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Analysis of Auxiliary Device in a Gas-solid Cyclone by Experimental and Computational Approaches

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Abstract

An auxiliary device, called Post Cyclone (PoC), had been introduced and primarily examined in earlier works which proved the reduction of the emission of fine dust from the gas-solid cyclones without incurring significant increase of cost and pressure drop. It has been known that the PoC has some advantages over other secondary dust treatment devices such as (a) simple design, (b) low cost of manufacture, (c) minimum additional pressure drop, (d) high recoverbility of the product dust, and (e) simplicity of operation. Despite the potential advantage, however, lack of practical data confined its plausible application in wide areas. Thus, in this work, a few serial experiments were conducted in terms of a few operation conditions, and the particle trajectories throughout the cyclone set-up were visually analyzed by using a commercial computer simulation program (FLUENT).

Key words : Gas solid cyclone, Particle separation, PoC (Post Cyclone), Computer simulation

1. INTRODUCTION

Cyclone separator is one of the most widely used devices to separate and recover the industrial dusts from air or process gas streams. Due to low manufacturing and maintenance costs, simple operation, and flexibility, cyclone separator has been favorably utilized in various industrial operations including powder processing. A variety of researches to improve the performance are here still undergoing (Dirgo and Leith, 1985). However, low collection efficiency for the fine parti-cles smaller than 10 μm has been indicated as a disad-vantage, specifically when stringent regulation on air discharge of particulates essentially calls for invisible stack emission. Since its inception over a century ago, in order to qualify for frequent application in practice many researchers have contributed to the large volume of work on improving the efficiency of cyclone by introducing new design and operation variables (Jiao and Yamamoto, 1993; Molerus and Gluckler, 1989; Mothes and Loffler, 1985; Koch and Licht, 1977). An auxiliary device, named Post Cyclone (PoC), has been intro-duced and tested in association with control of the fine particle emission (Jo *et al.*, 2000; Ray *et al.*, 1997).

In a simple design, the PoC is fixed on the gas outlet vortex finder and utilizes the residual swirl energy of the gas as it exits from the mother cyclone. According to fluid mechanical calculation, about 80% of the max-

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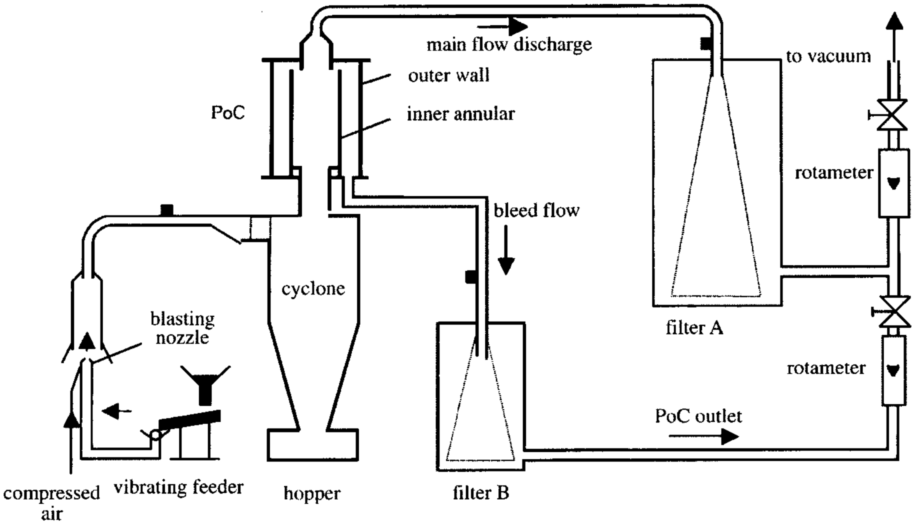


Fig. 1. Schematic diagram of experimental set-up.

imum swirl occurring in the separation zone of the cyclone remains at the vortex finder of the cyclone (Ray *et al.*, 1997). Although being weakened due to the slight expansion, feature of the swirl remains nearly same in the PoC. In a conventional reverse-flow cyclone, a centrifugal force introduced by a tangential inlet forces the solids to migrate to the wall, and the particles loose the inertial forces and finally settled at the bottom of the cyclone. Whilst, in the PoC, as like a uniflow cyclone, gas and solids exit in the same direction from vortex finder. As flowing through the double cylindrical columns, main gas stream flows along the central core and a more dense stream exits through the gap of two columns. Thus, the residence time within the PoC is only relatively short, and the force to expel the particles toward the potential zone of separation near the inner wall becomes very weak due to less vortex power. Therefore, a variety of theoretical and experimental studies can maximize its performance.

Jo (1999) attempted to evaluate the separation performance of the PoC by applying Leith and Licht model (1972) which defined the radial velocity of particles within the vortex regime to this auxiliary device. Furthermore, in this work, more detailed particulate behavior in the PoC was studied through a commercial fluid dynamics simulation program (FLUENT).

2. APPARATUS AND METHOD

2. 1 Experimental apparatus

Fig. 1 illustrates the overall diagram of experimental set-up. As closely described in a previous paper, the PoC is composed of two stainless columns, and vertically placed on the voltex finder of the main cyclone (Jo, 1999). Cyclone was prepared with 15 cm of body according to Staimand standard. The flow of Dust laiden air with possessing swirl effect enters the PoC through the vortex finder.

A split flow, so called bleed flow, enters the annular space in 2.5 cm width between inner annular and outer wall. The bleed flow was adjusted with 20% out of main flow, flowing into an outlet hole in the bottom of annular space (ϕ2 cm), and discharged to air after cleaned by high efficiency fabric filter.

Test dust was $Ca(OH)_2$ of which specific gravity was 1.5 with a mass mean diameter 17 μm. Sample dust was dried at 110°C for at least 2 hours in a vacuum

Table 1. Boundary conditions of CFD for PoC.

Boundary conditions	Value
inlet velocity	7.1~21.4 m/s
outlet-1	78% of total flux
outlet-2 (bleed flow)	22% of total flux

oven. It was then premixed with 2% by weight of a silica type dispersant (Aerosil 200) before fed to the cyclone through a vibratory dust feeder. It prevented unwanted agglomeration during aeration.

2. 2 Experimental method

Compressed dry air was supplied to the inlet pipe through a blasting nozzle. The fluid flow across the system was maintained by a vortex blower (Samjin, HS-060-E). Inlet flow velocity varied at 6~21 m/s, and feed dust concentration was 3.5~6.5 g/m^3. Size of the particles was measured by on-line connection of Malvern Mastersizer (Malvenr Inst., Master sizer-S). Separated solids in each position: hopper, discharge (filter A) and PoC (filter B) were collected and weighed in order to evaluate the separation efficiency.

Simulation work by FLUENT (V.60, Fluent Co.) enabled to understand the flow pattern and particle trajectories in the cyclone and PoC according to inlet velocity and particle size. In operation of FLUENT, wall function was applied to the lower hopper, RNG k-ε model was chosen for analysis of turbulent flow, which is the most suitable to the vortex field amongst turbulent models provided in FLUENT (FLUENT 1996). Momentum was evaluated by Quick method, simultaneous analysis of pressure-velocity was made by Simplec. Turbulence kinetic energy and turbulence dissipation rate were calculated with 2nd order upwind differential method. Three dimensional body fitted the grid was used, and the flow was assumed as a steady turbulent flow. More detailed specification including boundary condition is summarized in Table 1. The residence time of the fluid was evaluated from the inlet to the vortex finder by tracking of the massless particles. Limitaton was achieved by 320 iterations in the present work.

3. RESULTS AND DISCUSSION

In order to comprehend the characteristics of the main cyclone, several tests as a function of flow rate and dust loading were carried out without the PoC. Under the various operation conditions, the PoC performance was then evaluated focusing on the overall efficiency by using following equations. The overall efficiency of the process is the combination of the removal performance of the cyclone and PoC, which is expressed by:

$$\eta_{overall} = \frac{m_h + m_p}{m_h + m_f + m_p} \quad (1)$$

Absolute mass efficiency of the PoC is defined as the ratio of dust collected in the PoC to the dust charged to the PoC, and shown below as:

$$\eta_{PoC} = \frac{m_p}{m_f + m_p} \quad (2)$$

3. 1 Effect of operation condition

3. 1. 1 Inlet velocity

Fig. 2 indicates the dependency of the inlet flow velocity on the measured overall collection efficiency. As increasing the inlet velocity, dust collection by the main cyclone increased, but gradually decreased in the

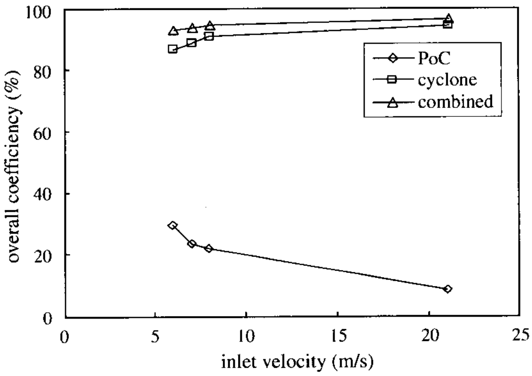


Fig. 2. Overall efficiency of cyclone and PoC with inlet velocity.

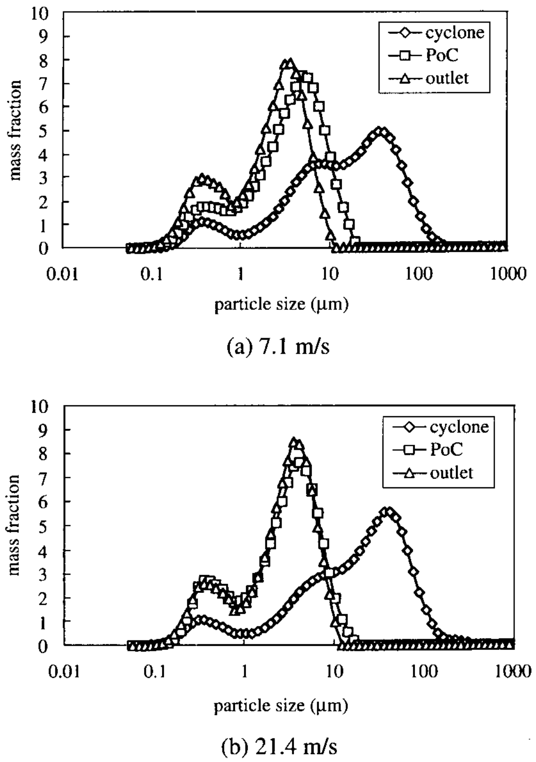


Fig. 3. Particle size distribution at each point.

PoC. In general, the inlet velocity of dust laden gas flow greatly affects the efficiency of a tangential inlet gas-solid cyclone. High velocity leads to a great vortex within the cyclone, ultimately increasing the tangential velocity, which would rise in the momentum force of solid particles toward the inner wall of the device. Rapid radial migration of the particles facilitates to loose its potential centrifugal force. Particles drop down by gravity force and are accumulated in the lower hopper.

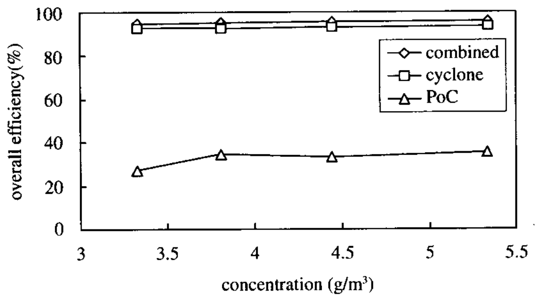
Such a kinetic theory of the cyclone has been known since long time ago, and it also was visually confirmed through the computer simulation (Venkata *et al.*, 1998). Decrease of the collection efficiency of the PoC at a high velocity inlet may be caused by the great mass collection in the main cyclone. More particles are separated in the lower cyclone, fewer particles may go up to the PoC. It diminishes the absolute separation by the PoC. Differing from the previous work (Jo, 1999) which tested mainly with fine mode dust (mostly less than 10 μm), since the present experiment has tested with more or less larger particles (D_v, 0.1 : 5.4 μm), the efficiency of the main cyclone can be maximized greater than 90%. As a consequence, relative contribution of the PoC to the overall collection will be reduced, in addition to the drop of its individual collection effect.

As increasing the inlet velocity, the size of the particles collected in the PoC became small as shown in Fig. 3. In the regime of great vortex under the high velocity, coarser particles are affected by frequent rebounce against the PoC inner wall. In subsequence, such relatively larger particles reentrained into the main flow and left the cyclone separator. At the same time, as can be seen in Fig. 3 (b), the particles between the final outlet and PoC showed the almost same size. It means that such a fine mode of particles is less affected by inertia force, and seldom separated by particle size or specific gravity. In addition, smaller particles are apt to be concentrated near the center of the vortex finder whereas the bigger particles were injected near the wall (Jo *et al.*, 2000). Thus, it just can provide the separation efficiency as much as the fraction of the bleed flow.

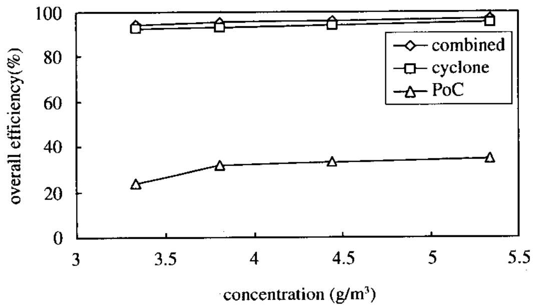
At any rate it was found that the PoC even in part contributes to the rise of separation effect of entire cyclone system with 2~8%. The PoC is more effective at low inlet velocity.

3. 1. 2 Dust concentration

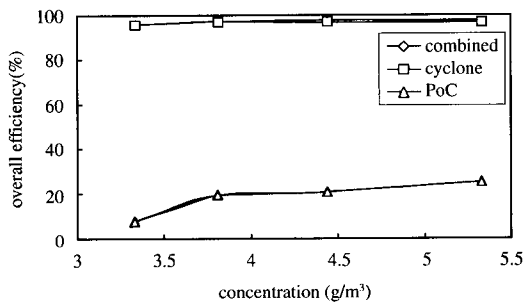
Fig. 4 shows the result of the effect of dust loading in the inlet gas on the overall collection efficiency including the PoC. As increasing the concentration of feeding dust, individual efficiencies of the cyclone and PoC were coincidently increased. It is well known that an increase of the dust concentration lowers pressure drop. The increase of the PoC efficiency is probably attributed to a large quantity of uncaptured dust by the lower cyclone. The particle concentration remains still high in the PoC even at greater collection of the main



(a) Ui : 7.1 m/s



(b) 8.6 m/s



(c) 21.4 m/s

Fig. 4. Overall efficiency of cyclone and PoC with concentration.

cyclone. Although an earlier work reported that the increasing particle concentration caused to the decrease of the centrifugal forces in the vortex flow (Yun *et al.*, 1978), many experimental works resulted in a steady increase of separation efficiency (Berezowski and Warmuzinski, 1993; Mothes and Loffler, 1985). More

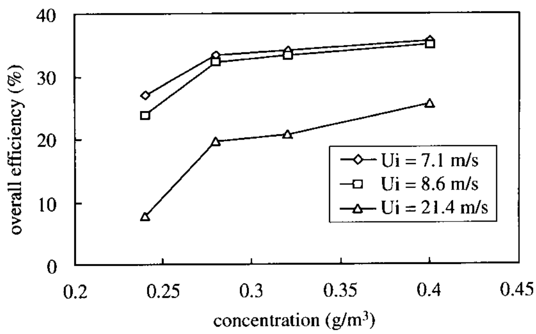


Fig. 5. Overall efficiency of PoC with feed concentration.

particles in the same gas volume may cause various potential interactions between the particles themselves or between particles and the wall. In particular, increasing particle concentration provides more frequent collisions, which can result in agglomeration of particles. In addition, in a highly concentrated dust stream, the large particles towards inner wall of the PoC tends to entrain other fine particles, and on top of that the impaction between small and large particles leads to a change in size distribution of the entering dust. It could also be inferred and was really observed that the aggregated particles could contact the inner annular of the PoC, sliding down the inner wall and finally accumulating on the bottom edge inside of the PoC.

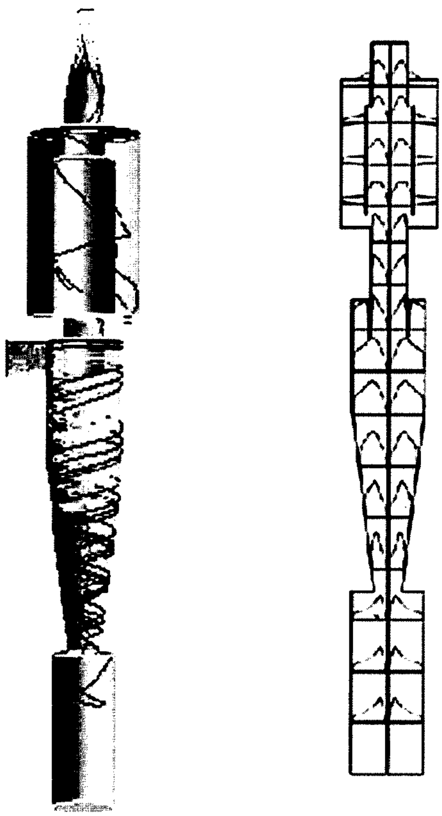
Fig. 5 clearly indicates the direct effect of concentration of the dust flowing into the PoC. In general, upward flow to the PoC maintains extremely diluted phase comparing to the feed flow. At a low velocity, the absolute amount of entering dust into the PoC became relatively increased, resulting in a high collection, but the increasing velocity lowered the PoC collection. Consequently the validity of the PoC depends completely on a given condition of the site of industry.

3. 2 Computational simulation

The use of CFD in modeling the flow pattern in cyclones has been found satisfactory in earlier studies (Ramana, 1999; Ray & Hoffman, 1977). This work attempted to trace the traveling path of particles with a few sizes at different flow velocities. The interaction between flow and particles were neglected.

3. 2. 1 Observation of flow pattern

Loci of the flow across the cyclone and PoC are displayed in Fig. 6. Mesh was structured on the basis of that the main cyclone and PoC were connected with one single system. Fluid was conditioned with pure air at ambient room temperature. When the feed velocity was set to 21 m/s, the maximum gas tangential velocity in this PoC was approximately 27 m/s, which is about 70% of the maximum swirl velocity of 38 m/s occurring in the separation zone of the cyclone. The visual simulation work reveals a typical flow motion appeared in the cyclone and the exit of a certain amount of the flow through the PoC discharging hole. The gas stream flowed up for about one and half rotations inside the PoC, which was similar to the experimental result by using a red tracer (snowcal 40, Blue Circle Industry). A set of the PoC for a visual observation was prepared with transparent acrylic columns, and the rotation number of the flow was counted with naked eye. It was about 1.7, apparently implying apparent residual vortex.



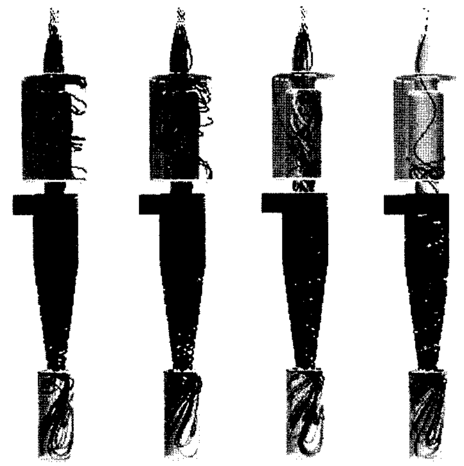
(a) (b)

Fig. 6. Flow pathline and tangential velocity profile across the cyclone and PoC.

3. 2. 2 Particle trajectories

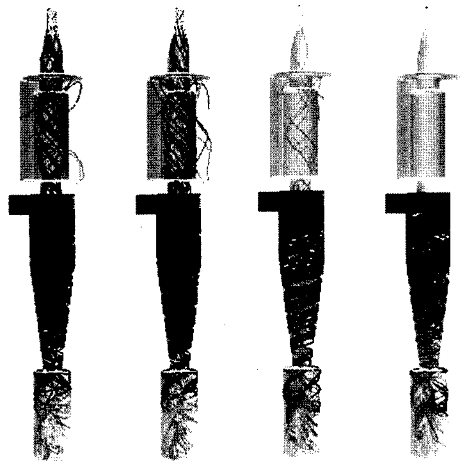
As a function of particle size and inlet velocity, the locus of particulate flow was traced by fluid dynamic simulation. Finding the individual particle trajectories help to discover the separation mechanism of the present combined design. Fig. 7 shows that the particles are spiraling up along the vortex finder inner wall and enter the PoC with certain amount of centrifugal force. Each particle of 1 μm, 2 μm, 5 μm and 10 μm in diameter was randomly injected into the flow field from the arbitrary positions at the inlet of the main cyclone. As expected, the larger particles (5 μm and 10 μm) rapidly collided the side wall, and were collected in lower hopper at a given velocity. Whilst, the small particles (1 μm and 2 μm) escaped through the vortex and entered the PoC as closely following the streamline swirls. However, it also depends greatly on the inlet velocity. For instance, a low velocity led a great amount of dust to head for the PoC without being separated by the main cyclone. The fine particles, as previously stated, would not be separated in the centrifugal field due to lack of individual mass and of chance to form agglomerates while traveling along the cyclone and PoC.

Most particles, 10 μm in diameter, were found to be collected in the mother cyclone as commonly expected, and those would hardly flow out through the annular space within the PoC at all velocities. At a high velocity, 21 m/s, a large proportion of the 2 μm particles was collected in the lower cyclone due to turbulent agglomeration resulting from their high inertia(Mothes and Friedrich, 1985), and part of the unseparated ones exited without capturing by the PoC. As a consequence from the visual simulation, it could be found that the



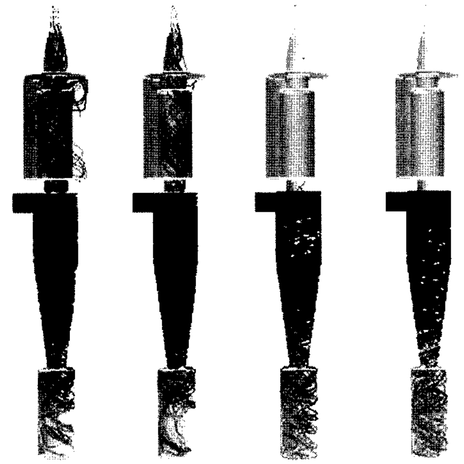
(a) 1 μm (b) 2 μm (c) 5 μm (d) 10 μm

(Ui : 7.1 m/s)



(e) 1 μm (f) 2 μm (g) 5 μm (h) 10 μm

(Ui : 14 m/s)



(i) 1 μm (j) 2 μm (k) 5 μm (l) 10 μm

(Ui : 21.4 m/s)

Fig. 7. Particle trajectories for different particle sizes and inlet velocities (inlet velocity = 7 m/s (a-d), 14 m/s (e-h), 21 m/s (i-l)).

PoC could be obviously effective in separation of fine mode of dust.

4. CONCLUSIONS

The present study has been carried out in order to observe the effectiveness of the PoC which had been designed to improve the fine dust collection in the conventional cyclone system. Installation of the PoC enhanced the overall dust collection up to 7~8%, particularly large particles which were reentrained by bounce effect in the mother cyclone. The separation both by the main cyclone and the PoC improved appreciably with increasing solids concentration. The computer simulation by using CFD enabled to understand the particle trajectories and the separation mechanism. It was found from the examination of different inlet dust concentration and feed velocity that there must be an optimum operation condition. Consequently low inlet velocity makes better performance of the PoC, however it critically depends on the practical situation. Further work to predict the radial position of entering particles to the PoC across the vortex finder will be carried out with CFD modeling, and applied to the residence time model which was discussed in the previous paper (Jo *et al.*, 2000). It will approach to more practical prediction of separation efficiency.

ACKNOWLEDGEMENT

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NOMENCLATURE

m_f: mass of dust collected in discharge filter [kg]
m_h: mass of dust collected in hopper [kg]
m_p: mass of dust collected in PoC filter [kg]
η: efficiency of dust separation

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