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Experimental study on the gas–solid suspension flow in a square cyclone separator

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Abstract

A three-dimensional particle dynamic analyzer (3D-PDA) was employed to measure the gas–solid two-phase flow in a lab-scale square cyclone separator with downward gas-exit. Several cases of different inlet velocity and particle concentration were studied. The particle used in the test was glass bead of mean diameter 30–40 μm. Discussion was given on the distribution of flow vector, mean velocity, turbulent intensity and kinetic energy of both gas and particles of different diameter at different position in the separator. It was found that the center of the flow field deviated from the geometric center of the cyclone. The flow fields had the feature of Rankine eddy, i.e., strongly swirling region in the central part and pseudo-free eddy region of weak swirling intensity near the cyclone wall. Local vortex existed at the corners where the flow changed its direction sharply. When the cyclone wall was heated and the suspension temperature was elevated, the flow field became more uniform than that under room-temperature condition. The local vortexes at the corners were weakened and the swirling intensity became poorer which led to decreased total mean separation efficiency from about 81% to 76.5%. The right-side wall facing the suspension inlet gave the major contribution to the separation efficiency, where the largest downward velocity was measured. Back-flow (upward velocity) was found around the center of the separator above the gas-exit. The quasi-laminar motion of particles enhanced the turbulent motion at the corners due to particle–particle or particle-wall collision, which led to the local peak value of the turbulent kinetic energy and turbulent intensity. The corner was one of the major regions to cause pressure drop and was found to be beneficial to particle separation mainly because the strong fluctuating flow consumed much of the kinetic energy of both the particle and gas.

Keywords: Square-shaped cyclone separator; Circulating fluidized bed; Turbulent flow; Three-dimensional particle dynamic analyzer (3D-PDA)

1. Introduction

Circulating fluidized bed combustion has developed fast during the last two decades and is becoming a widely-used clean coal combustion technology in the world thermal power trade. CFB has the advantages of fuels flexibility, low pollutant emission, high combustion efficiency and broad range of load switching so that it could meet the need to save energy and protect environment. Gas–solid separator is a key part for a CFB boiler, which controls the CFB solids circulation rate. The performance of a separator is critical to the boiler's safe and economic operation. The arrangement and structure of the separator influence the overall arrangement of a boiler. However, the thermal inertia and huge volume of the traditional circular cross-section cyclone are major shortcomings for large commercial CFB boiler application. Foster Wheeler firstly developed a cooling type high temperature cyclone which was cooled by water or steam tubes on its inner walls. But it was too complex for manufacturing and installation of the tubes and the refractory wall. Another type of separator was studied by Chen et al. [1] and Liu et al. [2] which was a circular cross-section cyclone with downward gas exhaust for middle temperature application. Chen et al. [3] studied the separation mechanism inside a downward-exhaust cyclone and Chen et al. [4] further analyzed its pressure drop characteristics. Cen et al. [5] researched the separation mechanism of a finned tube impact gas–solid separator which was applied as a primary separation unit inside a CFB boiler. Ahlstrom Pyropower company developed a square water-cooled cyclone separator with upward exhaust exit for high temperature separation and applied to its compact CFB boiler design [6,7]. Other authors reported the application of such a separator to commercial CFB boilers [8,9]. A square cyclone separator can permit a traditional

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Nomenclature

K	turbulent kinetic energy
Tu	turbulent intensity
$\bar{u}'$	local fluctuating velocity
U_{mean}	mean velocity

arrangement of a CFB boiler. At the same time it is convenient to install heat transfer surfaces on the inner separator walls and carry out a water or steam–cooled separation at high inlet temperature, which can meet the demand of large CFB boilers. A type of square cyclone separator with downward-exhaust exit was developed and granted a Chinese patent [10]. Its separation efficiency was shown as good as that of the traditional cyclone of circular cross-section separator and its particle cut-diameter was around 15 μm [11]. Almost all the above researches on separators emphasized the separation efficiency and the pressure drop either by experimental or numerical ways and then deduced their claims of the separation mechanism.

Intensive study on the particle separation mechanism should be carried out in order to improve and optimize the separator's structure by measuring carefully the internal flow field. Theoretically, the flow field of the gas–solid suspension in a cyclone is a three-dimensional strongly swirling turbulent flow and there exist locally some small vortex. Many authors have given their efforts to the research on the traditional cyclone by different methods [12–18]. However, little attention was paid to internal suspension flow characteristics in the square cyclone for the application of compact CFB boilers.

It is interesting to understand the nature and characteristics of the suspension flow in the square cyclone separator and find out the factors affecting the particle motion. The authors employed a 3-Dimensional Particle Dynamic Analyzer (3D-PDA) to conduct an experimental investigation on a lab-scale separator model. To our knowledge, few papers reported the suspension flow field inside the special square cyclone. The use of laser Doppler to measure the flow field in a square cyclone seems to be a good means for getting the details for the suspension flow. Laser Doppler has been successfully used to study the gas–solid suspension flow by many authors from 1980s on, especially for the discussion of the effect of particles on the gas phase turbulence and the boundary layer in tubes and ducts. The present paper reported the authors' experimental results on the flow field in a square cyclone separator.

2. Experimental setup

2.1. Experimental system and particle used

The experiment setup was shown as Fig. 1. The air was supplied by an induced blower of 3.5 kW. Particles were fed into the riser by a screw feeder which was controlled by an electromagnetic engine. The circulating fluidized bed was a three-dimensional rectangular duct of 60 mm × 80 mm × 1900 mm. The suspension went through a riser and a horizontal duct and entered into the separator through the inlet of 20 mm × 60 mm. The separator was a square one and its edge length was 120 mm, body height 180 mm. The diameter of the vortex finder and the exhaust exit were both 60 mm. The height of the vortex finder was 90 mm. The distance between the bottom of the vortex finder and the top of the exhaust was 60 mm. The separated particles were collected by a discharge bin. The exhaust gas went through the downward exit to open air by an induced blower. The front side of the separator was glass window for PDA measurement. Fig. 2 shows the separator model and the measure sections.

The particle used was glass beads of mean diameter 30–40 μm and of density 2400 kg/m^3. The glass bead has good physical properties, e.g., sphericity around 0.95 and refraction index 1.5. Glass beads particles of diameter 0–5 μm were selected as the gas tracer. However, we should caution the readers that the particles used in this paper were much less than those typically seen in CFBC because of the PDA measure requirement. If there was too much particles in the swirling flow field, the laser beam may not be received well by the receiver. If the particle used was too coarse, the PDA system would also get

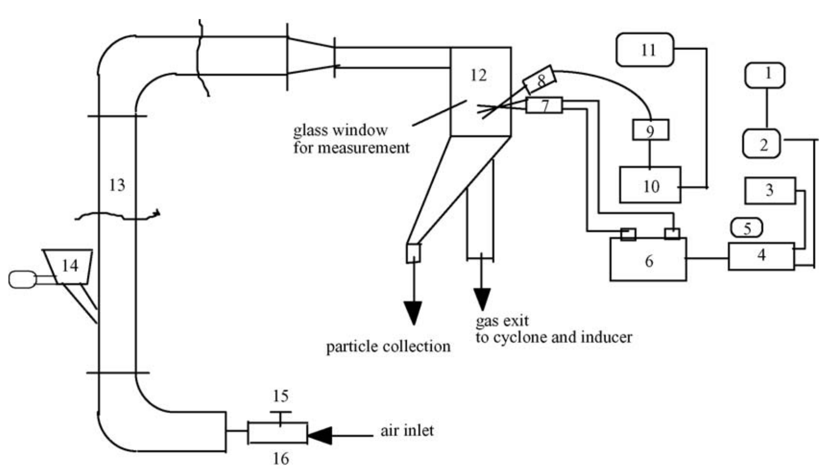

Fig. 1. Test rig (1) transformer, (2) power source, (3) water cleaner, (4) laser, (5) laser controller, (6) beam splitter, (7) laser transmitter, (8) receiver, (9) A/D converter, (10) signal processors, (11) computer, (12) square separator, (13) CFB riser, (14) particle feeder, (15) air control valve, and (16) flow meter.

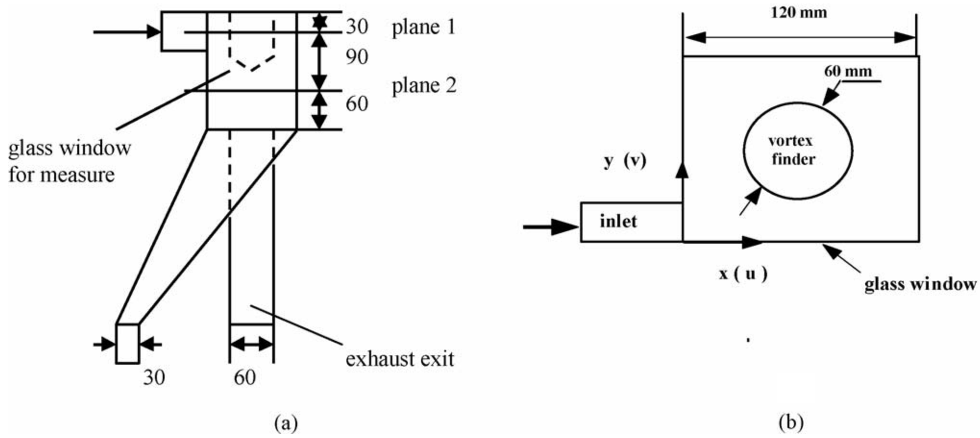

Fig. 2. (a) Measure plane and (b) cross-section of the separator.

trouble to detect enough particles and give the demanded statistical results. Theoretically the particle could be as course as 10,000 μm in diameter, but large particles would cause much noise and could not be measured easily. The particle was detected when it passed the measure volume which was formed when the three laser beams met. The larger the particle was, the smaller the possibility for the particle to be detected became. Hence most of the authors avoided using large particles. Of curse our particles included these which has a large diameter, e.g., 100–200 μm and the statistical results of such large particles could also be separated. But we think, its number was not enough and it gave small difference from the smaller particles. So we gave the typical results of particles of the mean diameter in this paper.

2.2. PDA system and its optical parameters

3-Dimensional Particle Dynamic Analyzer (3D-PDA) is based on the laser Doppler theory and is non-contact measurement technology. It does not disturb the flow field and gives simultaneously high accurate results on the velocity, diameter and concentration of both particle and gas phase. The optical arrangement of the 3D-PDA was a backward-scattered-light system supplied by Dentec, including a 5 W (max. power) Argon-Ion laser source, laser transmitting and receiving systems, signal processor and a computer. A frequency shift of 40 MHz was added to the green and blue beam of the laser. The measure point coordinate was automatically controlled by the transverse system of the PDA following the given coordinate before the running. Some optical parameters are listed in Table 1.

2.3. Experiment cases

Several cases of different inlet velocity and particle loads were tested at the two planes, as listed in Table 2. The PDA measures the velocity of a certain number of particles and calculates the statistically-averaged value as the result. Hence the more particles measured, the better the result is. At each measure point, 5000 particles were enough for the present study. The positive direction of the velocity *W* (vertical velocity) was set upward according to the frequency shift of the laser beam.

Table 1
PDA optical parameter and technical index

Parameters	Ux	Uy	Uz
Fringe spacing (μm)	2.1815	2.0691	2.0182
Number of fringe	18	18	18
Wave length (nm)	514.5	488	476.5
Gaussian beam dia. (mm)	1.4	1.4	1.4
Beam collimator exp.	1	1	1
Beam expander exp.	1	1	1
Beam separation (mm)	38	38	38
Lens focal length (mm)	500	500	500

	Velocity (m/s)	Diameter (μm)	Concentration (1/cm^3)
Measure range	0–500	0.5–10000	10^6
Measure error	1%	5%	30%

Table 2
Cases for PDA measurement

Case	Inlet velocity (m/s)	Inlet particle concentration (kg/m^3)	Note
1	25.3	0.231	plane 1
3	28.32	0.2	plane 2
4 (heated)	28.32	0.18	plane 2

3. Results

The separation efficiency is the most important issue for the cyclone. Any studies on the flow field, either numerical or experimental, are expected to serve for the improvement of the efficiency, so does the present study. But we would not discuss the efficiency in this paper, as references [11,20] gave this information in detail for this type of square cyclone for several sizes and conditions. The present paperwill provide the flow information for a typical design which may help understand the separation mechanism.

3.1. Flow vector

The velocity vector diagram at different section of both gas and particle phase are shown by Figs. 3, 4 and 6. Fig. 3 shows

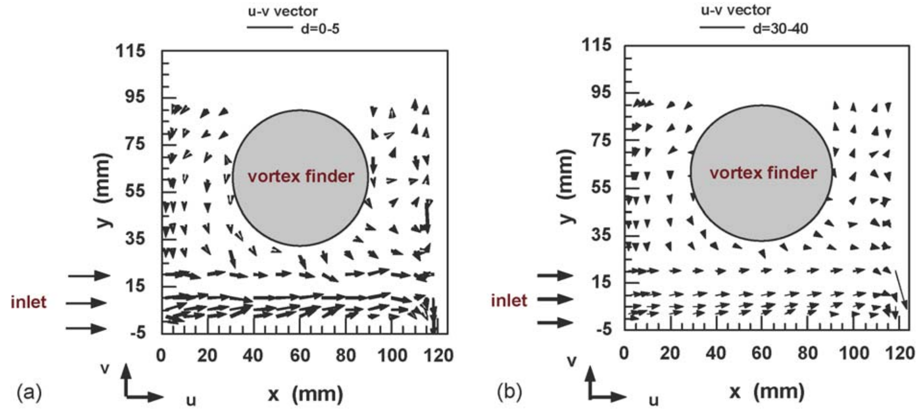

Fig. 3. (a) Vector plot for gas at plane 1–case 1 and (b) vector plot for particle (30–40 μm) at plane 1–case 1.

the velocity field at plane 1. The suspension entered the separator at inlet velocity and traveled along toward the facing wall. At the corner the suspension turned its direction sharply and the particles impacted the wall strongly. Some of the impacting particles rebounded and were carried away by the gas flow. Some of the particles, however, were deposited and fell down along the corner surface in a form of a particle strand as observed during the test.

The result of plane 2 is shown by Fig. 4. Good swirling flow was formed at plane 2. As shown by its distribution, the swirling core of the velocity field derived from the geometrical center of the cyclone cross-section. Local vortex existed at the corners, e.g., $x=0$, $y=0$ and $x=120$ mm, $y=0$, where the particle motion was very disordered. Particle trajectory was rather random due to the particle-wall and particle–particle collision. When particle impacted the wall or other particles at the corner, momentum and energy were exchanged which led to the decrease of velocity in the normal direction to the wall, while the velocity parallel to the wall would increase because of the particle rebounding and re-suspending by the gas phase. Larger particles were more possible to be collected at the corners because they exchanged more momentum and energy with the wall during the collision and they could not trace the gas flow as well as smaller particles did due to its larger inertia. The gas–solid suspension flow actually should be classified into three kinds of flow [19], i.e., laminar flow, turbulent flow and the so-called quasi-laminar flow. Quasi-laminar flow includes two types of fluctuating motion. One is the irregular motion of particles due to the inter-impact between particles or particle and wall surfaces as well as the fluid fluctuating motion induced by the particle fluctuating motion. This kind of fluctuating flow is almost random and has no coherence structure. It is similar to the thermal motion of gas molecular, but it is not completely chaotic. The other is the fluctuating motion in the particle wakes due to the relative motion of fluid and particles. This kind of fluctuating flow has coherence characteristics of very small scale, the order of particle diameter or smaller. There is an wake condition behind the particles, namely the condition for vortex shedding at the particle surface, by and large when the particle Reynolds number exceeds 100. The condition for inter-impact between particles is high particle concentration, especially for the particle flow of asymmetrical diameter. The impact between particle and wall surface mainly happens when the channel shrinks, bends or turns sharply. In general the fluctuating motion due to the above reasons exists only at local position. It was at the corner that the quasi-laminar fluctuating motion came into being and enhanced the gas or particle fluctuating velocity to form local vortex at the corners. Experimental data showed the largest falling velocity of particles was

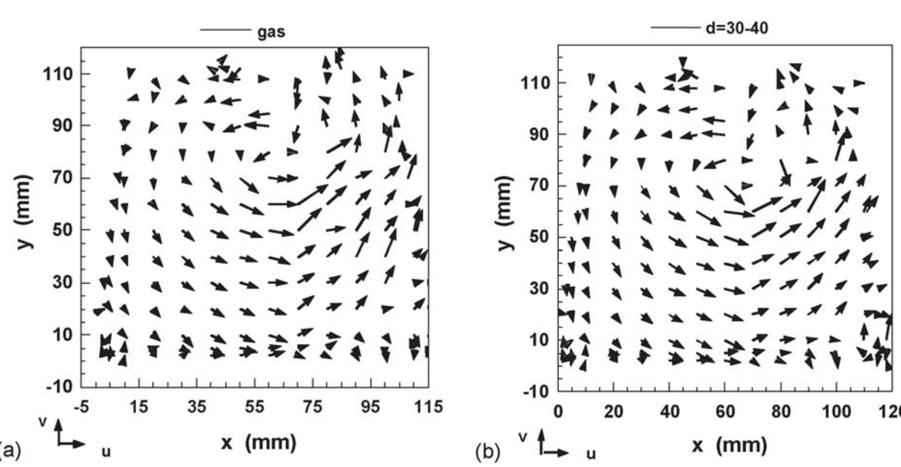

Fig. 4. (a) Vector plot for gas at plane 2–case 3 and (b) vector plot for particle (30–40 μm) at plane 2–case 3.

measured at the front right corner, i.e., $x = 115$, $y = 2$, 10 mm. According to the available experimental results, the corner vortex was in fact advantageous to increase the separation efficiency. When an arc-like device was installed at the corner to eliminate the local vortex and make the swirling velocity field to approach that in a conventional circular cross-section cyclone, however, it was found the separation efficiency decreased on the contrary [11,20].

From the vector distribution, it was seen that the suspension flow field in the separator consisted of the strong swirling flow of high velocity at the center and weak swirling flow of low velocity near the wall, and local eddies existed at the corners. The central flow field can be regarded as forced vortex region, while the flow near the wall can be regarded as quasi-free vortex. Hence, the flow in the square cyclone separator had the characteristics of Rankine vortex, which was very advantageous for particle separation. The strong swirling flow in the center gave rise to centrifugal force and threw the particles to the outer quasi-free vortex region, where particles were likely to be collected due to the weak swirling intensity, especially the larger particles.

In order to investigate the effect of temperature on flow field, three electrical heaters of 500 Ω were installed on the rear wall to elevate the temperature inside the separator. The temperature across the section was measured by thermal couples. The flow measurement began when the temperature was elevated to a steady value. Fig. 5 shows the temperature distribution at different time after the measurement for case 4.

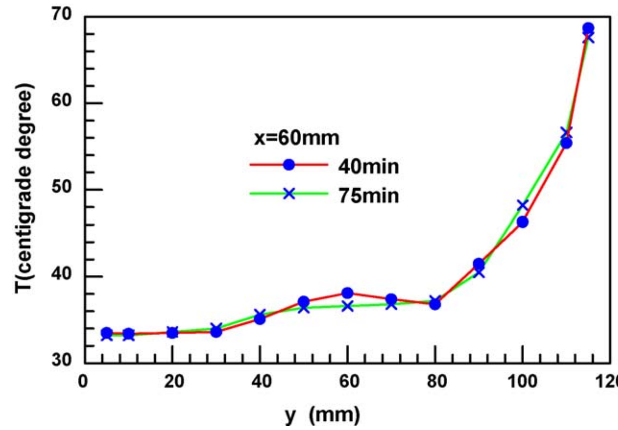

Fig. 5. Temperature distribution in separator-case 4.

Figs. 4 and 6 show the comparison of the velocity field of cases 3 and 4 (heated). The main difference for the heated case was that the local vortex at the corners was weakened and the whole velocity field became more uniform than that of case 3. However, the swirling intensity became a little lower than that under case 3 because of the increased viscosity of the gas phase at elevated temperature. When the separation efficiency was calculated by evaluating the ratio of the separated and fed particles for cases 3 and 4, it was found the overall separation efficiency of case 4 (about 76.5%) under heated condition was lower than that of case 3 (about 81%) under room-temperature at approximately the same inlet particle concentration and inlet velocity. From the comparison of the velocity field of the two cases, we can see, besides the weakened local corner vortex, that the particle movement to the free eddy region near the wall of the separator was also weakened, especially for the small particles including those of 0–5 μm regarded as gas phase, which led to the decreased probability of small particles to be collected by the free eddy region near the wall. Hence the overall separation efficiency decreased. Parker et al. [21] carried out a test on the collection efficiency of a circular cross-section cyclone at high temperature and pressure. They found that the collection efficiency decreased dramatically as temperature increased from 20 to 700 °C. Shin et al. [14], Patterson and Munz [22] also illustrated that the efficiency varied inversely with temperature by their experimental data on the conventional cyclone gas–solid separation for the same inlet velocity and similar particle loads.

In practice of CFB application, it is the hot gas–solid suspension flowing into the cyclone rather than the cold suspension flowing into the hot cyclone. The difference between the hot suspension flowing into the cyclone and the room-temperature suspension flowing into the cyclone and heated by the wall there will lead to the different motion of the particles near the wall surface. When the hot suspension flows into the cyclone, the particles, especially the fine particles, will move to the relatively cold wall due to the thermophoresis. While for the present study,

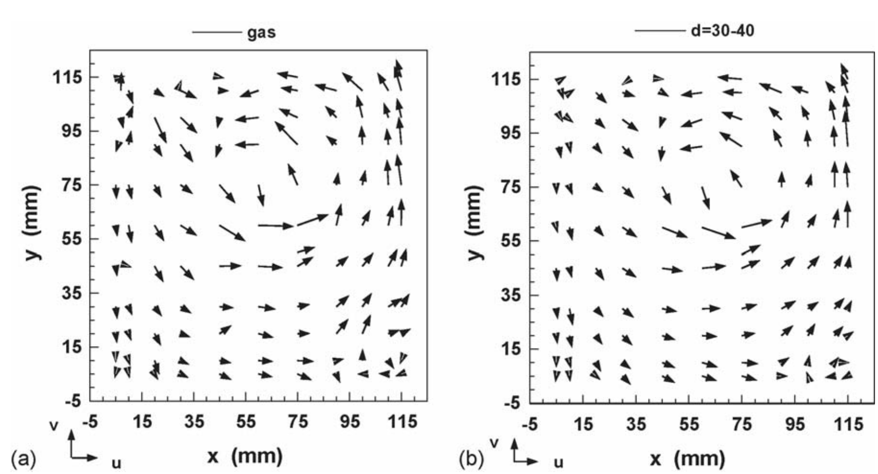

Fig. 6. (a) Vector plot for gas at plane 2–case 4 and (b) vector plot for particle (30–40 μm) at plane 2–case 4.

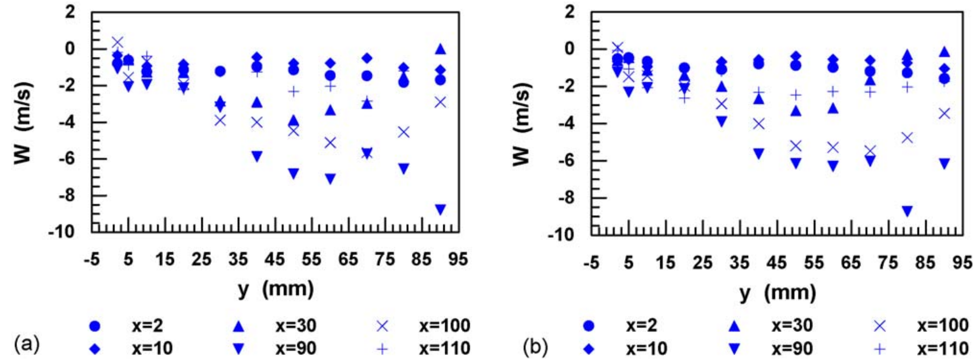

Fig. 7. (a) Distribution of gas velocity W at plane 1 and (b) distribution of W of particle of 30–40 μm at plane 1.

the wall is hot and the suspension flowing into the cyclone is room-temperature and heated by hot wall. Hence the fine particles move off the wall due to the thermophoresis, too, which may be a reason for the decreased separation efficiency. However, the temperature is the relatively more important factor that affects the particle collection. When the temperature is elevated, the gas becomes viscouser and the swirling flow becomes weaker. A weaker swirling flow generates a smaller centrifugal effect and viscouser gas generates larger viscous forces to carry the particles flowing with the gas. Therefore, the various forces result in the fact that the particles near the wall will be carried to flow with the gas rather than be collected by the wall, whether the particles move to or off the wall.

3.2. Mean velocity

The vertical velocity is important for the particle separation mechanism. Almost all particles and gas flew downward at any position at plane 1. The largest downward velocity was not near the wall of the separator, but at the right-side of the vertex finder. The velocity W at the right wall, i.e., the wall facing the inlet, was much larger than that at the left wall, as shown by Fig. 7(a) and (b).

But the distribution of the velocity W was different at plane 2, where both gas and particles had upward velocity at the center part of the cyclone. The re-circulation flow was due to the change of the pressure distribution. The largest downward velocity W was at the right wall of the separator at plane 2. The velocity W at the left wall was relatively much smaller, as shown by Fig. 8(a) and (b). This implied the right wall gave more contribution for particle collection than the left wall did, especially the front corner at the right wall.

3.3. Turbulent kinetic energy and turbulent intensity

The turbulent kinetic energy of the two phases was defined as

$$K = \frac{1}{2}(\bar{u}'^2 + \bar{v}'^2 + \bar{w}'^2) \quad (1)$$

The local turbulent intensity was defined as the ratio of the mean square root of the fluctuating velocity and the mean velocity at any local position.

$$\mathrm{Tu} = \frac{\sqrt{\frac{1}{3}(\bar{u}'^2 + \bar{v}'^2 + \bar{w}'^2)}}{\sqrt{U_{\mathrm{mean}}{}^2 + V_{\mathrm{mean}}{}^2 + W_{\mathrm{mean}}{}^2}} \quad (2)$$

where $\bar{u}'$ and U_{mean} are the local fluctuating and mean velocity, respectively.

Fig. 9(a)–(f) show the turbulent kinetic energy and turbulent intensity of cases 3 and 4. The turbulent kinetic energy was deduced by the distribution of the fluctuating velocity that the turbulent energy inside the cyclone was larger at the right part than that at the left part. The peak turbulent kinetic energy was found at the front corner facing the inlet side. The motion at the four corners was different from each other mainly due to the the different intensity of the quasi-laminar fluctuating motion there. While You [23] applied the hot-ware anemometer to investigate

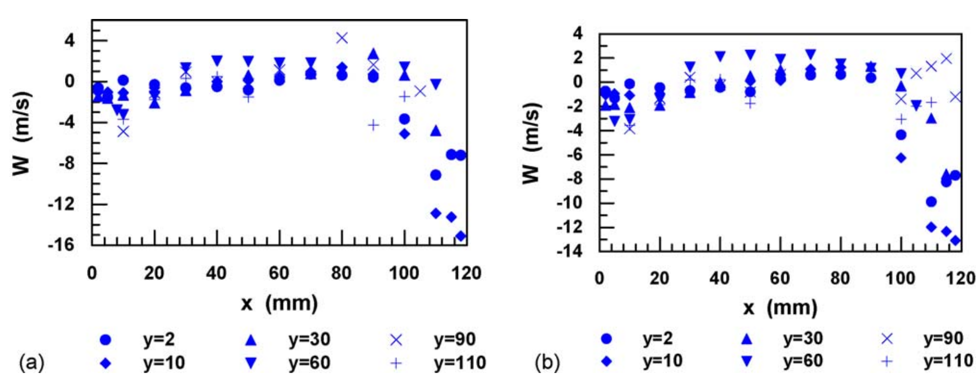

Fig. 8. (a) Distribution of gas velocity W at plane 2–case 3 and (b) distribution of W of particle of 30–40 μm at plane 2–case 3.

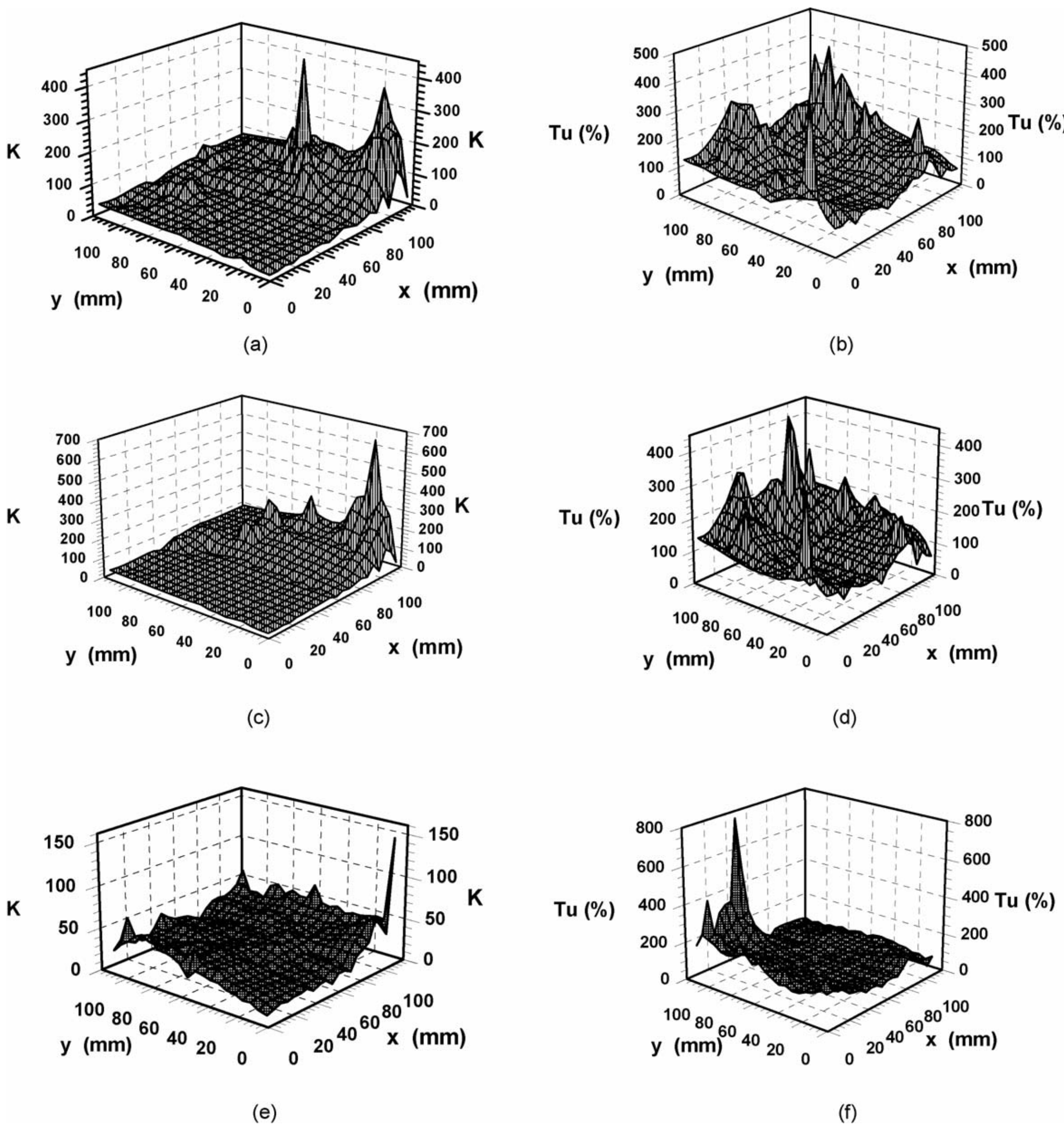

Fig. 9. (a) Gas turbulent kinetic energy distribution for case 3, (b) local gas turbulent intensity distribution for case 3, (c) particle (d = 30–40 μm) turbulent kinetic energy distribution for case 3, (d) local particle (d = 30–40 μm) turbulent intensity distribution for case 3, (e) particle (d = 30–40 μm) turbulent kinetic energy distribution for case 4, (f) local particle (d = 30–40 μm) turbulent intensity distribution for case 4.

the turbulent flow in another type of square cyclone separator with upward exhaust exit [24] and found that the maximum turbulent kinetic energy was at the center in the upper part of the cyclone. He also found the kinetic energy had a larger value at the corners.

The local turbulent intensity also showed peak value at the corners, however the local maximum turbulent intensity was not found at the front corners, but at the rear part. The strong turbulent flow at the corners consumed much of the flow energy and caused pressure drop. Qiu et al. [11] found from their experiment that the overall pressure drop decreased when an arc-like device was installed at the corner to eliminate the local vortex and make the swirling velocity field to approach that in a conventional circular cross-section cyclone. However, the separation efficiency also decreased. Hence, the corner gave contribution for particle seperation mainly due to the strong fluctuating there which comsumed the kinetic energy of both the gas and particle.

4. Conclusion

A Three-dimensional Particle Dynamic Analyzer (3D-PDA) was employed to measure the gas–solid two-phase flow in a lab-scale square cyclone separator with downward gas-exit under several cases. The center of the flow field deviated from the geometric center of the cyclone. The flow fields had a feature of Rankine eddy, i.e., strongly swirling region in the central part and pseudo-free eddy region of weak swirling intensity near the cyclone wall. Local vortex existed at the corners where the flow changed its direction sharply. When the cyclone wall was heated and the suspension temperature was elevated, the flow field became more uniform than that under room-temperature condition. The local vortexes at the corners were weakened and the swirling intensity became poorer which led to decreased total mean separation efficiency from about 81% to 76.5%. The right-side wall facing the suspension inlet gave the major contribution to the separation efficiency, where the largest downward velocity was measured. Back-flow (upward velocity) was found around the center of the separator above the gas-exit. The quasi-laminar motion of particles enhanced the turbulent motion at the corners due to particle–particle/wall collision, which led to the local peak value of the turbulent kinetic energy and turbulent intensity. The corner was one of the major regions to cause pressure drop because the suspension at the corners consumed more energy of the flow. The corners were beneficial to particle separation mainly because the strong fluctuating flow consumed much of the kinetic energy of both the particle and gas. The results of this paper provide a further understand of the separation mechanism and guidance for the optimization of the square cyclone separator structure.

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References

[1] H. Chen, Z. Lin, D. Liu, et al., New type of separator for CFBs with low pressure drop and high efficiency, in: Proceedings of the 10th Int. Conf. on Fluidized Bed Combustion, vol. 1, 1989, pp. 413–417.
[2] D. Liu, H. Chen, Z. Lin, et al., Design of PICFB boilers, in: Proceedings of the 11th Int. Conf. on Fluidized Bed Combustion ASME, vol. 1, 1991, pp. 585–588.
[3] H. Chen, L. Huang, Z. Lin, D. Liu, The separating mechanism of a cyclone separator with downward exhaust gas in a CFB boiler, J. Huazhong Univ. Sci. Tech. 23 (3) (1995) 111–115.
[4] H. Chen, L. Huang, Z. Lin, D. Liu, The pressure drop of a new-type cyclone separator with downward exhaust gas, J. Huazhong Univ. Sci. Tech. 23 (8) (1995) 28–32.
[5] K. Cen, X. Li, Y. Li, et al., Experimental study of a finned tubes impact gas-solid separator for CFB boilers, Chem. Eng. J. 66 (3) (1997) 159–169.
[6] R.J. Gamblt, T. Hyppanen, et al., Pyroflow compact – a second generation CFB boilers by Ahlstrom Pyropower., in: Proceedings of the 12th Int. Conf. On Fluidized Bed Combustion, ASME Press, San Diego, 1993, pp. 751–760.
[7] S.L. Darling, Pyroflow compact: the next generation CFB boiler, in: Proceedings of the 1995 International Joint Power Generation Conference, ASME, vol. 1, NY, USA, 1995, pp. 403–412.
[8] G. Shibagaki, N. Akio, Foster wheeler Circulating Fluidized Bed (CFB) boilers in pulp and paper industries and the recent technology development, Jpn. J. Paper Technol. 42 (5) (1999) 59–64.
[9] P. Makkonen, W. Foster, CFB with the new superheater, VGB Power Tech. 80 (2) (2000) 30–34.
[10] K. Cen, et al. Square-shaped heat exchanging cyclone separator with downward-exhaust. China patent No. 942,232,76.3 (1996).
[11] K. Qiu, J. Yan, X. Li, et al., Experimental study and structure optimization of a uniflow square-shaped cyclone separator, J. Eng. Thermal Energy Power 14 (3) (1999), 193, 194, 199.
[12] L.X. Zhou, S.L. Su, Gas solid flow and collection of solids in a cyclone separtor, Powder Technol. 63 (1990) 45–53.
[13] S. De, P.K. Nag, Pressure drop and collection efficiency of cyclone and impact separators in a CFB, Int. J. Energy Res. 23 (1999) 51–60.
[14] M.-S. Shin, H.-S. Kim, D.-S. Jang, J.-D. Chung, M. Bohnet, A numerical and experimental study on a high efficiency cyclone dust separator for high temperature and pressurized environments, Appl. Thermal Eng. 25 (11/12) (2005) 1821–1835.
[15] S.-Y. Liu, Y. Zhang, B.-G. Wang, Cyclone separator three-dimensional turbulent flow-field simulation using the Reynolds stress model, Trans. Beijing Instit. Technol. 25 (5) (2005), 377–379, 383.
[16] L.Y. Hu, L.X. Zhou, J. Zhang, M.X. Shi, Studies on strongly swirling flows in the full space of a volute cyclone separator, AIChE J. 51 (3) (2005) 740–749.
[17] R. Zhang, P. Basu, Simple model for prediction of solid collection efficiency of a gas-solid separator, Powder Technol. 147 (1–3) (2004) 86–93.
[18] B.T. Zhao, A theoretical approach to pressure drop across cyclone separators, Chem. Eng. Technol. 27 (10) (2004) 1105–1108.
[19] D. Liu, Two-Phase Flow Dynamics, Higher Education Press, Beijing, 1993.
[20] S. Liang, 1997. Gas-solid separation mechanism at high temperature and it's experimental study. Ph.D. Thesis, Zhejiang University, China.
[21] R. Parker, R. Jain, S. Calvert, D. Drehmel, J. Abbott, Particle collection in cyclone at high temperature and high pressure, Environ. Sci. Technol. 15 (4) (1981) 451–458.
[22] P.A. Patterson, R.J. Munz, Cyclone collection efficiency at very high temperature, The Canadian J. Chem. Eng. 67 (1989) 321–328.
[23] C. You, 1996. The experimental investigation and numerical simulation of the turbulence flow in the square shaped separator. Ph.D. Thesis, Beijing, Tsinghua University, China.
[24] G. Yue, X. Zhang, Y. Li, et al. Water cooled square-shaped cyclone separator with an accelerating inlet. China Patent No. 93,235,842.X (1995).