

Article

Experimental Investigation on Turbulent Flow Deviation in a Gas-Particle Corner-Injected Flow

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Abstract: An experimental model of a corner-injected flow is built to investigate the turbulent flow behavior by employing the PIV technique. The influences of the ideal tangential circle, the additive particles and the initial gas mass flux on the corner-injected flow are analyzed systematically. To be specific, the flow deviation, the velocity profile, the vortex evolution and the turbulent flow development are discussed quantitatively. The influences of the increasing ideal tangential circle on the turbulent jet deviation are shortened gradually, and the impinging circles are obviously narrowed with the injection of particles. The gas-particle corner-injected flow can obtain a good rotation when the ideal tangential circle is 0.25 times the width of the impinging chamber. The momentum decay of the corner-injected flow diminishes with the increasing ideal tangential circle and the decreasing initial gas velocity. The rotation strength of the vortex is more affected by the injection of laden particles, while the angular distortion enhances when increasing the ideal tangential circle. The increasing initial gas mass flux plays a dominant role in the development of the corner-injected flow, secondly the increasing ideal tangential circle, and last the injection of particles. All these findings can provide theoretical support in the design of a corner-fired furnace.

Keywords: corner-injected flow; PIV technique; turbulent flow deviation; gas-particle interactions



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1. Introduction

Tangentially fired boilers are widely applied in coal-fired power plants in Asian countries, and the corner-injected flow is the fundamental configuration in tangentially fired boilers [1]. The four adjacent jets create an intensive rotation flow in the whole chamber, resulting in an increase in the momentum and energy transfer between coal and gas [2].

For decades, many studies have been conducted on the tangentially fired furnace to investigate the flow behaviors, combustion efficiency and pollutant emissions [3–8]. The RANS-like simulations have been widely employed to simulate the pulverized-coal combustion process in these industrial-scale furnaces because of the affordable calculation capability. For example, Tian et al. [3] investigated the influence of the vertical burner tilt angle on the flow field and coal combustion in a tangentially fired pulverized coal boiler. Chen et al. [4] conducted numerical calculations on a utility boiler under different tangential arrangements of burners to find the best performance. Zhou et al. [5] studied the effects of a multi-group arrangement of separated over-fire air on pulverized coal combustion in a 1000 MW tangentially fired boiler. Obviously, the dispersed pulverized coal particles can achieve better combustion with an appropriate rotation flow in the furnace. However, there exists no standard design for the ideal tangential circle for the tangentially fired furnace [1–8]. The inner mechanism between gas and pulverized coal particles in mesoscale is vague, which is important for the dispersion and combustion of coal particles in the furnace.

Limited to the complex measurement conditions, it is hard to measure the flow field in the combustion furnace. Some experts tried to establish the laboratory-scale cold model scaled to the industrial furnace and employed multi-sets of hot wire anemometers to measure the velocity distribution [9–13]. For example, Zhou et al. [9] applied a set of hot wire anemometers to measure the flow velocity in the cold model furnace, which was scaled 1:25 by the tangentially coal-fired boiler. Liu et al. [10] measured the velocity parameters at fixed seventy positions in a cold scaled-down tangentially fired furnace. He et al. [11,12] established a cold model of a coal-fired furnace and invented a hot wire probe with six sensors to measure the vorticity in such a turbulent flow. Moreover, the velocity and vorticity distribution were compared with the simulation results of such a large-scale utility furnace [13]. However, the hot wire anemometer can only measure the gas velocity of a fixed position and the flow field would be greatly affected by multi-sets of hot wire probes.

To avoid disturbing the flow field, advanced optical velocimetry, such as particle image velocimetry (PIV), has been developed rapidly these years [14–21]. Li et al. [14] employed the PIV technique to study the turbulence modification in axisymmetrically opposed jets flow at a high Reynolds number. Mizeraczyk et al. [15] measured the flow field in an electrostatic precipitator by using the PIV technique. Lindken and Merzkirch [16] developed a novel PIV technique to investigate the velocity profiles in a two-phase flow. Capone et al. [17] applied the PIV technique to study the interactions between gas and rod-like particles in a turbulent pipe flow. Lau and Nathan [18] investigated the velocity profiles influenced by the Stokes number in a gas-particle jet by employing the PIV technique. Hence, it is realizable to employ the PIV technique to observe the turbulent rotation flow behaviors caused by the corner-injected flow.

The corner-injected flow is the fundamental configuration of tangentially fired furnace. The coal combustion is greatly influenced by the flow field and particle dispersion in the turbulent rotation flow caused by corner-injected jets. Hence, an experimental system of corner-injected flow is established to investigate the turbulent flow behaviors by employing the PIV technique in this study. The influences of ideal circle diameter and initial gas velocity on the turbulent flow profiles are analyzed. To be specific, the velocity distribution, the vortex evolution and the turbulent flow development are systematically discussed.

2. Experimental Details

2.1. Experimental Setup

Figure 1a shows the PIV experimental system of a gas-particle corner-injected flow and Figure 1b is the sketch map of a captured cross section of such a corner-injected flow. The horizontal cross section of the impinging chamber is 200 mm in both width and depth, and the height of the chamber is 1000 mm. The gas and particles are injected into the chamber from four round tubes installed at four corners of the impinging chamber. The long round tube is with the inside diameter $D_{in} = 10$ mm and the length $L = 1000$ mm, which ensure that this turbulent two-phase flow could develop fully. The particles are fed into the gas by a self-designed fluidized bed in every branch, and its mass flux is controlled by the flow valve and flow meter installed in the bypass. The tracer particles for gas are generated by the aerosol generator, and its diameter is about $0.5\ \mu\text{m}$.

The PIV measurement system consists of a high-resolution camera, a double-pulse laser, a synchronizer and an image collector. The particles dispersed in one horizontal cross section are illuminated by the double-pulse laser sheet from the optical window, and the interval of the double pulse lasers is $100\ \mu\text{s}$. A total of 100 pairs images are captured in one measurement routine. The main experimental setup parameters are shown in Table 1.

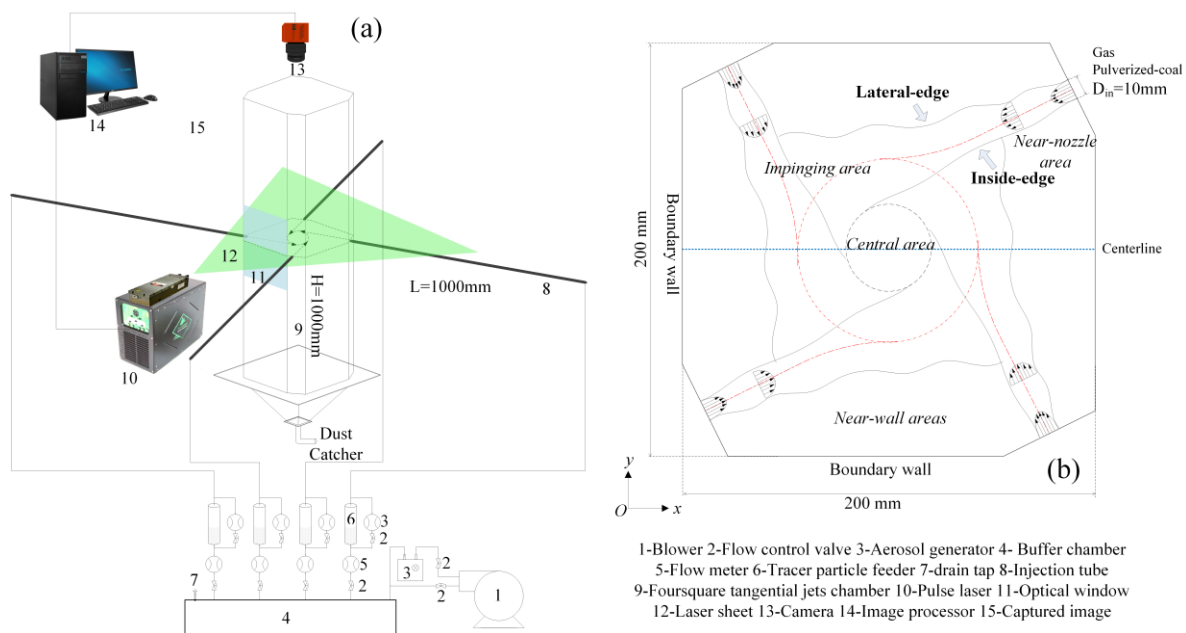


Figure 1. (a) Schematic diagram of the experimental setup and (b) sketch map of the captured horizontal cross section of corner-injected flow.

Table 1. The experimental setup parameters.

Apparatus	Parameters	Typical Value
Impinging chamber	Height (mm)	1000
	Width (mm)	200
	Depth (mm)	200
Injection tubes	Injected diameter (mm)	10
	Length (mm)	1000
Gas parameters	Gas temperature ($^{\circ}\text{C}$)	15
	Gas pressure (MPa)	0.1
	Gas density (kg/m^3)	1.22
Aerosol generator	Gas tracer diameter (μm)	0.5
Quantel EverGreen pulse	Time interval of Pulse 1 and 2 (μs)	100
	Laser lasting time (nsec)	5
	Light sheet thickness (mm)	0.5
	Wavelength (nm)	532
ILA CMOS Camera	Resolution (pixel)	2560×2160
	Frame rate (Hz)	4
	Prime lens (mm)	50
	Aperture (f)	1.8
ILA Synchronizer	-	-
Image collector	Image number	100

2.2. Measurement Duties

The cross section of the gas-particle corner-injected flow is shown in Figure 1b. The ideal tangential circle (D_i) is formed by four axle wires of four nozzle inlets, and the diameter of the actual tangential circle (D_a) can be estimated as the distance of maximum velocities of the chamber central axis. The inner circle (D_{inner}) has tangency to four inside edges, while the outer circle (D_{outer}) has tangency to four lateral edges. The aim of this study is to investigate the influences of the ideal tangential circle and initial velocity on gas-particle flow behaviors emphasized in this study. Hence, three different ideal tangential circles ($D_i = 16, 37$ and 53 mm) for gas flow and four different tangential circles ($D_i = 16, 37,$

53 and 74 mm) for gas-particle flow are set to figure out the turbulent flow characteristics affected by ideal tangential circles. Three different gas mass fluxes ($Q_0 = 2, 3$ and $4 \text{ m}^3/\text{h}$) for gas-phase flow are set to investigate the influences of gas mass flux on the turbulent flow deviation. Table 2 lists the measurement duties. The injected particles are made of SiO_2 , and they are measured by the laser particle size analyzer LS-200. Figure 2 shows the measured particle diameter distribution. The mean particle diameter is $19 \text{ }\mu\text{m}$ and the density is 2200 kg/m^3 .

Table 2. The measurement duties.

Case	D_i (mm)	Q_0 (m^3/h)	U_0 (m/s)	d_p (μm)	Tracer
I-1	16	3	8.7	-	Oil mist
I-2	37	3	8.7	-	Oil mist
I-3	53	3	8.7	-	Oil mist
II-1	16	3	8.7	19	99.9% SiO_2
II-2	37	3	8.7	19	99.9% SiO_2
II-3	53	3	8.7	19	99.9% SiO_2
II-4	74	3	8.7	19	99.9% SiO_2
III-1	37	2	5.8	-	Oil mist
III-2	37	3	8.7	-	Oil mist
III-3	37	4	11.6	-	Oil mist

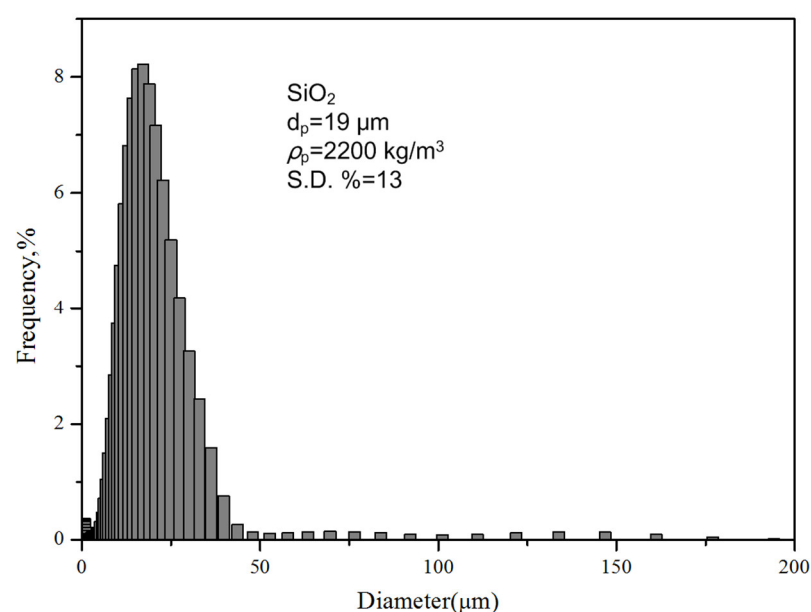


Figure 2. The measured particle size distribution and main material parameters.

2.3. Image Processing

The oil mist is used to represent the gas phase, and the laden particles can be measured directly. The grey processing is applied on the captured raw images so as to remove the influences of laser sheet dissipation [22]. Each pair of captured raw images is processed to calculate the instantaneous velocity profiles by employing a cross-correlation method. The maximum effective measurement is about a square with $200 \times 200 \text{ mm}^2$, and the camera resolution is 2560×2160 pixels. Hence, the spatial resolution is $78.125 \text{ }\mu\text{m}/\text{pixel}$ in the x direction and $92.592 \text{ }\mu\text{m}/\text{pixel}$ in the y direction. The interrogation area covers 32×32 pixel in both x and y directions, and the measured spatial resolution is 2.5 mm and 3 mm in the x and y directions, respectively. Hence, a total of 5214 (79×66) vectors are calculated in one frame. The mean flow properties are computed from 500 pairs of images in one computer routine.

2.4. Uncertainty Analysis and Statistical Feasibility Analysis

The measurement uncertainty of this experimental system is resulted from the systematic error and the random error. The random error is inevitable and unimportant, and it could be resulted from the experimental setup, particle size distribution, mass flux deviation, particle shape, background noise, etc. Li et al. [14] tried to estimate the random error in a PIV measurement on opposed round jets and recognized that the random error is much lesser than the systematic error. The systematic error is primarily generated by the cross-correlation interrogation algorithm in the area with large velocity gradient [23,24]. In our previous study, the systematic error in this corner-injected flow was estimated as 2.9% in the x direction and 5% in the y direction [21]. The Kolmogorov length (η_κ) and the integral length (Λ) are applied to check whether spatial resolution (X) is applicable in this experiment. The Kolmogorov length scale and the integral length scale are applied to estimate the smallest vortex and the coherent vortex, respectively. The Kolmogorov length scale can be calculated by the fluid viscosity (ν) and the dissipation rate (ϵ), written as $\eta_\kappa \cong \left(\frac{\nu^3}{\epsilon}\right)^{1/4}$, and the integral length (Λ) is evaluated by the turbulence kinetic energy (κ) and the dissipation rate (ϵ), following as $\Lambda \cong \left(\frac{3\kappa}{2\epsilon}\right)^{3/2}$. The dissipation rate is calculated based on a dynamic equilibrium assumption, employing the sub-grid scale (SGS) concept [25]. The turbulent dissipation rate is estimated as $\epsilon = \epsilon_{SGS} = -2\tau_{SGS}S_{ij}$, where the solved strain rate tensor $S_{ij} = \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)$, and the SGS stress tensor $\tau_{SGS} = -C_s^2\Delta^2\sqrt{2S_{ij}S_{ij}}S_{ij}$. The Smagorinsky constant $C_s = 0.17$ and the grid size Δ is equal to the spatial resolution $X = 2.5$ mm. The Kolmogorov length scale (η_κ) and the integral length (Λ) are compared with the spatial resolution (X) in Figure 3. Obviously, the spatial resolution (X) is much greater than the Kolmogorov length scale (η_κ) and smaller than the integral length scale (Λ) in most impingement area. It means that the present filter scale is applicable, smaller than the coherent vortex scale and larger than the smallest vortex scale. Hence, the applied PIV apparatus is appropriate to observe the turbulent gas-particle flow behavior in such a corner-injected flow.

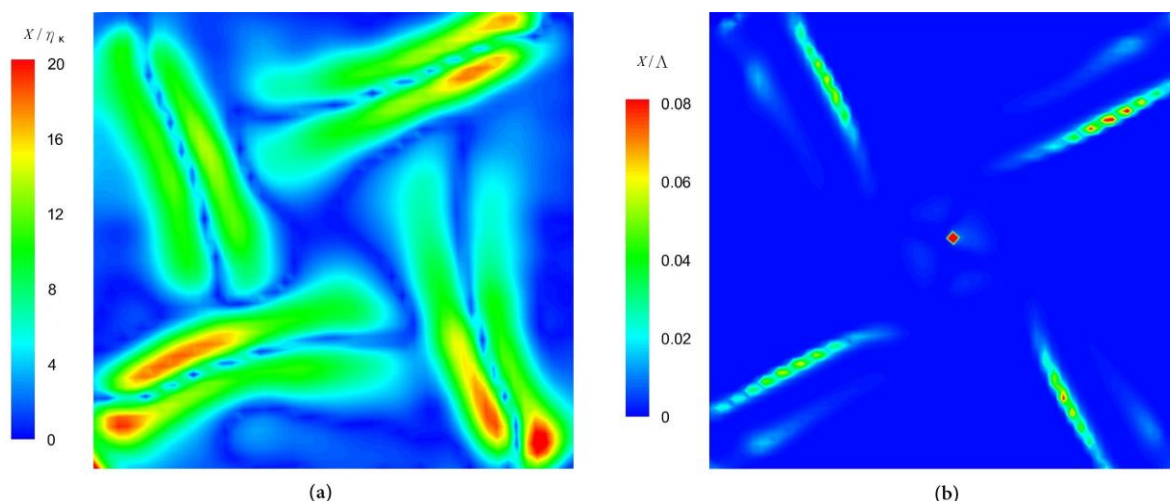


Figure 3. The ratio of PIV spatial resolution (X) to (a) Kolmogorov length scale (η_κ) and (b) the integral length (Λ).

3. Results and Discussions

3.1. Corner-Injected Flow Characteristics

The velocity vectors of gas and particles for three different ideal tangential diameters ($D_i = 16, 37$ and 53 mm) are compared in Figure 4. A rotation flow is formed by four adjacent jets as expected. We have to point out that the differences among the inlet velocity are mainly caused by the experimental system. In this experiment, the oil mist is used for the gas tracer, and it is generated by an aerosol generator. The gas mass flux is adjusted by the flow control valve, and its accuracy is influenced by the oil mist. On the other hand, the

total path length for four routes is different, which could cause the inlet velocity differences at the four nozzles exits. For each case, the maximum velocity occurs at the nozzle exits and decreases sharply when encountering the adjacent flow. For the same ideal tangential circle, the actual tangential circle for the particles (bottom) is obviously smaller than that formed by the gas flow (top). The particle velocity is greater for gas velocity at the nozzle exit area. All of this means that the rigidity for turbulent jet augments greatly with the injection of dispersed particles. There is no doubt that the actual tangential circle grows with the increasing ideal tangential circle, whatever the gas-phase flow and gas-particles two-phase flow. The appropriate tangential circle is of great significance for the operation of the industrial pulverized coal-fired boilers because the big circle will lead to serious coal slagging in the water walls and the small circle will result in uneven coal distribution in the chamber. In this experimental study, the turbulent flow deviation becomes unstable with the growing tangential circle. The turbulent gas-particle flow is unsteady at the small ideal tangential circle because of the great impingement in the chamber center. To sum up, the gas-particle corner-injected flow can acquire good rotation flow at about $0.25 D$ ($D_i = 53 \text{ mm}$), while the gas-phase flow is about $0.18 D$ ($D_i = 37 \text{ mm}$).

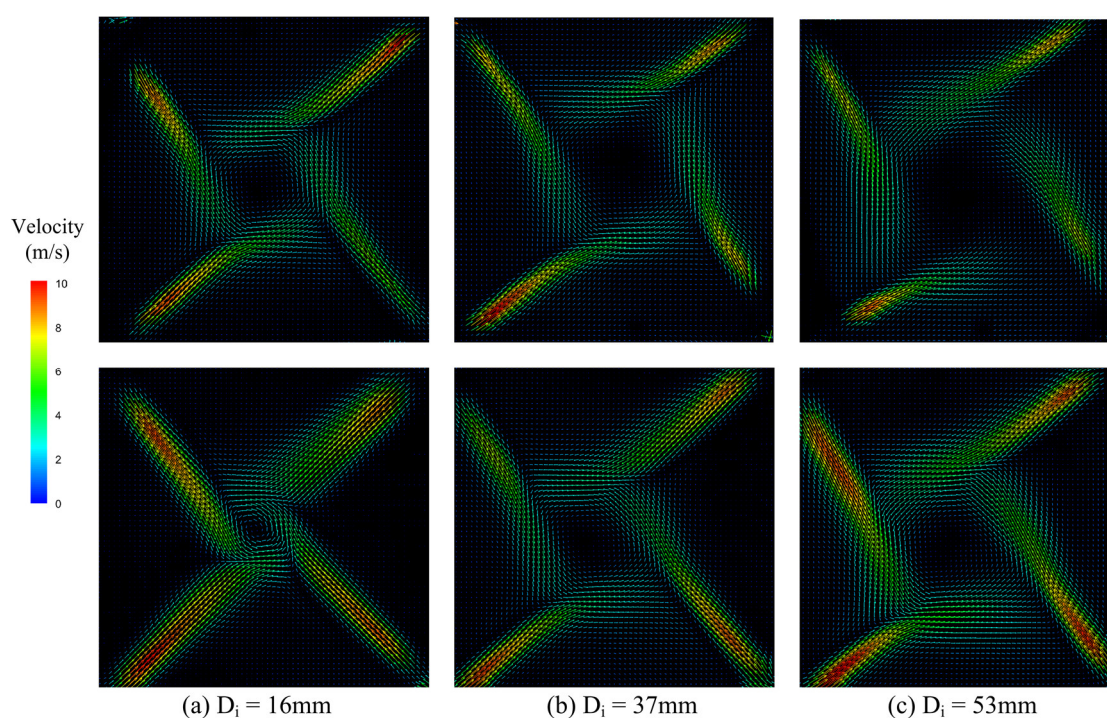


Figure 4. The velocity vector for gas (**top**) and particles (**bottom**) on cross-section under three different ideal tangential diameters.

To analyze the flow characteristics quantitatively, the velocity ratios of the measured velocity to the initial velocity for all cases are compared along the centerline in Figure 5. The velocities for both gas and particles increase from the wall boundaries and reach a peak at the impinging area, and then decrease sharply to the bottom at the chamber center. The maximum velocity value grows with the increasing ideal tangential circle, which means the decay of momentum is diminishing because of the moderate impinging. On the other hand, the distance between the two peaks (D_a) extends gradually with the growing ideal tangential circle. The effects of the ideal tangential circle on the actual tangential circle are weakening in the large ideal tangential circle. At a given ideal tangential circle ($D_i = 37 \text{ mm}$), the velocity ratio increases obviously with the increasing initial gas mass flux, even though the heavier impinging is resulted from the great initial gas velocity. There exists an interesting observation that the distance between two peaks is little influenced by the initial gas velocity.

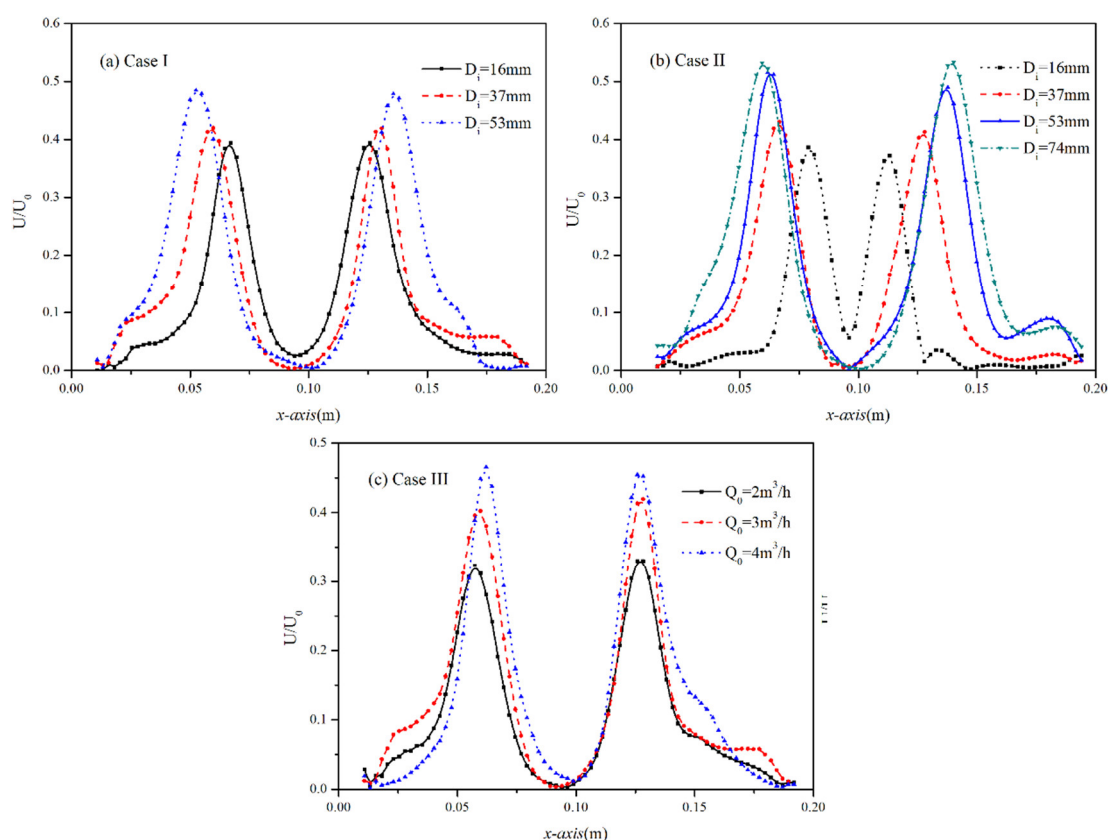


Figure 5. The velocity ratio (U/U_0) along the centerline under three cases.

As mentioned above, the distance between two peaks of the velocity ratio is seen as the diameter of the actual tangential circle (D_a). Similarly, the distance between two points when the velocity ratio is equal to 0.2 near the wall boundaries is regarded as the diameter of the outer circle (D_{outer}), while that between two points near chamber center is seen as the diameter of inner circle (D_{inner}). The diameters of the impinging circles formed by corner-injected flow are compared under different ideal tangential circles. At the same ideal tangential circle, the impinging circle formed by the gas-phase corner-injected flow is bigger than that formed by the gas-particle flow. It means the rigidity of the turbulent enhances with the additive particles. The influences of the increasing ideal tangential circle on the turbulent flow deviation of corner-injected flow are weakened gradually. Compared with Figure 6, the gas-particle corner-injected flow can obtain a better rotation flow in the chamber when the actual tangential circle is about 1.5 times the ideal tangential.

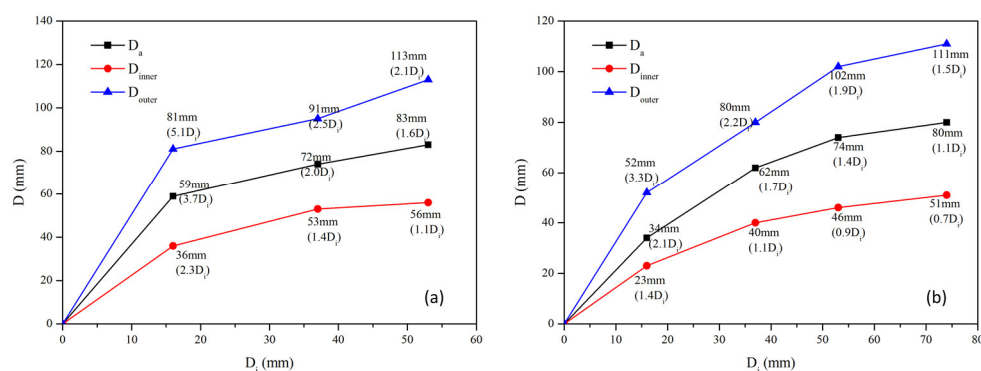


Figure 6. The diameters of the impinging circles formed under different ideal tangential circles for (a) gas-phase corner-injected flow and (b) gas-particle two-phase corner-injected flow.

3.2. Vortex Evolution Characteristics

For the viscous fluid, the vortex evolution can be divided as rotation, linear deformation and angular distortion. The velocity gradient in the z direction is ignored in the present 2D PIV measurement. Hence, only the vorticity in z direction, the linear deformation in the x and y directions and the angle in the xy plane are considered in this study. The expression of vorticity is defined as $\omega_z = \frac{1}{2} \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right)$, while the angular distortion in the xy plane is defined as $\epsilon_z = \frac{1}{2} \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right)$. The linear deformation in the x and y directions is the velocity gradient, which can be calculated as $\epsilon_{xx} = \frac{\partial u}{\partial x}$ and $\epsilon_{yy} = \frac{\partial v}{\partial y}$, respectively. The rotation and angular distortion are emphasized in this part.

Figure 7 shows the comparison of vorticity distribution along the centerline at different corner-injected flows. When $\omega_z = 0$, the vortex at that point has no rotation. In this study, the vortex presents clockwise rotation when $\omega_z < 0$ from the planform view, while it presents anticlockwise rotation when $\omega_z > 0$. The vortex shows clockwise rotation near the wall boundaries and presents anticlockwise rotation in the chamber center area. For the gas-phase flow, the rotational strength is little influenced by the ideal tangential circle at a given initial gas velocity. However, the vorticity shows greater value in the circle center when the ideal tangential circle is decreasing. At a given ideal tangential circle, the vorticity value increases obviously with the rising initial gas mass flux. Comparing Figure 7a,b, the vorticity is greatly increased by the laden particles. The rotational strength enhances slightly with the shortening ideal tangential circle. For $D_i = 16$ mm at the gas-particle corner-injected flow, the vortex in the circle center presents, obviously, anticlockwise rotation. On the other hand, it is found that the anticlockwise rotational strength is a little larger than the clockwise rotation, resulting in anticlockwise rotation in the whole chamber.

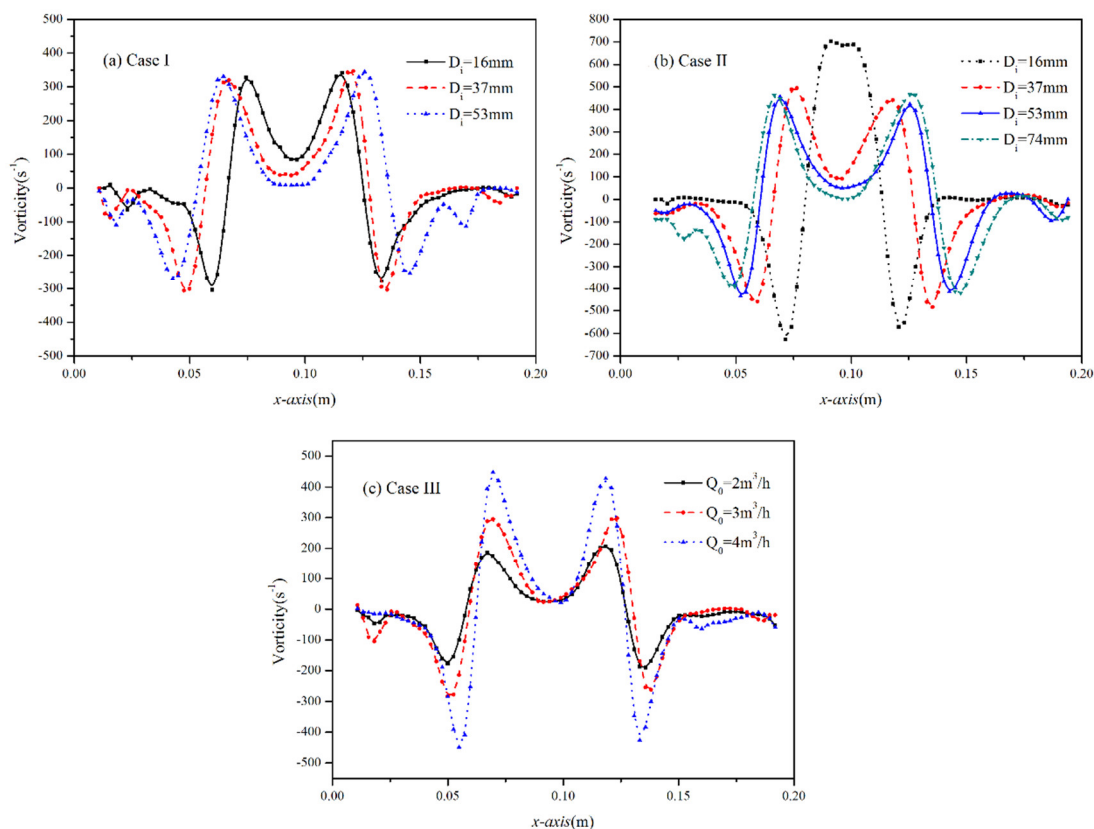


Figure 7. The gas vorticity distribution (ω_z) along the centerline under three cases.

As mentioned above, the angular distortion in the xy plane is described as the shear force of the viscous fluid. The shear force distributions along the centerline are compared

in Figure 8 to investigate the influences of the ideal tangential circle, laden particles and initial gas mass flux on the angular distortion of vortex evolution. When $\epsilon_z = 0$, the vortex at that point has no angular distortion. The vortex shows forward distortion when $\epsilon_z < 0$ from the front view, while it displays reverse distortion when $\epsilon_z > 0$. The vortex distortion is dependent on the friction between layers. The angular distortion of the vortex presents forward distortion near the left and right walls, and it shows reverse distortion in the chamber center. The angular distortion strength attenuates with the growing ideal tangential circle at a given initial gas mass flux. The vortex angular distortion is little affected by the additive particles, which is in contrast to the vortex rotation. The angular distortion is augmented obviously when increasing the initial gas mass flux, which is consistent with the vortex rotation discussed above. Similarly, the forward distortion plays a dominant role along the centerline in the x direction, because the anticlockwise rotation flow shows a forward distortion in x from the front view.

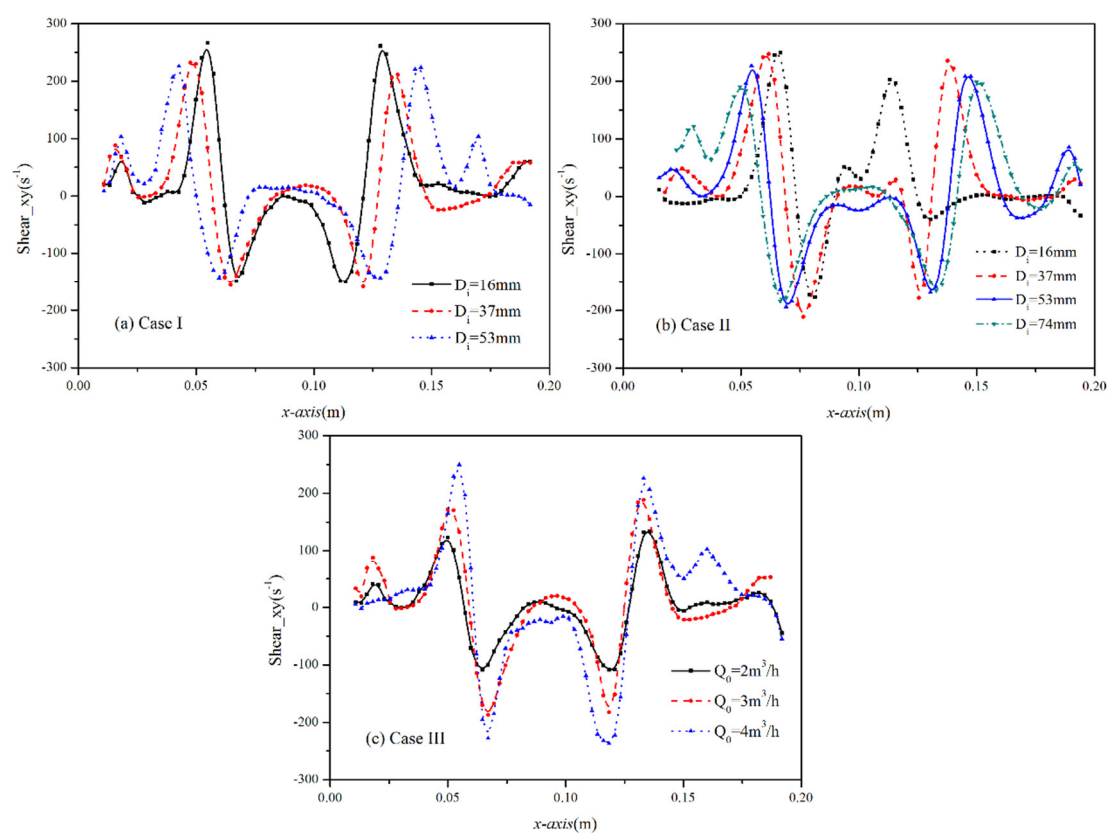


Figure 8. The shear_{xy} force distribution (ϵ_z) along the centerline under three cases.

3.3. Turbulent Flow Development

The turbulent kinetic energy is always applied to show the development of turbulent flow, which can be evaluated as $\kappa = \frac{3}{2}(\overline{U} \cdot I)^2$. In this 2D PIV measurement, the time-averaged velocity is calculated as $\overline{U} = \sqrt{u^2 + v^2}$, and the turbulence intensity is evaluated as an empirical expression $I = 0.16Re^{-1/8} \propto \overline{U}^{-1/8}$ [26]. Hence, the turbulent kinetic energy is greatly influenced by the measured velocity. The corner-injected flow shows full development in the impinging areas along the actual tangential circle. The turbulent kinetic energy increases slightly with the increasing ideal tangential circle at a given gas initial velocity, while it soars obviously when increasing the initial gas velocity. Comparing Figure 9a,b, it is found that the turbulent flow can acquire more full development in the impinging chamber due to the injection of particles.

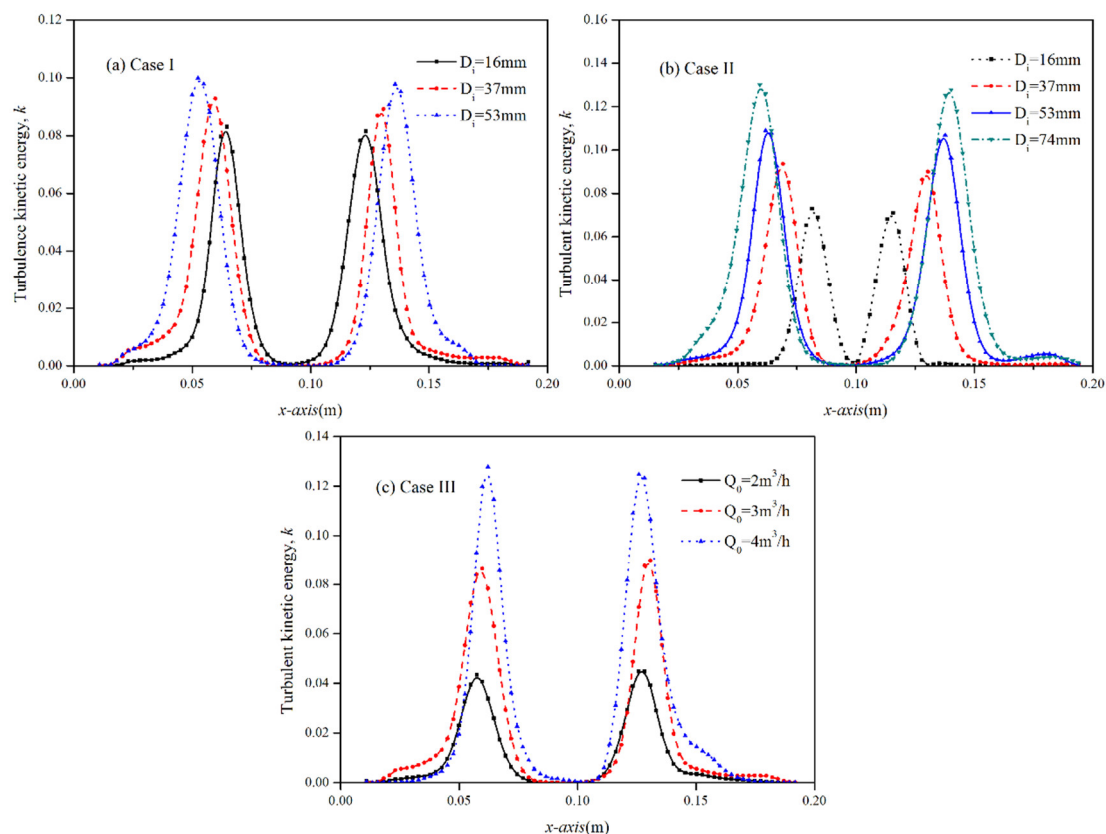


Figure 9. The turbulent kinetic energy (κ) along the centerline under three cases.

4. Conclusions

A PIV experimental system is established to investigate the influences of the ideal tangential circle, additive particles and initial gas mass flux on the turbulent flow characteristics of such a corner-injected flow. To be specific, the flow deviation, the velocity profile, the vortex evolution and the turbulent flow development are analyzed quantitatively. The main findings are summarized as follows:

- (1) The influences of the increasing ideal tangential circle on the turbulent jet deviation are shortened gradually, and the impinging rotation flow is obviously narrowed with the injection of the laden particles. The gas-particle corner-injected flow can obtain good rotation when the ideal tangential circle is 0.25 times the width of the impinging chamber.
- (2) The momentum decay of the corner-injected flow diminishes with the increasing ideal tangential circle and the decreasing initial gas velocity. The actual tangential circle is little affected by the initial gas velocity at an appropriate range.
- (3) The rotation strength of vortex is more affected by the injection of laden particles than the ideal tangential circle. On the contrary, the angular distortion of vortex attenuates gradually with the growing ideal tangential circle, but is little affected by the additive particles. Both the rotation and distortion increase when increasing the initial gas velocity.
- (4) The increasing initial gas mass flux plays a dominant role in the development of the corner-injected flow, secondly the increasing ideal tangential circle, and last the injection of particles.

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Nomenclature

C_s	Smagorinsky constant, dimensionless
d_p	The diameter of particle, μm
D	The width and depth of impinging chamber, mm
D_a	The diameter of actual tangential circle, mm
D_i	The diameter of ideal tangential circle, mm
D_{in}	The inside diameter of round tubes, mm
D_{inner}	The diameter of inner circle tangency to four inside-edges, mm
D_{outer}	The diameter of outer circle tangency to four lateral-edges, mm
I	The turbulence intensity, dimensionless
L	The length of four tubes, mm
PIV	Particle Image Velocimetry
Q_0	The initial mass flux for gas, m^3/h
Re	Reynolds number, dimensionless
S_{ij}	The strain rate tensor, dimensionless
u	The measured instantaneous velocity in x direction, m/s
U_0	The initial gas velocity, m/s
$\bar{U}$	The time-averaged gas velocity, m/s
x, y, z	Three dimensions, dimensionless
v	The measured instantaneous velocity in y direction, m/s
w	The measured instantaneous velocity in z direction, m/s
Greek letters	
X	Spatial resolution of velocity vectors, mm
ε	Turbulence dissipation rate, m^2/s^3
ϵ_{xx}	The linear deformation of vortex in x direction, 1/s
ϵ_{yy}	The linear deformation of vortex in y direction, 1/s
ϵ_z	The angular distortion of vortex in xy plane, 1/s
η_k	Kolmogorov length scale, m
κ	Turbulence kinetic energy, dimensionless
Λ	Integral length scale, m
μ	Dynamic viscosity of the gas, $\text{Ps}\cdot\text{s}$
ν	Gas kinematic viscosity, m/s
ω_z	The vorticity in z direction, 1/s
ρ_p	Particle density, kg/m^3
ρ_g	Gas density, kg/m^3
τ_{SGS}	Stress tensor, dimensionless
Subscripts	
g	Gas
p	Particle
SGS	Sub-grid scale
i, j	x, y directions

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