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Effects of the prolonged vertical tube on the separation performance of a cyclone

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Abstract

This article aims at the gas flow into the dustbin of conventional cyclones, the prolonged cyclone (attaching a vertical tube at the bottom of the dust outlet) is proposed by some researchers, which can make flow with dust enter into the tube and separate further. The Reynolds stress transport model (RSTM) has been employed to predict the gas flow fields of the conventional and prolonged cyclones. The tangential velocity, axial velocity profiles and turbulent kinetic energy profiles are presented, and the downward flow rates into the dustbin of the three cyclones are compared. The separation performances of these three cyclones are tested. The result indicates that the tangential velocity, axial velocity and turbulent kinetic energy in the dustbin reduce greatly when the prolonged vertical tube attaching into the dust outlet, which can avoid the re-entrainment of already separated dust effectively. Furthermore, the prolonged vertical tube increases the separation space of dusts. The downward flow rate into the dustbin of the prolonged cyclone decreases compared with the conventional cyclone. The experimental results show that the prolonged vertical tube can improve the separation efficiency by a slightly increased pressure drop. However, for an even longer tube, the separation efficiency is slightly reduced. Thus, there is an optimal tube length for a given cyclone.

Keywords: Cyclone; Vertical tube; Numerical simulation; Experimental study

1. Introduction

The cyclone is a two-phase device for the separation of dispersed particles from their carrying fluid flow. It is now commonly employed in industry for the removal of dust dispersed solid particles which have a difference in density from that of air. In comparison with other types of dust removal devices, such as the electrostatic, fabric and wet collectors, the cyclone has the advantage of being simple in design, very reliable in performance and considerably low cost in maintenance. The cyclone also possesses a relatively large effective collection region and a relatively low-pressure drop. However, it is not very efficient and cost effective for the separation of very fine particles.

A dustbin is attached to the dust outlet for conventional cyclones. Some experiments had indicated that much gas flow entered into the dustbin through here. However, because the bottom of the dustbin is stifled, the gas flow will return and re-enter into the separation space, which will disturb some separated particles and bring them into the inner core vortex, and lead to so-called “re-entrainment”, thus will reduce the separation efficiency of the cyclone. Hoffmann et al. [1] and Obermair et al. [2,3] have attached a vertical tube into the dust outlet, which can make flow with dust enter into the tube and separate further, and they have conducted detailed experiments on cyclones of different dust outlet geometries and found that these parts have important influence on separation efficiency of the cyclones. However, determining the influence of different dust outlets geometries and operation conditions on the separation efficiency of cyclones by means of experiments will waste a lot of time and resources. On the other hand, with the rapid development of the computer and computational fluid dynamics (CFD) techniques, the use of numerical simulations to predict the performance of the cyclone has received much attention and it is at present under intensive development [4–11]. An evident advantage of CFD calculations with respect to experiments is that a large number of flow and geometry variables can be varied at

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Nomenclature

a	height of cyclone inlet (m)
b	width of cyclone inlet (m)
B	dust outlet diameter (m)
D	diameter of cyclone body (m)
D_e	diameter of cyclone vortex finder (m)
h	length of cyclone cylinder (m)
H	length of cyclone (m)
i, j, k	(=1, 2, 3) components in the Cartesian coordinate system
k	turbulence kinetic energy of (m^2/s^2)
L	upward or downward flow rate (m^3/s)
S	deepness of vortex finder insertion (m)
u	velocity (m/s)
V_{in}	inlet velocity (m/s)
V_z	axial velocity (m/s)

Greek letters

ΔP	pressure drop
ε	dissipation rate of turbulent kinetic energy ($kg/m\,s^3$)
ρ	gas density (kg/m^3)
ξ	pressure drop coefficiency
$-$	average value

relative low costs. Therefore, this paper used CFD simulation to study the gas flow fields of the conventional cyclone and the prolonged cyclones. In addition, comparison of the separation performances of the three cyclones is made to reveal how the length of the vertical tube influences their performances.

2. Numerical study

The geometry of cyclone is fully described in Fig. 1. The parameters in Fig. 1 are as follows: $a = 0.091$ m, $b = 0.040$ m, $D = 0.200$ m, $D_e = 0.065$ m, $H = 0.756$ m, $h = 0.261$ m, $S = 0.178$ m and $B = 0.080$ m. The diameter and length of the dustbin are all 0.2 m. The finite difference grid used in this calculation is shown in Fig. 2. The grid consists of about 45,000 control volumes for the conventional cyclone, and about 70,000, 78,000, 86,000 control volumes for the cyclone with a prolonged vertical tube at the bottom, respectively. Grid refinement tests are conducted in order to make sure that the solution is not grid dependent.

For the turbulent flow in cyclones, the key to the success of CFD lies with the accurate description of the turbulent behavior of the flow. A number of turbulence models are available, ranging from the industry standard k–ε model to the more complicated Reynolds stress transport models (RSTM). The k–ε model involves the solution of transport equations for the kinetic energy of turbulence and its dissipation rate and the calculation of a turbulent contribution to the viscosity at each computational cell. This model has been shown to be inadequate for the calculation of flows with swirl [5–12]

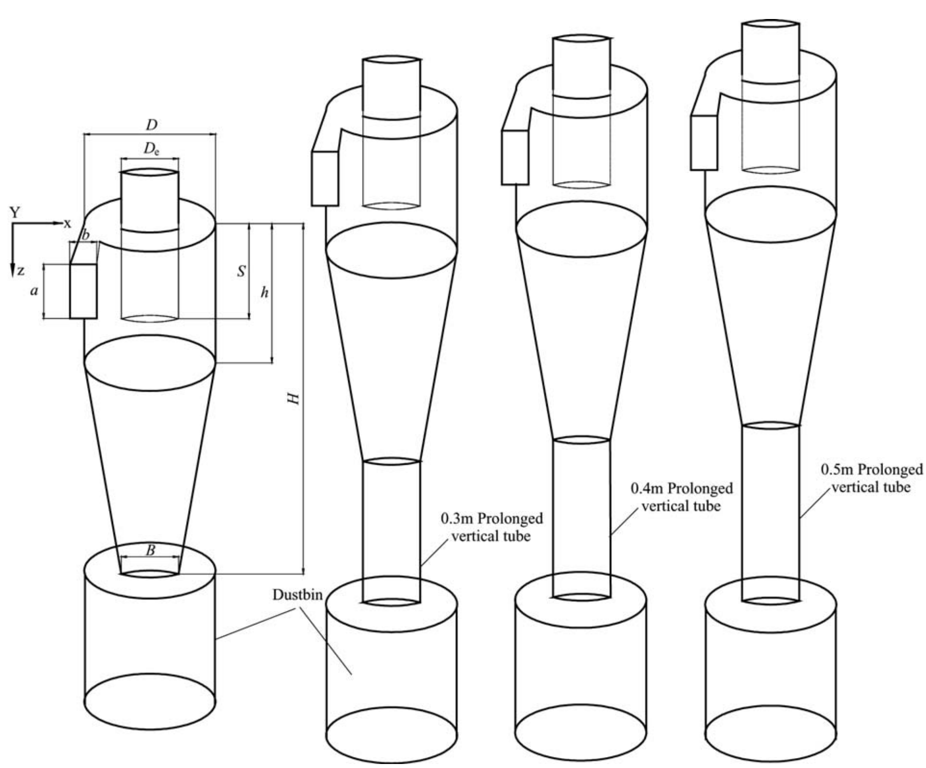

Fig. 1. Cyclone geometry.

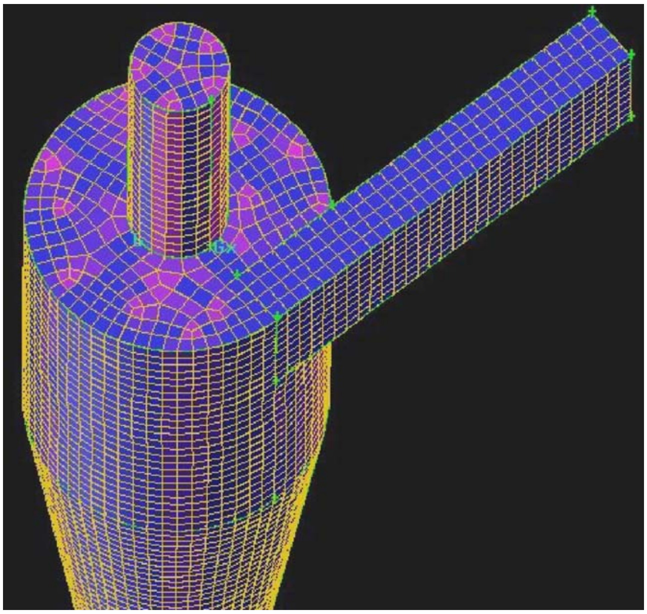

Fig. 2. CFD grid which was used in this simulation.

because it leads to excessive levels of turbulence viscosity and unrealistic tangential velocity distributions. The RSTM, on the other hand, requires the solution of transport equations for each of the Reynolds stress components as well as for dissipation transport without the necessity to calculate an isotropic turbulent viscosity field. Although the RSTM performs much better than k–ε model in swirling flows, it has the disadvantage of being computationally expensive. The solution of these equations by numerical techniques have been made possible by the advent of powerful digital computers, opening avenues towards the calculation of complicated flow fields with relative ease.

This study will use the commercial finite volume flow solver Fluent V6.1 to simulate the gas field flow of conventional cyclone and the cyclone with a prolonged vertical tube at the bottom. In RSTM, the transport of each Reynolds stress is described by its own partial differential equation. These equations can be written in a compact form by Cartesian tensor notation as follows [13]:

$$\frac{\partial}{\partial x_k}(\rho u_k \overline{u_i' u_j'}) = D_{ij} + P_{ij} + \Phi_{ij} - \varepsilon_{ij} \quad (1)$$

where the term P_{ij} represents the (exact) expression for the generation of the stress $\rho\overline{u_i' u_j'}$. The terms D_{ij}, Φ_{ij} and ε_{ij} are the turbulent diffusion, redistribution of turbulent kinetic and the rate of dissipation, respectively.

Although the first-order upwind scheme discretization yields better convergence, it generally will yield less accurate results. According to this, the QUICK discretization scheme was used in calculating momentum and turbulence kinetic energy and its dissipation rate equations. The first-order upwind scheme discretization was used on the Reynolds stress equations. SIMPLEC arithmetic was used in pressure–velocity coupling in order to accelerate the convergence of the continuity equation. The PRESTO! scheme was applied in discretizing pressure gradient taking into account non-staggered grid. A “velocity inlet” boundary condition was used at the cyclone inlet, and the inlet velocity was 18 m/s in each simulation. The boundary condition at the gas exit used was the “out-flow” condition. No slip boundary condition was used in wall boundary, and near-wall treatment was standard wall function.

3. Experiment

The objective of this experiment is to measure the grade efficiencies and pressure drops of these three cyclones. The test facility is illustrated in Fig. 3. To facilitate visual observation all cyclone parts are constructed of perspex.

Experiments were conducted at 10–20 m/s inlet gas velocities. Talcum powder of wide size distribution (mean particle size: 6.39 μm, particle density: 2750 kg/m^3) was employed as the test dust (Fig. 4), and the inlet particle load was 10 g/N m^3. Inlet size distribution was periodically checked and remained constant. Solid flow rate and overall collection efficiency were obtained at the end of each test run by weighting collected solids inside the dustbins. Samples of solids were collected to obtain grade efficiencies. Size analysis was performed by centrifugal particle size analyzer (SA-CP3, SHIMADZU Corporation).

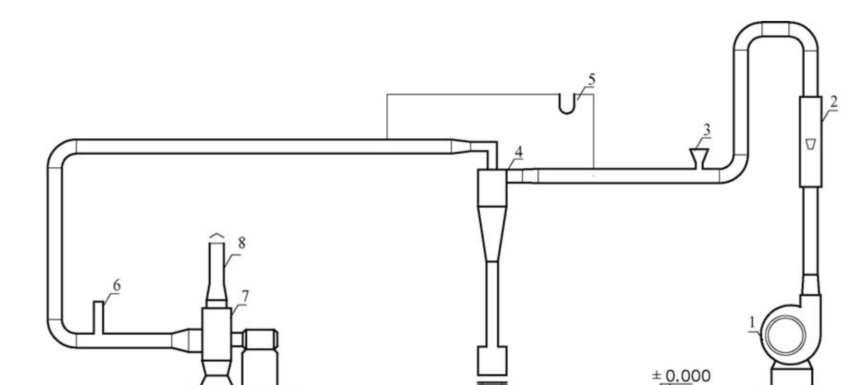

Fig. 3. Experimental setup: (1) fan, (2) flow meter, (3) powder feeder, (4) cyclone, (5) U-shape tube, (6) sluice valve, (7) suction fan and (8) gas outlet.

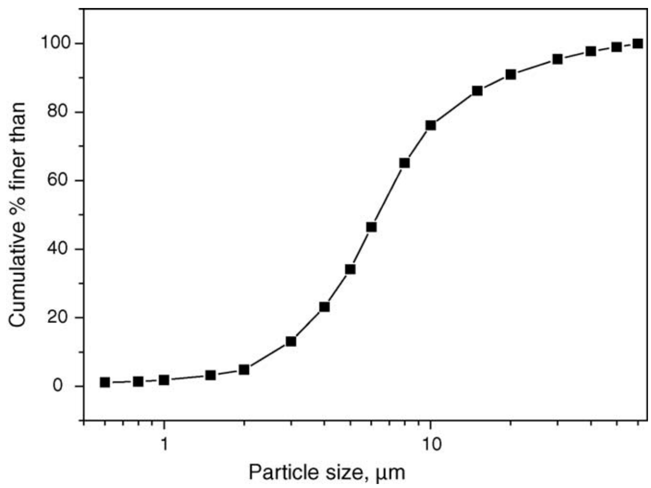

Fig. 4. Cumulative size distribution of the test dust at the cyclone inlet.

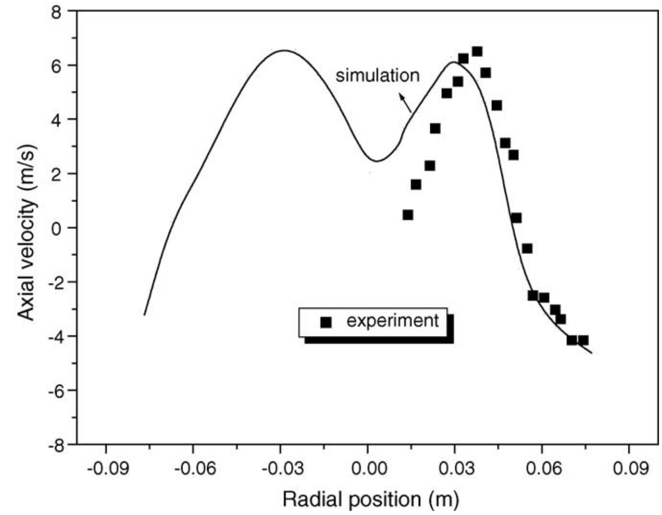

Fig. 6. Comparison between the axial velocity at $Z = 0.59$ m as predicted by the RSTM model and experimental data.

4. Results and discussion

4.1. Comparison of velocities between experiment and simulation

Fig. 5 compares the predicted and measured tangential velocity distributions along the radius at one axial station on a vertical plane through the cyclone center ($Y = 0$). The experimental data were cited from [14]. Considering the complexity of the gas flow in a cyclone, the agreement between the simulation and experiment can be regarded as acceptable. Same agreement was found for the axial velocity distribution (Fig. 6).

4.2. Comparison of the flow fields of conventional and prolonged cyclone

Tangential velocity, axial velocity and turbulent kinetic energy are the important components of the gas flow in a cyclone. Tangential velocity results in the centrifugal force for particle separation [9]. Axial velocity makes particle transport to the dustbin. Turbulent kinetic energy denotes the intensity of turbulent fluctuating. The tangential velocity profiles of the conventional and prolonged cyclones in $Y = 0$ plane are presented in Fig. 7. From this figure (including Figs. 8 and 9), the flow fields of the conventional and prolonged cyclone have good axis-symmetries. Fig. 7 shows that the tangential velocity in a cyclone exhibits a combined vortex structure, i.e. the tangential velocity increases with increasing radius in the neighborhood of the axis, which is called quasi forced vortex, reaches a maximum approximately at the vortex finder radius, and decreases thereafter with increasing radius, which is called quasi free vortex. The maximum tangential velocity is located at 0.7–0.8 radius of the vortex finder. The flow fields in the vertical tube and in the dustbin are similar to that in the cyclone, i.e. the tangential

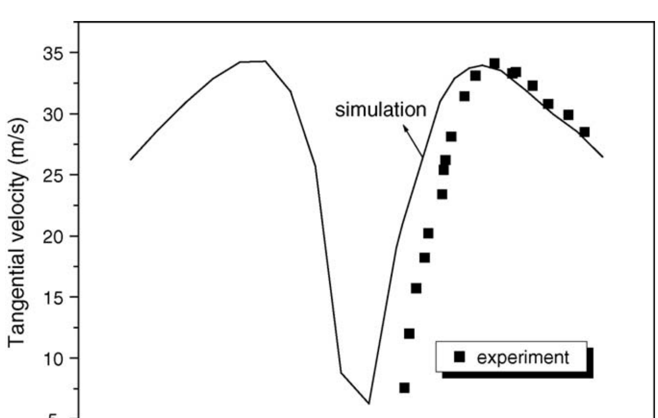

Fig. 5. Comparison between the tangential velocity at $Z = 0.32$ m as predicted by the RSTM model and experimental data.

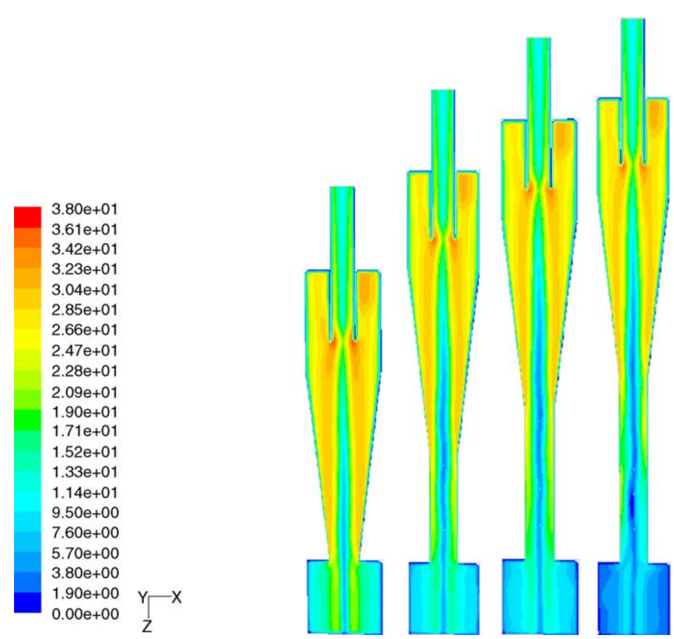

Fig. 7. Tangential velocity profile of cyclones at $Y = 0$ plane (inlet velocity is 18 m/s).

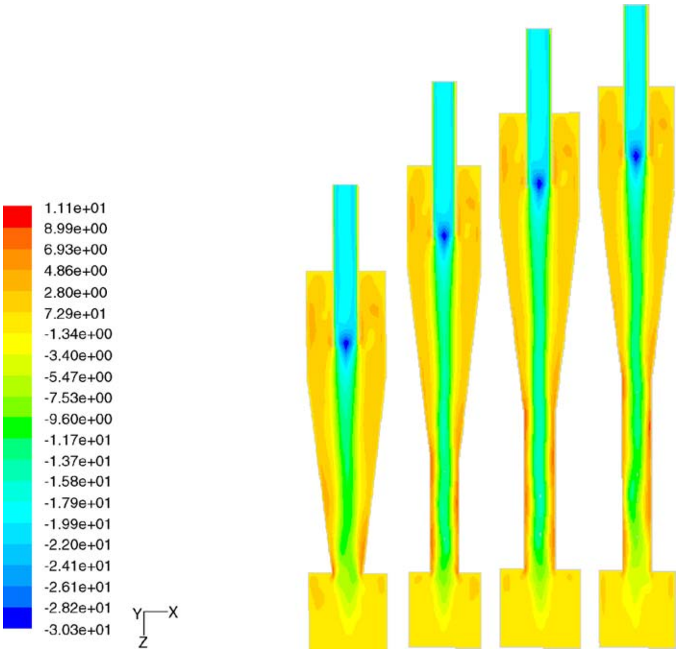

Fig. 8. Axial velocity profile of cyclones at $Y=0$ plane (inlet velocity is 18 m/s).

velocity here also assumes double-vortex frame. Axial velocity profile of cyclones at $Y=0$ plane is presented in Fig. 8. For the four cyclones, there is a downward flowing vortex at the wall of the cyclone and a second vortex flowing concentrically upwards. Tangential gas velocity profiles along radius position at $Z=0.9$ (Conventional cyclone), 1.2 m (0.3 m prolonged cyclone), 1.3 m (0.4 m prolonged cyclone) and 1.4 m (0.5 m prolonged cyclone) in $Y=0$ plane are presented in Fig. 10. This figure indicates that the gas tangential velocity is large in the dustbin for the conventional cyclone, and the maximum is up to 21 m/s. With a dustbin only, the potential vortex continues from the cyclone cone into the bin. Due to the strong flow and the high turbulent kinetic energy in the dustbin (Fig. 9), a cyclone with such a bin will not result in good separation efficiency. On the other hand, the gas tangential velocity of prolonged cyclone in the dustbin is reduced greatly. Fig. 11 are turbulent kinetic energy profiles along radius position at $Z=0.9$ m, 1.2 m, 1.3 m and 1.4 m in $Y=0$ plane. From this figure, we also can find that the turbulent kinetic energy of the dustbin in the conventional cyclone is much more than that in the prolonged cyclone. Large gas tangential velocity and turbulent kinetic energy will produce the re-entrainment of already separated dust, and worsen the separation process.

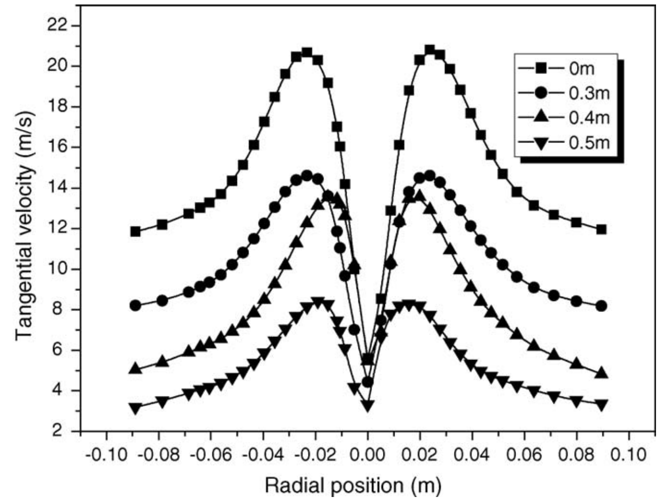

Fig. 10. Tangential gas velocity profile along radius position at $Z=0.9$ m, 1.2 m, 1.3 m and 1.4 m in $Y=0$ plane.

Owing to the high tangential velocity in the vertical tube and relative turbulence, the upward flowing gas is exposed to a high centrifugal field. In the point of the fact, the prolonged cyclone can provide more separation space, which is useful to increase the separation efficiency.

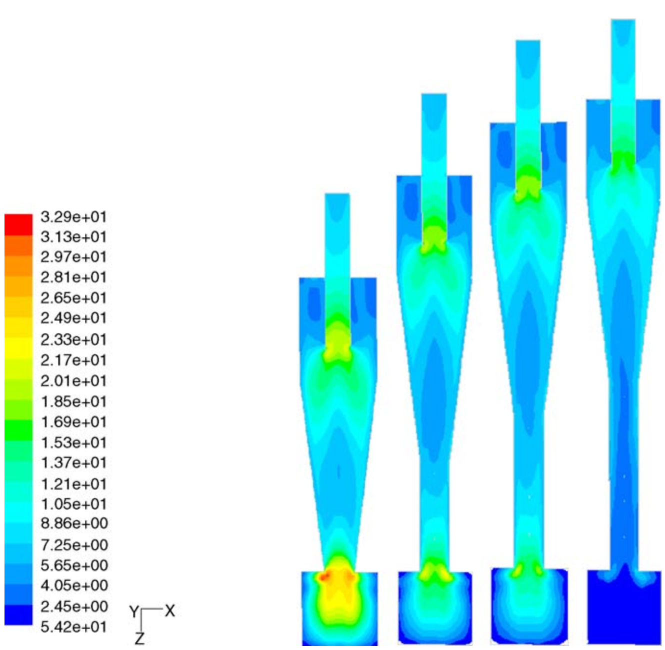

Fig. 9. Turbulent kinetic energy profiles of cyclones at $Y=0$ plane (unit: m^2/s^2).

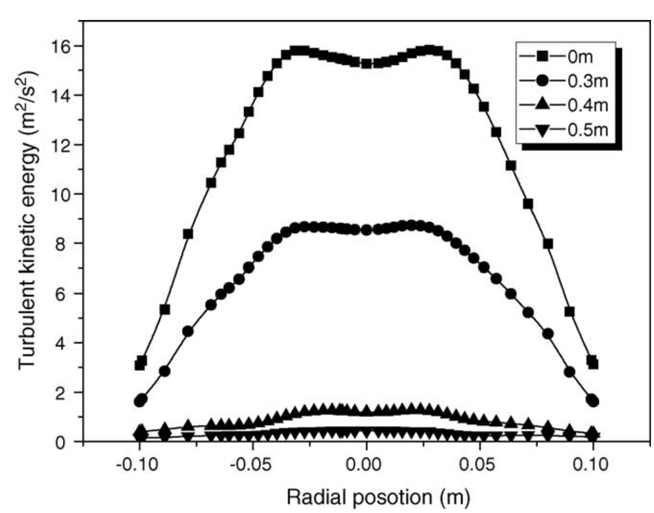

Fig. 11. Turbulent kinetic energy profile along radius position at $Z=0.9$ m, 1.2 m, 1.3 m and 1.4 m in $Y=0$ plane.

Fig. 7 also indicates that the tangential velocity is reduced in the conical part or the cylindrical section of the cyclone with the prolonged vertical tube, owing to the increased friction of the larger wall surface. Reduced tangential velocity will lead to worse separation efficiency, which can be offset by the additional separation process in the vertical tube and the reduced dustbin re-entrainment.

Ji et al. [15] shows that there is a dust ring at the bottom of the vertical cylinder by means of dust investigation, and the axial width of this ring is about $D/4$. This result was consistent with Alexander's [16] experimental observation. He concluded that the maximum of tangential velocity of the plane where the dust ring was located was only about 12% the maximum tangential velocity of the bottom of vortex finder by means of flow field measurement. Additionally, the tangential velocity profile of the plane where the dust ring is located is flat, and more than 90% of the axial velocity had been attenuated. Therefore, he defined the distance from the dust ring to the bottom of the vortex finder as the natural vortex length. From above simulation results, for conventional cyclone, the natural vortex length should be longer than the physical length of cyclone, i.e. the vortex end is not located at the bottom of the cone. Given the separation space, the vortex will circumvolve downwards. Gil et al. [17] considered that only space that is above the end of the vortex effects the dust separation. In point of this fact, cyclones whose natural vortex length is longer than physical length are advisable. On the other hand, the prolonged cyclone can make the vortex end locate in the vertical tube and even in the dustbin, and increase the efficient separation space, thus improves its separation performance. However, for the cyclone with 0.5 m prolonged vertical tubes, the vortex end will locate at the bottom of the vertical tube. Therefore, dust deposition will appear near the vortex end (Fig. 15), which will lead to adverse influence on the separation of the particle.

Fig. 12 is the axial velocity profiles along radial position at $Z = 0.756$ m (conventional cyclone), $Z = 1.056$ m (prolonged cyclone with 0.3 m vertical tube), $Z = 1.156$ m (prolonged cyclone with 0.4 m vertical tube) and $Z = 1.256$ m (prolonged cyclone with 0.5 m vertical tube) in $Y = 0$ plane, which shows that near the dust outlet of the conventional cyclone and the prolonged cyclone, the axial velocities do not have good axis-symmetries. Furthermore, the axial velocity of the conventional cyclone in this position does not attenuate completely, whose maximum value is about 9 m/s. However, the axial velocity of the prolonged cyclone here decreases compared with the conventional one. Axial velocity is divided into two parts along radial position, i.e. upward flow and downward flow, and between the two flows, the axial velocity is zero. Each section in cyclone, the upward flow rate and downward flow rate can be calculated by integrating the axial velocity with the area, i.e.:

$$L = \int_{r_1}^{r_2} 2\pi r V_z \, dr \qquad (2)$$

The flow rate above the line that the axial velocity is zero is the downward flow rate. From Eq. (2) and the axial velocities of simulation, the downward flow rates of three geometries are 18.476%, 11.438%, 10.499% and 9.5852%, respectively, which show that there is some gas flow entering into the dustbin. However, the bottom of the dustbin is plugged up, the gas flow should re-enter the inner-swirl flow of the cone, which will return some separated dust and throw some fine dust into the inner-swirl flow, which will effect the separation efficiency of cyclone badly. However, the prolonged vertical tube can reduce the downward flow rate of this position, for example, for the cyclone with 0.3 m prolonged vertical tube, the gas flow that enters into the dustbin reduces slightly, which shows that the length of the vertical tube can be increased in order to improve the separation efficiencies of the cyclones from the point of the downward flow rate of this position.

It is noted that, when simulating the cyclone without the dustbin, there should be an axial velocity dip along the axis of the cyclone (Fig. 6). However, in this paper, the cyclone includes the vertical tube and the dustbin except for the cylinder and cone. Therefore, these parts should affect the flow field of the cyclone (Shalaby et al. [18] and Hu et al. [19]).

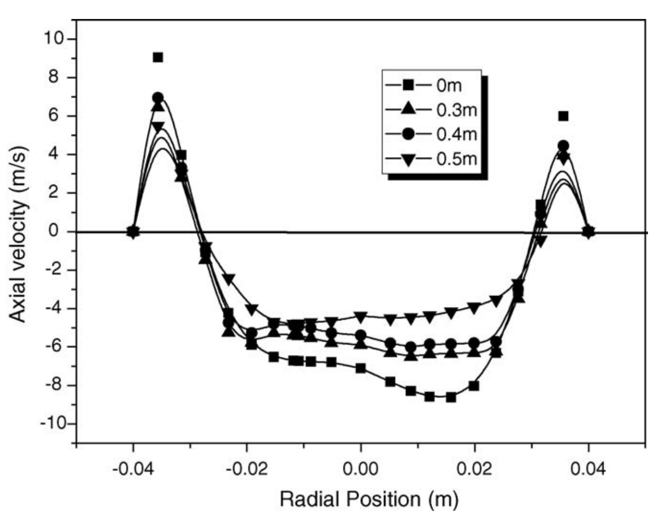

Fig. 12. The axial gas velocity profile at $Z = 0.756$ m, 1.056 m, 1.156 m and 1.256 m in $Y = 0$ plane of different cyclones.

4.3. Comparison of the separation performances of the four cyclones

4.3.1. Comparison of the pressure drops of the four cyclones

Cyclone pressure drop is essentially a consequence of the vortex energy, the solid loading and the gas-wall friction. The main contribution is the former, but it cannot be reduced because it may affect separation efficiency. Generally, cyclone pressure drop is proportional to the velocity head and can be written in the form of:

$$\Delta P = \xi \frac{\rho V_{\mathrm{in}}^2}{2} \qquad (3)$$

The cyclone pressure drop is calculated as the pressure difference between the inlet and the average pressure across the vortex finder exit [20]. Comparison of pressure drops of the four cyclones is presented in Fig. 13. From this figure,

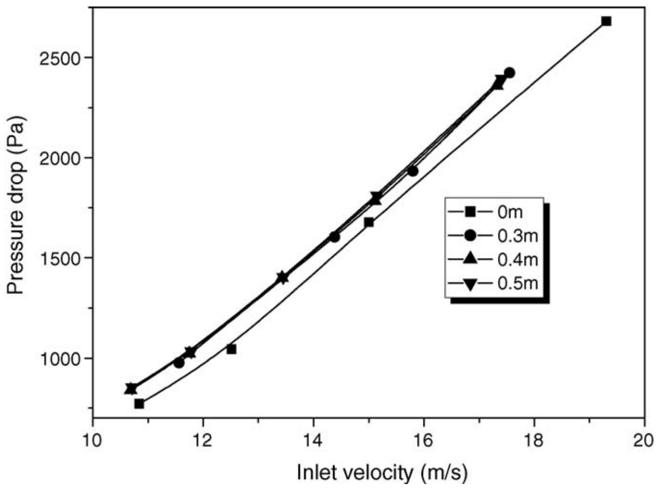

Fig. 13. Evolution of pressure drop with inlet velocity.

the prolonged vertical tube will produce the slightly increased pressure drop. This can be explained by the reduced wall friction in the cyclone, arising from the fact that less dust is re-entrained from the dustbin into the cyclone. This causes less particle wall friction and means further that the wall deposits in the cyclone are reduced or disappear when a vertical tube is used.

4.3.2. Comparison of the grade efficiencies of the four cyclones

Separation efficiency in a cyclone is the fraction of the inlet solid flow rate separated in the cyclone. As a cyclone usually collects a wide solid inlet distribution, it is common to express the cyclone efficiency as a function of the particle size, leading to the fractional efficiency curve. Comparison between the grade efficiencies of the four cyclones is presented in Fig. 14. Figs. 13 and 14 indicate that the improvement of efficiency is accompanied by a slightly increased pressure drop. It is noted that the separation efficiency of the cyclone with a 0.5 m prolonged vertical tube is lower than that of the cyclone with a 0.3 m and 0.4 m vertical tube. From Figs. 7–9, for the cyclone with a 0.5 m prolonged vertical tube, the vortex end will locate at the vertical tube. Additionally, dust deposition will appear near the vortex end (Fig. 15) [21]. However, the dust deposition will lead to the re-entrainment of separated particles (Fig. 16), which will worsen the separation process of cyclones. In point of these facts, we found that there was an optimal length for the prolonged cyclones. For the given cyclone which is presented in this paper, we can conclude that the optimal length is between 0.3 m and 0.5 m, i.e. 0.4 m or so. On the other hand, the prolonged vertical tube produced the slightly increased pressure drop.

Fig. 15. Dust deposition at the wall of the vertical tube.

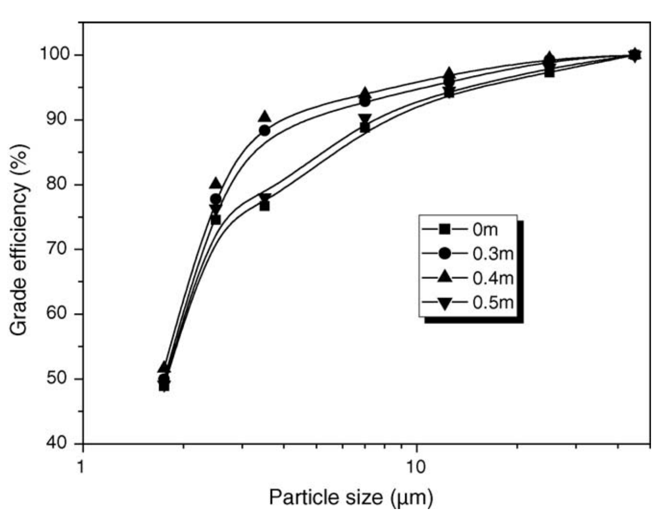

Fig. 14. Comparison among the grade efficiencies of the four cyclones (inlet velocity is 18 m/s).

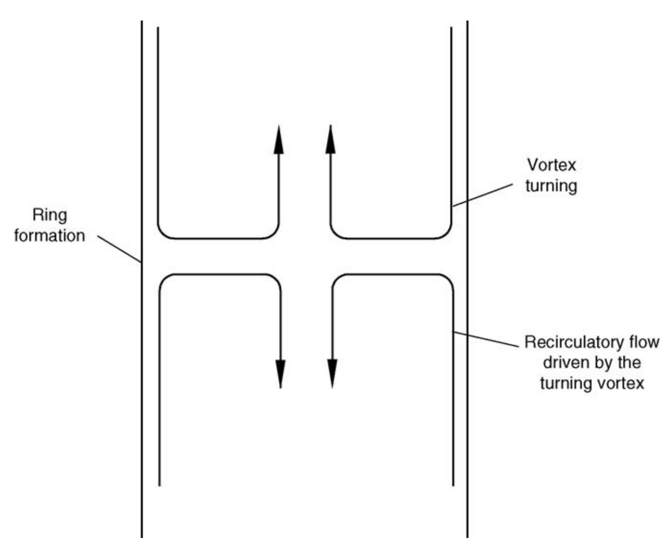

Fig. 16. The possible flow pattern at the end of the vortex.

5. Conclusions

From the numerical and experimental studies of the conventional and prolonged cyclones, some conclusions can be presented:

(1) The tangential velocity, axial velocity and turbulent kinetic energy are still large in the dustbin of the conventional cyclone, and the average value is about 20 m/s, which indicates that the gas eddy here is still intense. This intense gas flow will disturb some separated particles, and worse the separation process of cyclones.
(2) There is some gas flow entering into the dustbin of the conventional cyclone through the dust outlet. This downward flow rate will produce the flow into the dustbin. On the other hand, when a prolonged vertical tube attached into the conventional cyclone, the swirl will enter into the tube, and make dust separate further. However, for the cyclone with a 0.3 m prolonged vertical tube, there is still some gas flow entering into the dustbin when the inlet velocity is large, which will result in the re-entrainment of some separated particles.
(3) For the cyclone with a 0.5 m prolonged vertical tube, the tangential velocity, axial velocity and turbulent kinetic energy are reduced greatly, and the vortex end located at the bottom of the vertical tube. Therefore, dust deposition will appear near the vortex end. However, the dust deposition will lead to the re-entrainment of separated particles, which will worsen the separation process of cyclones. From the experimental results, there is an optimal vertical tube length exiting in the prolonged cyclones.

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