



Study on flow field characteristics in a reverse rotation cyclone with PIV

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ABSTRACT

This study adopted particle image velocimetry (PIV) to understand flow-field movements in the conventional cyclone and reverse-rotation cyclone (RC). Tracer particles were prepared by preparing a 5-wt% sugar solution at normal temperature and pressure for velocity measurement, cloud and distribution velocity maps were generated at various flow rates using three cross-sections. Compared with conventional cyclone, the PIV testing results indicate that the tangential and radial velocities of RC increased at higher flow rates and decreased at lower heights, suggesting adequate radially symmetric distributions despite variations in heights and flow rates. The radial velocity exhibited adequate diagonally symmetric distribution, implying that the indicating excellent symmetry and regularity in the velocity distribution of the flow-field images of the separator, a sign of stable flow fields in the separator. Finally, the comparison showed a similar distribution and variation patterns, which was collected through PIV testing and computational fluid dynamics (CFD) simulation.

1. Introduction

A cyclone facilitates multiphase separation through the differences in particle density and size. Cyclones can be structurally classified as tubular, axial-flow, square, and cylindrical centrifugal separators [1,2]. They can be used as gas separation equipment for purifying smoke, dust, and fog. Differences in the inlet structure, cylinder length, cylinder diameter, and inlet-section angle of a cylindrical separator can directly affect its separation capacity [3–5].

By installing centrifugal volute inlets in traditional cyclone, Liu et al. presented particles with varying sizes and density using the effect of the centrifugal force by rearranging particles at the inlet [6–8]. This method reduces the effects of short circuit flow and increases the separation accuracy and efficiency of the cyclone. Yang et al. preferred the use of cylindrical particle sorters and installed them on cyclone [9–11]. Depending on the methods used to incorporate a particle sorter into a cyclone, a cyclone can be classified as conventional, positive-rotation, and reverse-rotation [12]. Reverse-rotation cyclone is a simple and feasible way to arrange fine particles in a quick material system that used the rotation centrifugal force field [13], which can obtain multi-products and achieve orderly sorting of different sized particles at the outlet. Simulation results have indicated that reverse-rotation separators have a more adequate separation capacity and more stable flow fields than do conventional and positive-rotation cyclone [14]. Fu et al. conducted experiments to study the effects of various heights of particle sorters on the separation capacity of a cyclone [15,16]. They

revealed that a centrifugal cyclone separator exhibits optimum separation efficiency when the cylindrical section height of its sorter is five times the height of the square inlet [17–19].

To examine the flow velocity in experiment, multiple technologies, such as dye tracking, velocity transducers, and laser measurement [20–22], were developed. In the past few decades, laser measurement technologies have experienced substantial development and have been incorporated with multiple new technologies to develop particle image velocimetry (PIV), an interference-resistant method that is used for accurate fluid velocity measurement. Liu et al. showed the instantaneous whole-field tangential, axial, and radial velocities were measured simultaneously in the cyclone with gas inlet velocity of 7.2–15.2 m/s examined by Stereoscopic PIV [23]. Liu et al. contributed the axial velocity distribution in a gas cyclone examined with 2D-PIV and 3D-PIV and reported that 2D-PIV data agree well with 3D-PIV results [24].

The aforementioned studies have examined the flow fields of various cyclone separators only through simulations and did not consider the actual velocities in experiment [25,26]. Thus, PIV was used to test the cyclone separator and obtained actual data on high-speed rotating flow fields. Images of particle flow velocity fields were generated by computations and thereby perform further analysis.

2. Experiment

According to two consecutive photos were acquired by the laser

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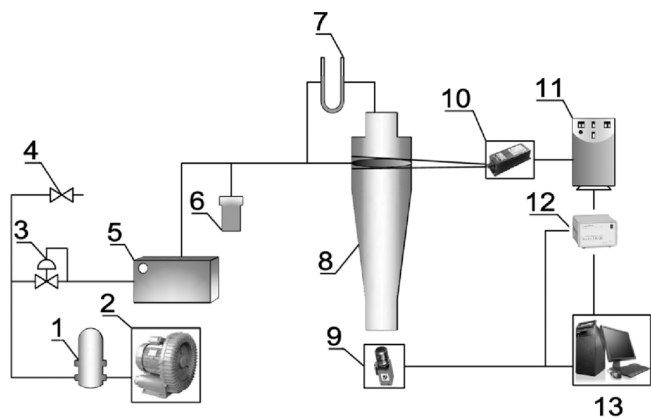


Fig. 1. Flow diagrams of the PIV measurement experiment.

1 Air filter, 2 Wind turbine, 3 Control valve, 4 Bypass valve, 5 Atomizer, 6 Pitot tube, 7 U-tube, 8 cyclone separator, 9 CCD camera, 10 Laser pulse generator, 11 Laser controller, 12 Synchronizer, 13 Computer.

light illuminate, which were exposed during a very short period of time in plane area, velocity of particles could be calculated by a particle appeared in t_1 and t_2 . Transient velocity of particles equation was employed:

$$u = \lim_{t_1 \rightarrow t_2} \frac{X_2 - X_1}{t_2 - t_1} = \lim_{\Delta t \rightarrow 0} \frac{\Delta X}{\Delta t} \quad (1)$$

$$v = \lim_{t_1 \rightarrow t_2} \frac{Y_2 - Y_1}{t_2 - t_1} = \lim_{\Delta t \rightarrow 0} \frac{\Delta Y}{\Delta t} \quad (2)$$

Where u is known as the speed of x axis direction, v is known as the speed of y axis direction. According to the above equations, velocity of whole flow field can be acquired after the batch processing of point by point.

The experimental setup is illustrated in Fig. 1 after entering the air filter. Air flows were sent to the atomizer by the wind turbine. The bypass and control valves were adjusted to control the air flow. Atomized sugar particles were used as tracer particles and passed into the cyclone with the inflowing air. The differential manometer and pitot tube were employed to measure the total pressure and pressure drop in the tubes. The laser generator was used to project monochromatic light onto the measuring plane of the cyclone at a vertical angle. After the tracer particles were recorded by the charge-coupled device (CCD) camera, the data were inputted into a computer. The laser-pulse interval was established in advance using the synchronizer. Computer would coordinate control the laser generator and image capture with the synchronizer. The device name was shown in Table 1.

2.1. Geometrical structure of the cyclone

A reverse-rotation cyclone was used for the PIV testing experiment. Fig. 2(b) illustrates the structural design of the RC, and Table 2 lists its dimensions. This cyclone was optimized on the basis of conventional cyclone in Fig. 2(a). A particle configurator with a height of $5a$ was installed at the air inlet of the separator to sort particles according to

Table 1
PIV system parameters.

Equipment	Model number	Manufacturer
Air filter	AH	Suzhou Gaozhao Purify Science and Technology Co., Ltd.
Atomizer	ICP-MS	KRLAB
CCD camera	Nikon 630062	TSL
Laser pulse generator	Nd:YAG laser	Beamtech
Time synchronizer	LaserPulse	TSL
Computer	Dell	Dell

their sizes. The positions of the reverse-rotation cyclone are indicated in the top view in Fig. 2(c) to ensure adequate stability and separation efficiency.

2.2. Experiment materials

Air flow was set to the continuous phase. A 5-wt% dissolved sugar solution was prepared at normal temperature and pressure and converted into sugar particles with a particle diameter of $0.8 \mu\text{m}$ using a BX-03B atomizer. The sugar particles were treated as the dispersed phase. Sugar solution was determined through measurements to have a density of $1.58 \times 10^3 \text{ kg/m}^3$ and a refractive index of 1.54, and density could be changed by the number of the atomizer. The sugar particles were used as tracer particles to represent flow-field movements because they exhibit adequate scattering properties and high resolution, and they satisfy the measurement requirements. Fig. 3 presents the employed atomizer and the atomization process.

2.3. PIV testing system

PIV testing was implemented using a system manufactured by TSI Incorporated, a United States-based precision measurement instrument company. This system consists of a Nd:YAG double pulse laser generator (Beamtech) with 10 Hz and the time between the two pulses is from 1 μs to 0.1s, a time synchronizer (used for synchronizing all components), a Nikon 630062 CCD camera with a resolution of 4000×2700 , a. An image acquisition and analysis system (TSI Incorporated) was used to analyze flow-field movements, track tracer particles, which guaranteed the error of the testing system to $\leq 1\%$, which obtained by TSI company. Post-processing system of the particle images was composed of INSIGHT 3G and calculated data from particle image of camera with Hart arithmetic, and a velocity vector was obtained by the minimum concerning area of 4×4 pixels. Quartz glass with a thickness of 2 mm was installed at the overflow outlet to ensure air on both sides of the pipe walls, which guarantee the process of the measurement is almost not affected by refraction optical distortion.

The cylindrical and conic sections of the reverse-rotation cyclone were selected as the areas of interest. A rectangular coordinate system was established by setting the centroid of the overflow outlet as origin, the direction of the internal rotational flow as the z axis, the direction horizontal to the air inlet as the x axis, and the direction perpendicular to the air inlet as the y axis. Fig. 2(b) illustrates the five cross-sections (i.e., $z = 0, -50, -150, -250$ and -350 mm) that were selected as the featured cross-sections.

2.4. CFD simulation

A discrete phase model was employed to simulate the movements of the particles that were sorted by the configurator in the reverse-rotation cyclone separator. For the steady fluid flow in the cyclone, the following RSM model is employed that were computed by commercial software FLUENT 15.0. DPM (Discrete Phase Model) model was chosen to simulate the disperse phase. Number of grids were 854500 with hexahedron, SIMPLE scheme was selected as solution methods, and the value of grids vary from 0.1 to 0.4 were occupied 99.23% of the total count. Thus CFD grids fine enough. With air supplied in a continuous phase, an inlet air concentration and density of 2 mg/L and 893 kg/m^3 , respectively, and particle sizes of $0.3 \mu\text{m}$, $0.5 \mu\text{m}$, $1 \mu\text{m}$, $1.5 \mu\text{m}$, $3 \mu\text{m}$, $5 \mu\text{m}$, $10 \mu\text{m}$, $15 \mu\text{m}$, $20 \mu\text{m}$, $25 \mu\text{m}$, the trajectory and speed of single or multiple particles in the flow field were examined. The flow of the medium was mainly affected by turbulent flows and gravity. The effects of the interparticle, Magnus, Basset, and Saffman forces were excluded from this study. Fig. 4 presents a grid diagram of the RC.

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