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Numerical study of dispersion velocity in turbulent flow and the effects on separation efficiency in a cyclone separator

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Abstract
In this paper the effect of dispersion in turbulent two phase (gas-solid) flow on trajectory of particles in cyclone separators and the efficiency has been investigated. To predict flow field in cyclone simpler algorithm was used to solve Eulerian equations. Algebra stress model (ASM) solves the Reynolds stress in momentum equations and the dispersion of fluid velocity is simulated by the use of a stochastic Lagrangian model. Results show with increasing particles diameter, the dispersion effect is decreased. Also it is obvious that dispersion makes the separation efficiency decreased.

Key words: two phase flow, cyclone, dispersion, efficiency

Introduction

Cyclone separator is widely used in industries to separate dust from gas or for product recovery because of its geometrical simplicity, relative economy in power and flexibility. In the past decade, flow field in cyclone stimulate by the numerical calculation or experimental methods. To separate dust from gas some methods such as collision, streaming, electrostatic force, gravity, thermophoises force or centrifugal force is used. In separated cyclone with swirling inlet flow particles move to sides of cyclone However the geometry of cyclone is simple but some parameters such as turbulence, the effects of two phases on each other, shear layers and geometries of some parts of cyclone cause decrease separation efficiency [2]. Flow field in cyclone has been investigated with different models such as Separation surface model, axis equilibrium (Barth 1956, Muschelknautz 1972) and some empirical models [8]. 'Critical force theory' has investigated the effects of volume dust in flow on efficiency. However experimental results can be predicted but this theory can not be used for all kinds of cyclones. So application of computational fluid dynamics (CFD) for the numerical calculation of the flow field becomes more and more popular. In this paper numerical calculation is used and the effect of dispersion of fluid velocity on solid particles stimulated by the use of a stochastic Lagrangian model.

Governing equations

To predict the flow field in cyclones, the mass and momentum equations in cylindrical coordinates are used as follows:

$$\frac{\partial U}{\partial x}+\frac{1}{\mathrm{r}}\frac{\partial}{\partial x}(rV)=0 \tag{1}$$

$$\frac{1}{\mathrm{r}}\left[\frac{\partial}{\partial x}(r\,rU^{2})+\frac{\partial}{\partial r}(r\,rUV)\right]=-\frac{\partial P}{\partial x}-\frac{\partial}{\partial x}(r\,\overline{u'^{2}})-\frac{1}{\mathrm{r}}\frac{\partial}{\partial r}(r\,r\overline{u'v'})+M_{P,x} \tag{2}$$

$$\frac{1}{\mathrm{r}}\left[\frac{\partial}{\partial x}(r\,rUW)+\frac{\partial}{\partial r}(r\,rVW+rVW)\right]=-\frac{\partial}{\partial x}(r\overline{u'w'})-\frac{1}{\mathrm{r}}\frac{\partial}{\partial r}(rr\overline{v'w'})-\frac{1}{\mathrm{r}}r\overline{v'w'}+M_{P,q} \tag{3}$$

Where u, v and w are mean velocity and u´, v ´and w´ are dispersion velocities. M_{px} , M_{pr} and $M_{p\theta}$ terms in momentum equations show the transportation of momentum between gas and solid particles that they will be calculated. The cyclone is considered two dimensional because its axis metric. The above equations can be solved when Reynold's stress terms ($\overline{u'^2},\overline{v'^2},\overline{w'^2},\overline{u'v'},\overline{u'w'},\overline{v'w'}$) are calculated. So the suitable model is needed.

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ulence, so it is not suitable model for the flow in a cyclone which has anisotropic turbulence. In this paper ASM model was used to predict Reynold's stress. ASM model solves two differential equations for k and ε and six algebraic equations for Reynold's stress [4].

Governing equations on particle

According to the Newton's second law if centrifugal, drag and gravity force are equaled to particle's acceleration then the location and initial velocity of particle can be obtained. The Lagrangian equations in cylindrical coordinate can be expressed as

$$u_P = U + u' - \frac{g}{f} + (u_{P,0} - U - u' + \frac{g}{f})\exp(-f(t - t_0)) \quad (4)$$

$$v_P = V + v' - \frac{w_{P,0}^2}{f\, r_{P,0}} + (v_{P,0} - V - v' + \frac{w_{P,0}^2}{f r_{P,0}})\exp(-f(t - t_0)) \quad (5)$$

$$w_P = W + w' + \frac{w_{P,0} v_{P,0}}{f r_{P,0}} + (w_{P,0} - W - w' + \frac{w_{P,0} v_{P,0}}{f r_{P,0}})\exp(-f(t - t_0)) \quad (6)$$

To predict the turbulence effect of trajectory of particles gas velocity terms divided in two groups: dispersion and mean velocity terms. In momentum equations for solid particles, mean velocity terms of gas and dispersion velocity can be obtained by solving governing momentum equations of gas and Stochastic method, respectively. Dispersion velocity terms are obtained by using an isotropic Gaussian distribution that can be expressed as [5]:

$$\sqrt{\overline{u'^2}} = \sqrt{\overline{v'^2}} = \sqrt{\overline{w'^2}} = \sqrt{\frac{2K}{3}}$$
$$w' = h\sqrt{\overline{w'^2}}\ ,\ v' = h\sqrt{\overline{v'^2}}\ ,\ u' = \eta\sqrt{\overline{u'^2}} \quad (7)$$

Dispersion velocity terms are constant in the lifetime of eddies. Lifetime of eddies due to k and ε can be expressed

$$t = 0.16\frac{k}{e} \quad (8)$$

To chose time step of Equation the smaller magnitude of either eddies lifetime or the time it takes that particle pass the standard volume are considered. In calculation particles divided into ten groups due to their sizes. For each group the momentum equations are integrated independently.

Momentum transportation between two phases (gas-solid)

Momentum Transportation between two phases causes some complexity in solving two phase flow. With adding Momentum Transportation (are expressed as below) to source term the effect of solid phase is considered.

$$\Delta M_{px} = -F(t - t_0)\left[0.5(u_p - u_{p,o}) - U - u'\right]\dot{m}_p \quad (9)$$
$$\Delta M_{pr} = -F(t - t_0)\left[0.5(v_p - v_{p,o}) - V - v'\right]\dot{m}_p \quad (10)$$
$$\Delta M_{p\theta} = -F(t - t_0)\left[0.5(w_p - w_{p,o}) - W - w'\right]\dot{m}_p \quad (11)$$

Where $\dot{m}_p$ is mass flow of ten groups of particles that they are obtained by Rousin-Rumler distribution function [2].

Model description

Control volume method is used to solve governing equations [3]. In this method the geometry was divided into small volumes and discritized equations are obtained. To obtain diffusion and convection flux use power method that is more accurate than other methods such as combined method is used. So discritized equations are expressed as

$$\sum(A_i - S_p)\varphi_p = \sum A_i\,\varphi_i + S_u \qquad i = N,S,E,W \quad (12)$$

Where Φ is dependant variable, A_i is obtained by combination of diffusion and convection fluxes. Su, Φp are linear source terms. Some discritized equations are solved by Simpler algorithm and some of them are obtained by other methods such as Gouse-Sidel or TDMA methods. For boundary condition near solid, that variation is important, use wall functions [2].

Results and discussion

The cyclone as shown in fig(1) has 0.974m length and 0.205m diameter and its cone's length is 0.512m that experimental data are accessible [2]. Figure (2-5) show axial and tangential velocity at x = 0.5m in cylindrical part and at x = 0.9m in cone part. These figures show high magnitude of dispersion velocity at cone part and near cyclone's side because of high turbulence energy in these parts. Figure6-8 compare mean and dispersion of Reynold's number. They show when particles move to cone part of cyclone, Reynold's number of particles increase. As Reynold's number increased the difference between fluid and particle velocity increase. So it can be concluded trajectory of particles are similar to stream line if particles become very small.Figure 9 shows as particle's diameter increased the effect of dispersion of velocity on trajectory of particles decreases. The simulation results are in good agreement with the experimental results [9].As figure 10 shows, the efficiency is dependent on Stoke's number. Stoke's number is the dominant parameter in analysis of cyclone. Fruid's number shows the effect of gravity on efficiency. Hence, when efficiency of cyclone is high, gravity can be neglected. The simulation results are in good agreement with the experimental results [9].In figure 11 compares separation efficiency with mean and dispersion velocity. As it shows dispersion of velocity decreases the cyclone's efficiency.

Conclusion

In this paper the effect of dispersion on trajectory of particles in cyclone separators and the separation efficiency with stochastic method has been investigated. Regarding to turbulence energy, dispersion velocity at cyclone's cone and near cyclone's side is greater than the other parts. With increasing particles diameter, the dispersion effect was flow instabilities are decreased. Also as Stoke's number increased, more particles collected near sides of cyclone. Finally, It is shown that dispersion makes efficiency decreased the which is predictable with experimental data.

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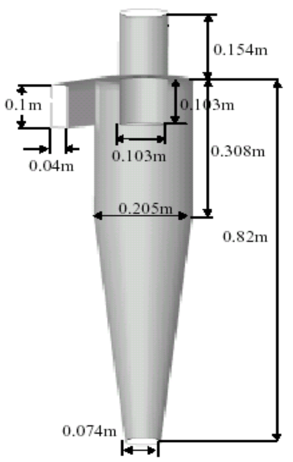


Fig.1-Schematic of the cyclone considered

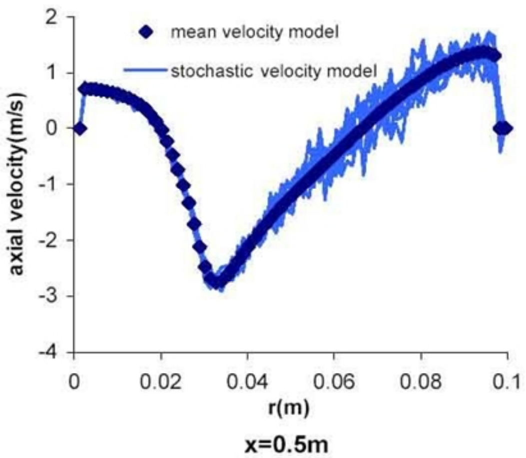


Fig.2-Axial velocity in cone part of cyclone

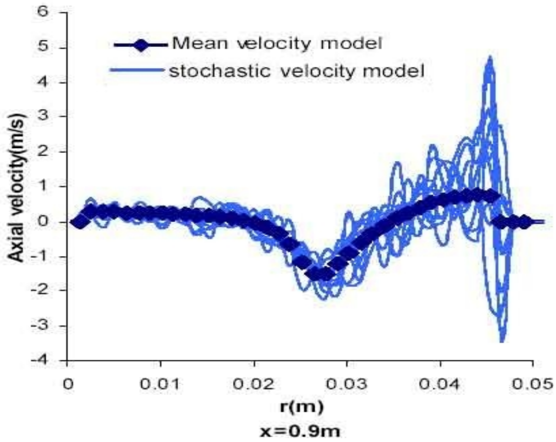


Fig.3- Axial velocity in cylindrical part of cyclone

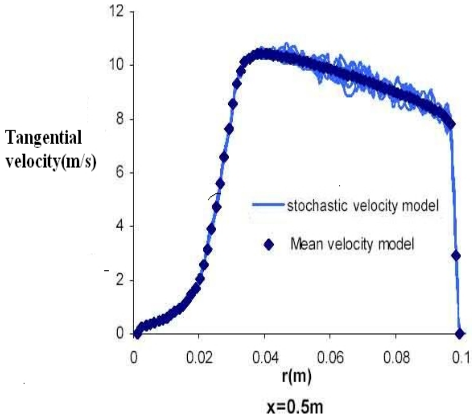


Fig.4- Tangential velocity in cylindrical part of cyclone

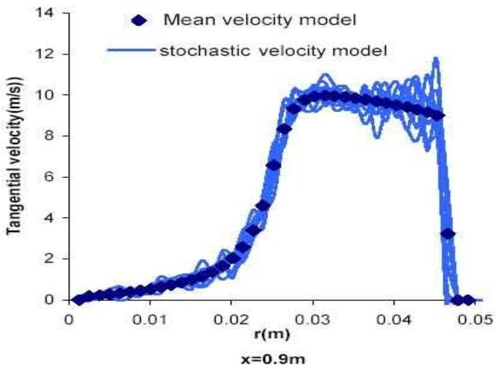


Fig.5-Tangential velocity in cone part of cyclone

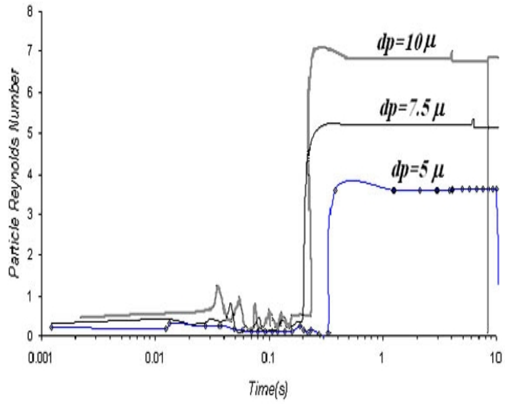
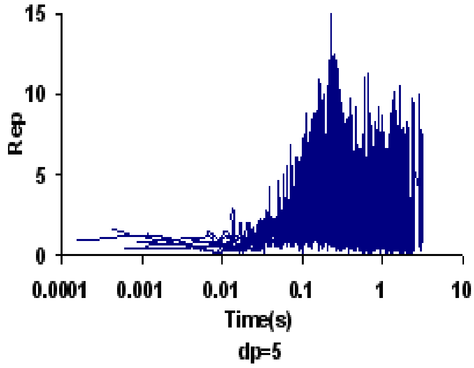


Fig.6- Reynold's number profiles of the cyclone at three size diameter



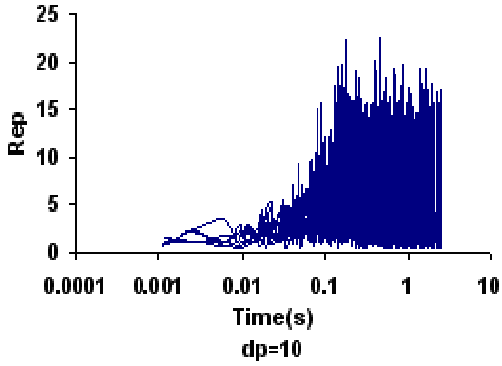
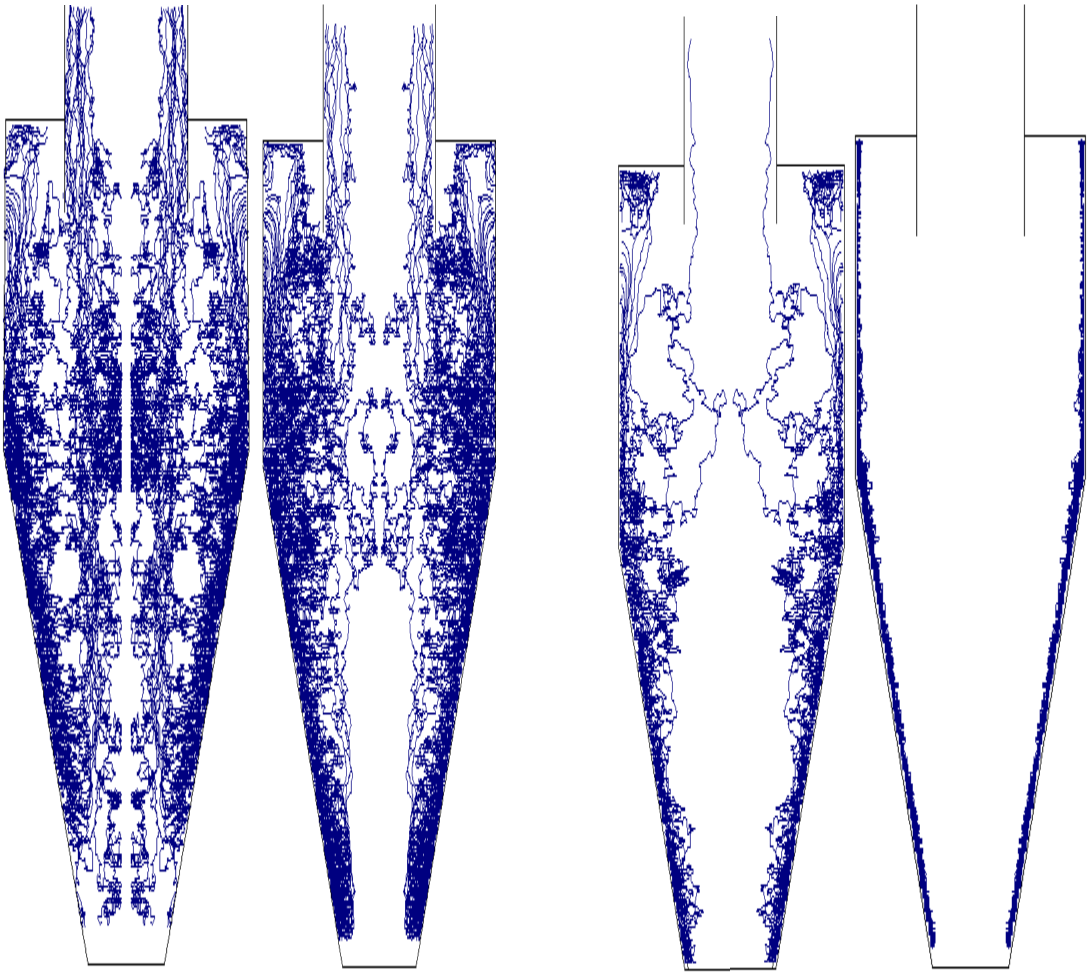


Fig.7-Dispersion Reynold's number for 5E-6m diameter

`Fig.8-Dispersion Reynold's number for 10E-6m diameter



1E(-6)m 5E(-6)m 10E(-6)m 50E(-6)m

Fig.9- The trajectories of particles with different diameters

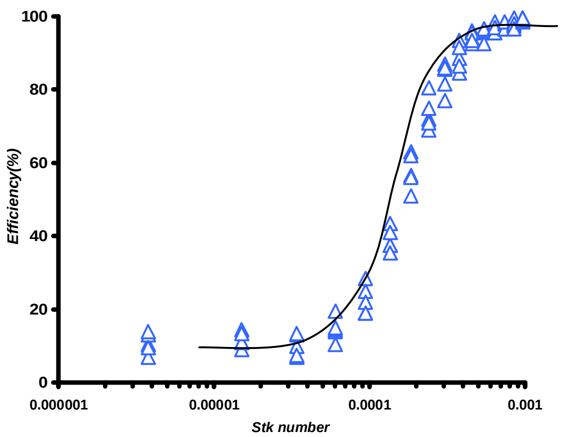


Fig.10-separation efficiency with different diameters(1E-6-20E-6)m and different density(500-2500)kg/ m3

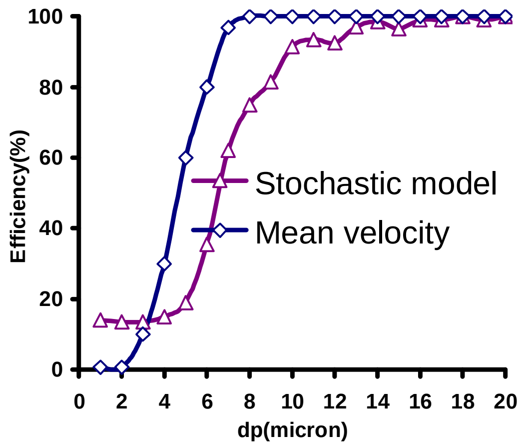


Fig.11-separation efficiency with mean and dispersion velocity