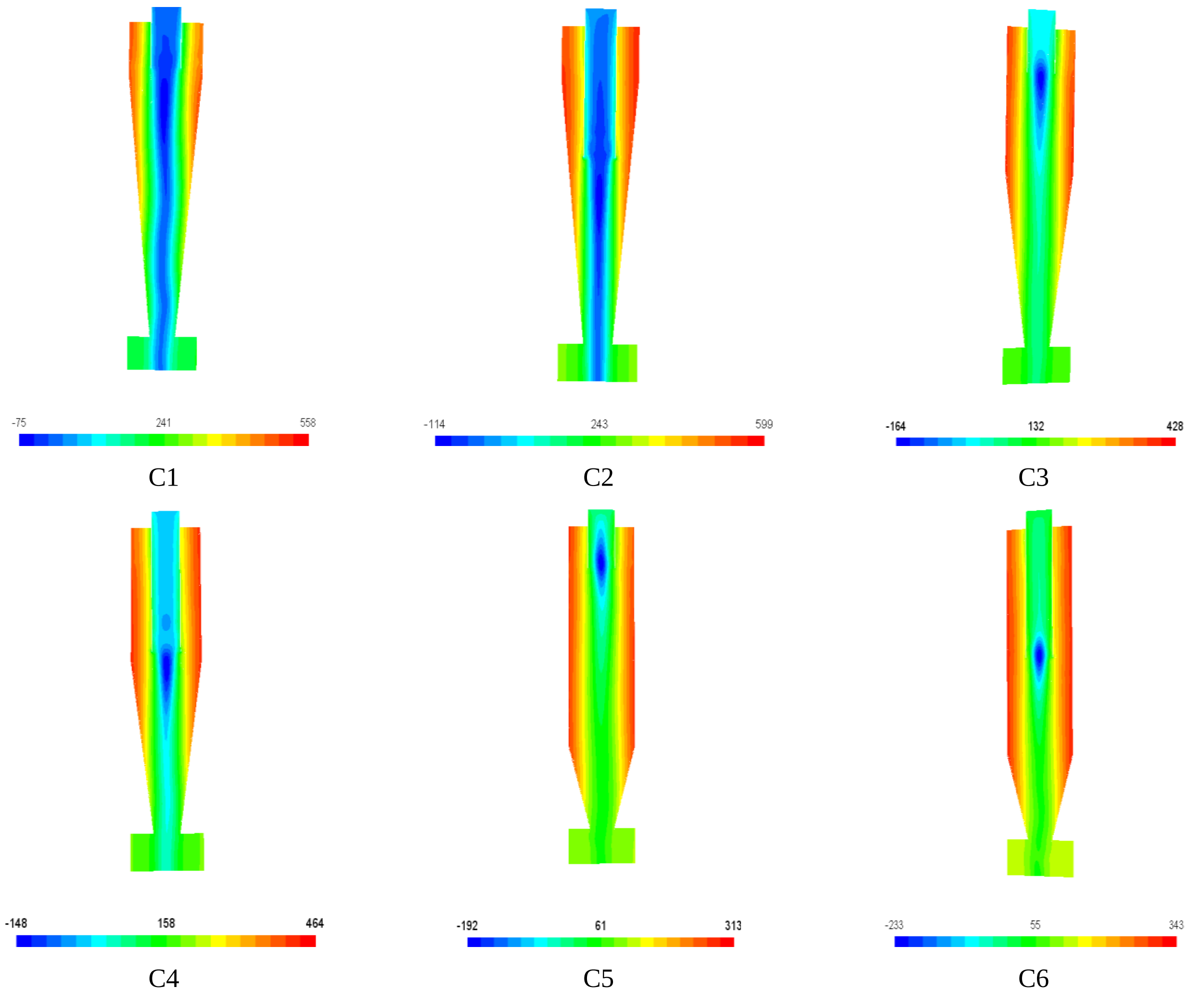

Figure 3. Pressure profile for the cyclones using the k-ε turbulence model.

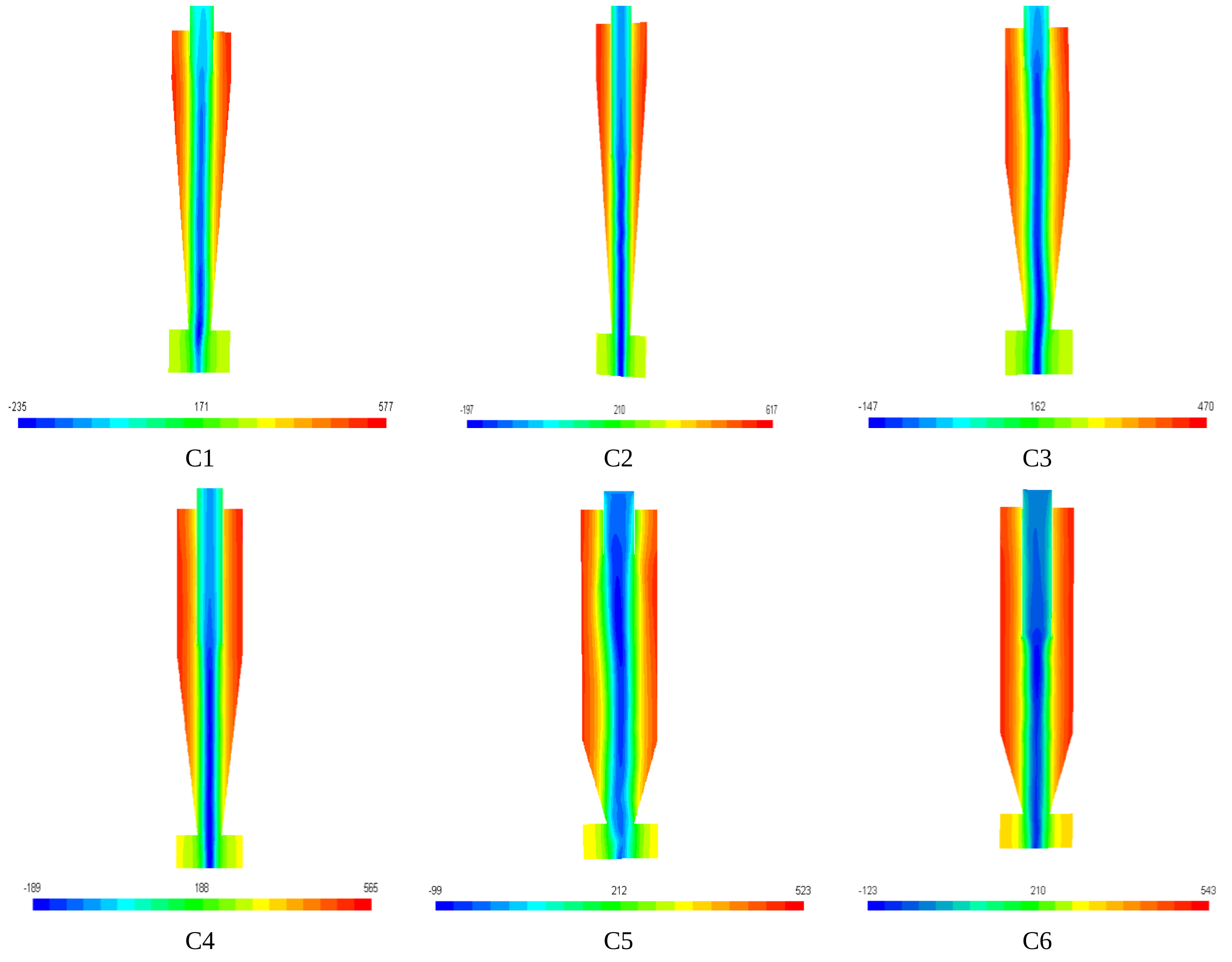

Figure 4. Pressure profile for the cyclones using the RSM turbulence model.

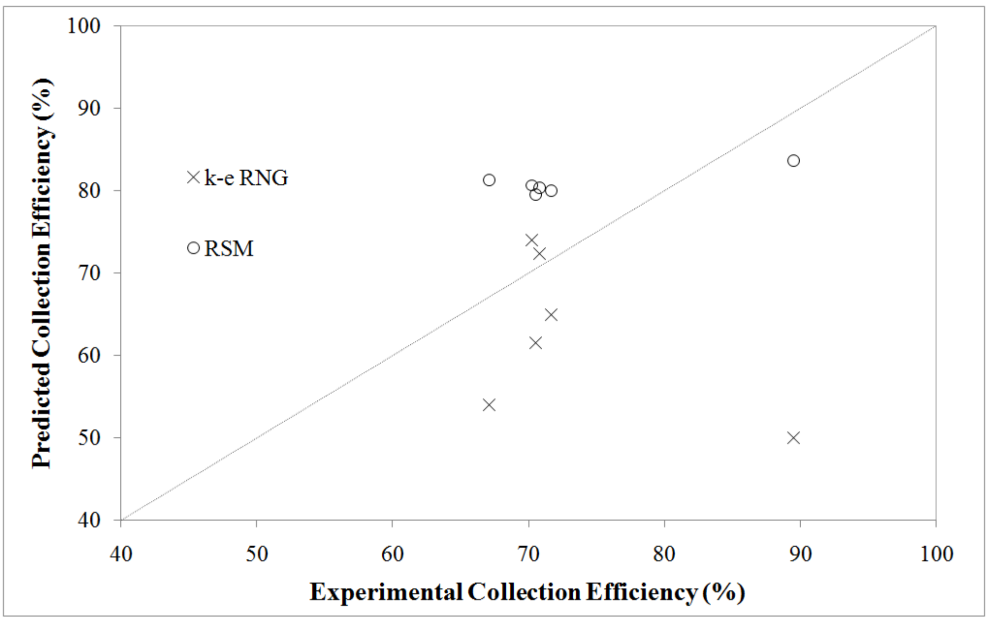

Figure 5. Collection efficiency predicted by the two turbulence models used.

None of models performed well in predicting collection efficiency for the 1.33e-6 m particle, as shown in Fig. 5. The RSM model significantly over predicted most cases, while the k-ε RNG model under predicted. According to Hoffmann and Stein (2008), no CFD model so far has been able to predict collection efficiency in cyclones better than the older empirical correlations. The flow of the particulate phase is very complex, including phenomena such as turbulence modulation due to the presence of the particles, and sand dune like flow of particles near the surfaces. It should also be noted that Fluent's native boundary condition for particle-wall interaction is too simplistic.

4. CONCLUSIONS

The main conclusions of this study are:

- The pressure drop in five of the six cyclones studied was better predicted when the RSM model was used instead of the k-ε RNG model;
- The RSM model exhibited a tendency to over predict the pressure drop, while the k-ε RNG model to under predict it;
- The RSM model outperformed the k-ε RNG model in collection efficiency prediction for only two out of the six configurations examined, although both models deviated, in average, approximately 15% of the experimental data.
- Again, the RSM model showed a tendency to over predict collection efficiency data for the 1.33e-6 m particles studied.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Boysan, F., Ayers, W.H. and Swithenbank, J., 1982, "Fundamental mathematical modelling approach to cyclone design", Vol.60, No. 4, pp. 222-230.

Dirgo, J. and Leith, D., 1985, "Cyclone collection efficiency: Comparison of experimental results with theoretical predictions", Vol.4, pp. 401-415.

Fraser, S.M., Abdel Razek, A.M., and Abdullah, M.Z., 1997, "Computational and experimental investigations in a cycole dust separator", Vol.211, No. E4, pp. 247-257.

Griffiths, W.D. and Boysan, F., 1996, "Computational fluid dynamic (CFD) and empirical modeling of the performance of a number of cyclone sampler", J. of Aerosol Sci., Vol.27, pp. 281-304

Hoffmann, A.C. and Stein, L.E., 2008, Gas cyclones and swirl tubes, 2a ed., Springer Verlag.

Launder, B.E., Reece, G.J. and Rodi, W., 1975, "Progress in the development of a Reynolds-stress turbulence closure",. J. of Fluid Mech., Vol.68, No. 3, pp. 537-566.

Meier, H.F., 1998, Modelagem fenomenológica e simulação bidimensional de ciclones por técnicas da fluidodinâmica computacional, Ph.D. Dissertation, State University of Campinas, Brazil.

Salcedi, R.L. and Pinho, M.J., 2003, "Pilot- and industrial-scale investigation of numerically optimized cyclones", Vol.42, No. 1, pp. 145-154.

Scarpa, J.D.A.S., 2000, Influência de características geométricas no desempenho de um ciclone, M.Sc. Dissertation, Federal University of São Carlos, Brazil.

Shi, L. and Bayless, D.J., 2007, "Comparison of boundary conditions for predicting the collection efficiency of cyclones", Powder Technology, Vol.173, pp. 29-37.

Yakhot, V. and Orszag, S.A., 1986, "Renormalization group analysis of turbulence: I. Basic theory", J. of Scientific Computing, Vol.1, No. 1, pp. 1-51.

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