

## Original Paper

# Reutilization of regenerated exhaust gas from the centrifugation-filtration coupled purification system: a closed-loop process

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## ABSTRACT

The regenerated exhaust gas was reutilized to configure a centrifugation–filtration coupled purification system (CFCPS), aiming to achieve a closed-loop gas purification process. It can be foreseen that this optimization will bring objective economic savings without sacrificing separation efficiency. A series of typical tests were carried out to analyze the influence of the reutilized exhaust gas on the pressure drop and the separation efficiency. Compared with the purification system without the reutilized exhaust gas, the purifier exhibited optimal performance at  $Q = 800 \text{ m}^3/\text{h}$ ,  $RV = 25\%$ , and  $C_i = 30.24 \text{ g/m}^3$ . Notably, the median size of outlet particles decreased from  $1.67 \mu\text{m}$  to  $0.82\text{--}1.04 \mu\text{m}$  and the size range was narrowed when the exhaust gas was recycled. Moreover, the grade efficiency of the dust particles below  $3 \mu\text{m}$  was improved significantly with reutilization. The study indicates that the exhaust gas reutilization is an effective means to solve particle pollution, and further measurements are needed.

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## 1. Introduction

Fluid catalytic cracking (FCC) serves as the main process for heavy oil (high molecular weight and viscosity) conversion in refineries. In the refining process, metal impurities present in the feedstock accumulate on the catalysts due to thermal coking and catalytic coking, which leads to the deactivation of the catalysts and the emission of particulate matter (such as dust particles) (Gambino et al., 2020). When regenerating used catalysts to burn off coke, these metallic contaminants are also transferred into the exhaust gas, ultimately being released into the atmosphere as particulate pollutants (de la Campa et al., 2011). Produced in regenerators operating at  $650\text{--}750 \text{ }^\circ\text{C}$ , this gas stream typically contains  $12\text{--}15 \text{ vol}\% \text{ CO}_2$ ,  $0.5\text{--}2 \text{ vol}\% \text{ CO}$ ,  $200\text{--}1000 \text{ ppm SO}_x$  (dependent on feedstock sulfur content), and  $<300 \text{ ppm NO}_x$ , alongside entrained catalyst fines ( $50\text{--}200 \text{ mg/Nm}^3$ , primarily  $<40 \mu\text{m}$  particles). Normally, cyclones stand as prevalent solutions for capturing particles in the FCC regenerators. The working

principle of the cyclone is centrifugal separation formed by a highly swirling flow (Hoffmann and Stein, 2007). Even though the most advanced inertial gas cleaning systems can capture over 90% of dust particles larger than  $5 \mu\text{m}$ , its performance diminishes notably when confronted with fine-dispersed particles below  $2.5 \mu\text{m}$  (which constitute up to 90% of the total particle amount). Thus, only coarse catalysts can be effectively collected by the cyclone separator. Liu et al. (2012) conducted experimental investigations on a novel “1 + 2” dual-stage cyclone separator, demonstrating. Noh et al. (2018) experimentally integrated multiple auxiliary cyclone units into a tangential inlet separator configuration, which resulted in a significant reduction (over 50%) of fine dust emissions through enhanced particle capture efficiency. Accomplishing the purification requirements is a critical concern for the FCC industry, particularly from a sustainability perspective.

Owing to the low separation efficiency, the mass concentration of dust at the regenerator outlet typically surpasses  $150 \text{ mg/m}^3$  and the proportion of the particulate matter below  $5 \mu\text{m}$  is still as high as 75% (Amoatey et al., 2019). As a result, several improved methods have been developed to manage fine dust emissions, such as electro-acoustic ultrasonic nebulization, heterogeneous condensation, electrostatic precipitators, etc. (Zhang et al., 2023). According to the principle of dust removal, it can remove some

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particles below 2.5 μm by introducing additional forces. The influence factors on the separation efficiency also increase, such as the residence time, electric field intensity, processing capacity, and so on (Bao et al., 2011). Nevertheless, these technologies require further enhancements, particularly in reducing energy consumption.

After thoroughly evaluating the limitations of the FCC cyclone and recognizing the significant need for improvement, the centrifugation-filtration coupled purification system (CFCPS) is proposed (Lu et al., 2020). The principle of particulate matter removal by this system involves a complex process of centrifugal force and particle filtration, as illustrated in Fig. 1. The cyclone shell was designed on the basis of the PV cyclone, and the built-in granular bed was a coaxial sleeve and the thickness of the inter-layer was 50 mm filled with the collector particles. Both the inner and outer walls were made of stainless Johnson screen. Firstly, most large dust particles (>10 μm) are removed from the main downward airflow and strike the outer cyclone wall as a result of centrifugal force. Fine dusts smaller than 10 μm are then retained in the inner granular bed (Chang et al., 2022a). Thus, the cleaned gas was obtained in the outlet duct. The filter media in the built-in granular bed moved downward from the feeder hopper located at the top of the bed to the riser. In the riser, the collector granules as well as the captured fine dust particles were carried into the spouted bed regenerator. The regenerated filter medium reentered the CFCPS for the next round of dust collection. By combining inertial impaction, interception, gravitation, electrostatic attraction, and Brownian diffusion in the granular bed filter

(Pendse et al., 2010), dust particles could be captured in CFCPS efficiently. It is expected to break through the bottleneck of efficient gas–solid separation and eliminate the high-temperature scaling phenomenon of catalytic cracking flue gas turbines.

In a moving bed, a stable or near-stable condition is anticipated when the quantity of dust particles entering the bed matches the amount leaving the bed along with the granules at the filter's base (Colver et al., 2002). The energy consumption and separation performance of the cyclone shell remain almost unchanged under fixed-bed operating conditions. In contrast, the pressure loss of the granular bed increases initially and then reaches a relatively stable or quasi-steady state. From the perspective of the CFCPS, the system pressure drop is mainly influenced by the moving bed filter. To this end, the dust particulates deposited in the bed should be continuously carried out, and the bed filter must be supplemented with sufficient clean particles as the bed particle levels decrease.

To maintain the continuous operation of the CFCPS, the riser-spouted regeneration section is utilized for the collector particles regeneration illustrated in Fig. 1. The filter media, along with the captured dust particles, are transported to the spouted bed via the riser. Because of the variations in material properties, the entrainment velocity of the collector particles is significantly greater than that of the fine dust particles. Consequently, the delivery gas velocity in the riser is set between these two velocities, allowing the mixtures to be efficiently separated in the spouted bed. The regenerated bed filter particles reenter the feeder hopper, while the fine dust particles are discharged into the atmosphere with the exhaust gas (Chang et al., 2024). However, fine dust

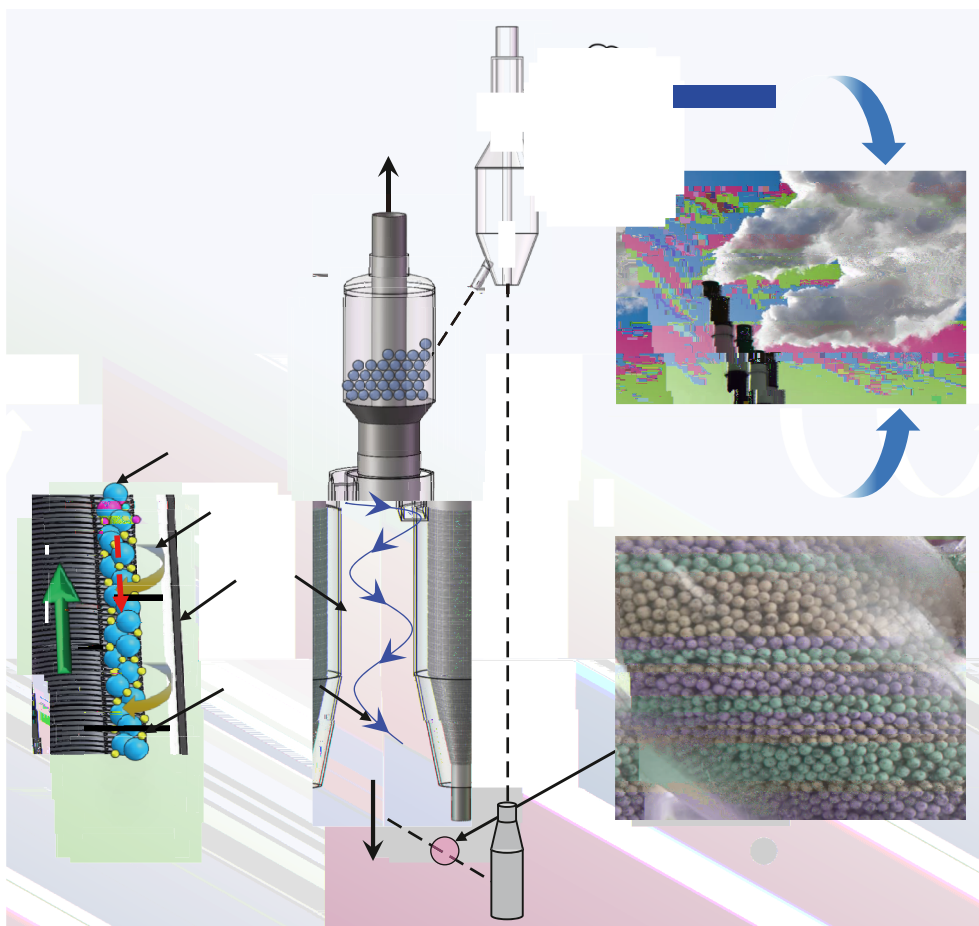


Fig. 1. Schematic of the CFCPS (Chang et al., 2022a).

particles in the regenerated exhaust gas must be collected as much as possible. Overall, the emission refinement issue is still not resolved and a relatively closed-loop gas purification process remains essential.

In previous study ([Chang et al., 2022b](#)), the regenerated exhaust gas was purified by a cyclone and a filter bag for post-treatment marked in [Fig. 1](#). However, the separation performance of the small-sized cyclone was limited and the filter bag needed to be

Moreover, the dust particles in the inlet, the dust bin, the outlet, and the reutilization pipe were sampled and then analyzed in a laser analyzer (Model: LS-909, manufactured by OMEC). It should be noted that the sampling method was isokinetic sampling, as explained in previous studies (Chang et al., 2022a). The total collection efficiency was obtained based on the dust concentration difference between the inlet and outlet:

$$\eta = \left(1 - \frac{C_{\text{out}}}{C_{\text{in}}}\right) \times 100\% \quad (3)$$

where  $C_{\text{in}}$  and  $C_{\text{out}}$  are the dust concentrations in the inlet and the outlet.

The efficiency contribution ratio of the centrifugal separation and bed filtration could be obtained:

$$\begin{aligned} e_c &= \eta_c \\ e_g &= (\eta - \eta_c)/(1 - \eta_c) \end{aligned} \quad (4)$$

## 2.2. Materials

Glass beads with average particle sizes of about 1.82 mm were used as the collector particles in the granular bed. The bulk density, the material density and particle density were 2400, 2421 and 1592 kg/m<sup>3</sup>, respectively.

Fig. 4. The mass median aerodynamic diameter of the dust particles was found to be 16  $\mu\text{m}$ , adhering to a Gaussian distribution. The particle size distribution and the median particle diameter were measured by a laser particle size analyzer (LS-909, manufactured by Zhuhai OMEC instruments Co., Ltd).

### **3. Results and discussion**

#### *3.1. The performance of the riser-spouted bed regenerator*

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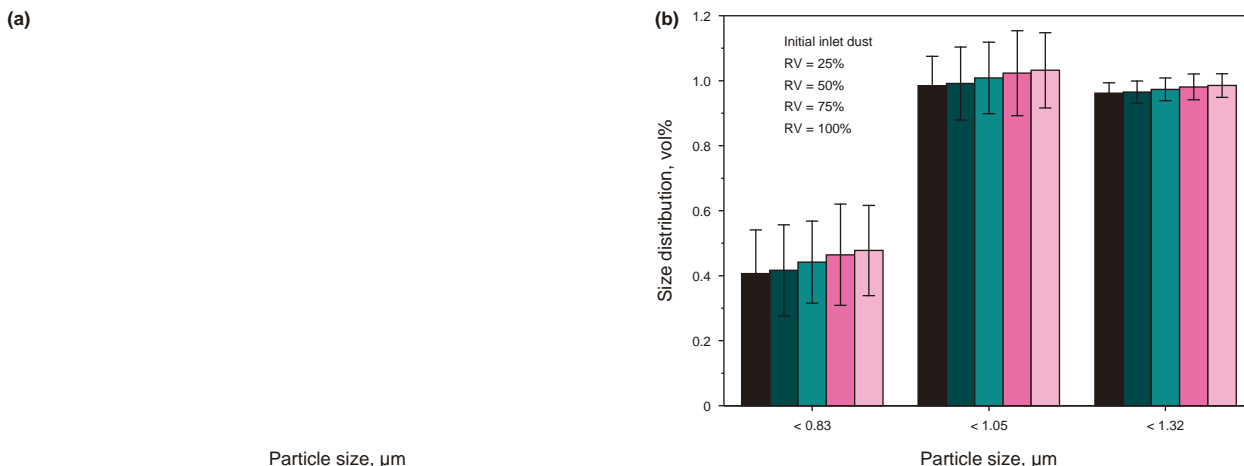


Fig. 6. The size distribution in the exhaust gas with different reflux volume ratio. (a) Whole particle size distribution. (b) Size distribution below 1.32 μm.

particles from the screw feeder and the reutilization pipe, could be computed and the results were also summarized in Fig. 6(b). The inlet size distribution was influenced by the exhaust gas mainly on the particles below 1.32 μm. Although the increment was not substantial, the fine dust particles were an important component of the dust cake formation. By reutilizing the regenerated exhaust gas, especially the airflow volume and fine dust particles, the centrifugal separation and the bed filtration would be both improved accordingly. Thus, the downstream operation unit equipment lifespan is extended by avoiding particle wear and coking in FCC industry. Moreover, a closed-loop gas purification process was likely to be achieved. These cost savings, combined with reduced regulatory non-compliance risks, position CFCPS as both an environmentally and financially sustainable solution.

Concerning the inlet dust particles, the dust size distributions at the beginning/end of the regeneration process were compared in Table 3. It seems that the dust size distribution before and after regeneration tended to be consistent, and the median size increased about 0.6 μm after regeneration. Two reasons could be attributed to the difference. Firstly, part of fine dust particles was carried out with the exhaust gas. Conversely, high gas velocity in the riser caused significant attrition of the bed particles, which interfered with the size analysis due to the debris. For example, particles larger than 10 μm were found in the mixtures after the regeneration. In general, the amount of fine dust particles and particle size returned to the purifier was greatly relevant to the regenerated exhaust gas reflux volume ratio. Further experimental investigation is imperative to validate theoretical models and elucidate underlying mechanisms.

Based on above results, the potential of the exhaust gas reutilization was confirmed preliminary on the performance improvement of the CFCPS. Firstly, a higher total airflow volume enhances the centrifugal separation and swirl intensity in the cyclone shell. For the moving bed filter, the changes in bed porosity and the dust cake resulting from the deposition of fine particles were advantageous for particle filtration. The chain effect in the recycling loop process, involving the purifier, regenerator, and regenerated exhaust gas, is discussed with a focus on separation performance.

### 3.2. The variation in the pressure drop

Pressure drop serves as a critical parameter for assessing device applicability, directly governing operational flexibility and economic feasibility. Fig. 7 illustrated the pressure drop sequences over time for various inlet dust concentrations and reflux volume ratios. Clearly, the pressure drop of the purifier was comprehensively determined by multiple factors and which factor played the dominant role depending on the specific operation conditions. As shown in the chart, significant differences could be observed. When the inlet dust concentration was low ( $C_i = 7.52 \text{ g/m}^3$ ), the pressure drop rose as the dust-laden operation progressed. Compared to  $RV = 0\%$ , the overall value increased with the reflux volume ratio. It appeared that the influence of the exhaust gas volume was indistinct as the reflux volume ratio increased. The dust particles below 5 μm from the exhaust gas became the dominant factor. As the fine dust particles escaped from the swirling flow, they were intercepted in the moving bed by several

Table 3 Particle size distribution of the dusts sampled before and after the regeneration.

Inlet dust concentration, $\text{g/m}^3$	7.52		14.99		22.50		30.35		37.04	
	Before	After	Before	After	Before	After	Before	After	Before	After
0–1	0.50	0.45	0.79	1.12	0.73	1.17	0.45	0.95	0.25	3.69
1–2	5.70	1.81	5.90	3.05	5.80	2.06	4.66	3.61	6.67	6.97
2–4	6.48	9.85	10.08	6.12	9.04	4.59	6.00	6.01	10.88	36.35
4–6	27.78	32.99	31.22	16.81	31.42	11.77	24.45	13.44	31.92	44.54
6–8	48.91	47.38	43.14	38.14	46.52	32.40	48.28	36.79	44.63	8.46
8–10	22.28	19.36	18.59	21.26	19.89	19.53	24.03	21.35	18.72	0.90
>10	10.63	7.52	8.88	31.48	6.49	39.54	16.15	35.68	5.65	0
$d_{50}$	6.1	6.2	6.2	7.1	6.0	7.3	6.4	7.2	6.1	6.4

filtration mechanisms. While the pressure drop tendency with  $RV = 75\%/100\%$  was almost identical, the dust cake



Fig. 8. The pressure drop sequence of the purifier with different inlet gas volume and reflux volume ratios. (a) RV = 0%, (b) RV = 25%, (c) RV = 50%, (d) RV = 75%, (e) RV = 100%.

exponentially with the swirling velocity in the cyclone shell. Moreover, the outer screen of the moving bed filter strengthened this effect. Besides, the swirl intensity in the cyclone shell and the cross-flow in the bed were both enhanced as the swirling flow velocity increased and the formation of dust cake in/on the moving bed was suppressed. It was important to note that the residence time in the swirl space also decreased. The possibility of fine dust particles entering the granular bed grew. After that, it was shown that large pressure drop growth occurred at a high reflux volume ratio. Consequently, modulating the reflux rate within optimized thresholds prevents excessive equipment pressure drop escalation, while strategically tolerating marginal efficiency losses proves paramount for maintaining systemic operational stability.

### 3.3. Collection efficiency in the purifier

In addition to considering pressure drop, separation efficiency is another crucial parameter. Fig. 9 showed the collection efficiency at various inlet dust concentrations and reflux volume ratios. The total collection efficiency exceeded 992%. The most important thing was that the efficiency was improved dramatically with the introduction of the regenerated exhaust gas. Interestingly, the purifier under  $C_i = 14.99 \text{ g/m}^3$ , RV = 25% achieved the highest collection efficiency. In other words, the optimum operating condition was discovered without considering the pressure drop temporarily. It was meaningful to study the reason that

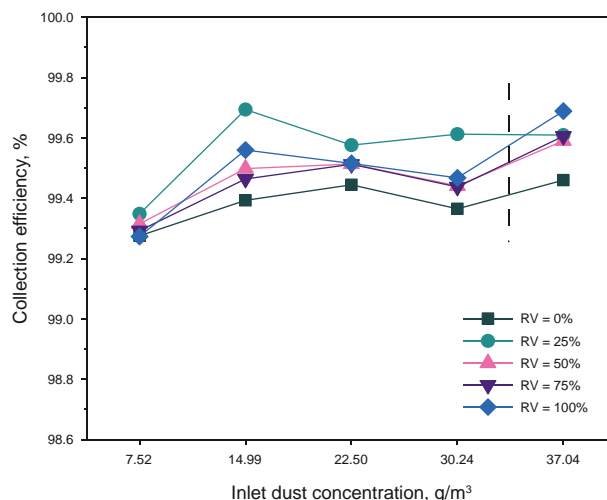


Fig. 9. The collection efficiency of the purifier with different inlet dust concentrations and reflux volume ratios.

affected the collection performance and further improve it in terms of the separator pressure loss. When the inlet dust concentration was  $7.52 \text{ g/m}^3$ , the collection efficiency increased slightly compared to RV = 0%. As the inlet dust concentration

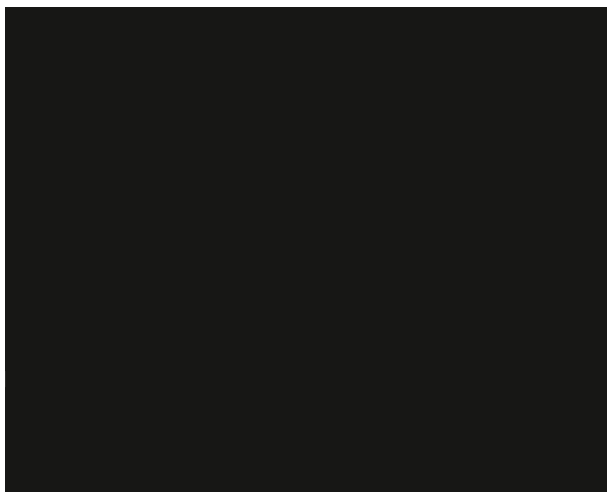


Fig. 10. The collection efficiency of the purifier with different inlet gas volume and reflux volume ratios.

increased, the differences between various reflux volume ratios became more pronounced. Comparison of the reutilized exhaust gas influence below  $C_i = 30.24 \text{ g/m}^3$  showed similar efficiency results: the fine dust concentration and gas volume with  $RV = 25\%$

ensured that the coupled purifier exhibited the best separation characteristics. For the purifier, the improvement of centrifugal separation efficiency meant that the amount of dust particles entering the moving bed filter was correspondingly reduced, and then the bed filtration was affected. More fine dust particles from the exhaust gas entered the bed filter directly through the cyclone shell, and the decrease in bed porosity compensated for the negative effect of “low volume efficiency”. On the other hand, high exhaust gas reutilization value increased the swirl intensity and the residence time of dust in the cyclone shell was shortened. The decrease in residence time reduced the possibility of the dust particles captured by the centrifugal mechanism. As mentioned above, the exhaust gas volume became the relative dominant factor when  $C_i = 37.04 \text{ g/m}^3$ . Considering the particle agglomeration characteristic, high separation efficiency was achieved in the cyclone shell especially when the regenerated exhaust gas was all reutilized.

The experimental results about the effect of the inlet gas volume and reflux volume ratio on the collection efficiency were presented in Fig. 10. Overall, the collection efficiency decreased with the inlet gas volume increasing. Although coarse dust particles separation was enhanced in the cyclone shell, the total collection efficiency was compromised by increased fine dust particles content from the exhaust gas. It was clear that the impact of the exhaust gas reflux volume ratio on collection efficiency differed with varying inlet gas volumes. At low inlet gas volume

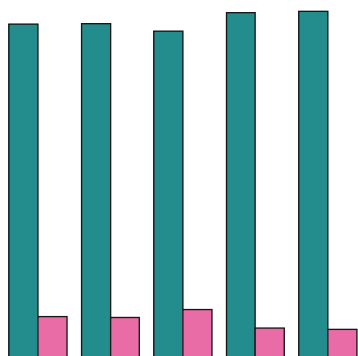


Fig. 11. The contribution ratio of the cyclone and the moving bed at varying inlet dust concentrations and reflux volume ratios. (a)  $C_i = 7.52 \text{ g/m}^3$ , (b)  $C_i = 14.99 \text{ g/m}^3$ , (c)  $C_i = 22.50 \text{ g/m}^3$ , (d)  $C_i = 30.24 \text{ g/m}^3$ , (e)  $C_i = 37.04 \text{ g/m}^3$ .

( $Q = 600 \text{ m}^3/\text{h}$ ), the collection efficiency remained above 995‰ due to the high proportion of the reutilized exhaust gas in the total inlet gas volume. Compared to other operation conditions, the dust cake filtration was enhanced by the dust particle deposition and the weaker swirl flow cleaning effect. While the collection efficiency at  $Q = 1000 \text{ m}^3/\text{h}$  was below 99%. Additionally, an obvious minimum value was shown at  $RV = 50\%$ . The collection efficiency enhanced by the gas volume from the regenerated exhaust gas could not cope with the entrained fine dust particles.

To figure out the effect of the reutilized exhaust gas on the centrifugal separation and bed filtration respectively, the efficiency contributions ratio under different inlet dust concentrations and reflux volume ratios were illustrated in Fig. 11(a)–(e). Clearly, the cyclone shell captured approximately 90% of dusts, which was crucial for gas purification. Additionally, the contribution ratio increased with rising inlet dust concentration. This enhanced contribution from the cyclone shell alleviated the load on the subsequent granular bed, helping to maintain high bed porosity. The operating cycle of the coupled equipment was extended because the filtration pressure loss was also reduced. The median particle size in the dust bin was around  $22.15 \mu\text{m}$  (larger than the initial inlet dust particle size), with a particle size range of  $4.28\text{--}44.82 \mu\text{m}$ . The dust particles above  $10 \mu\text{m}$  accounted for more than 92%, which was related to the characteristic of the centrifugal separation mechanism in the cyclone.

More importantly, the minimum value of the cyclone contribution ratio frequently appeared at  $RV = 50\%$  under different inlet

dust concentrations. Relatively speaking, the opposite trend occurred in granular bed filtration. It had been pointed out above that the fine dust concentration and gas volume from the reutilized exhaust gas at  $RV = 50\%$  were the intermediate value. Thus, it could be concluded that the centrifugal force was enhanced by high inlet mixed gas flow when  $RV < 50\%$ . At the same time, fine dust particles were collected efficiently. However, the centrifugal separation efficiency was weakened as the limited increase in reutilized exhaust gas volume at  $RV = 50\%$ . Considering the agglomeration, the separation process in the cyclone shell recovered as  $RV > 50\%$  and exceeded the efficiency at  $RV < 50\%$ . Moreover, the increasing content of fine dust particles below  $2 \mu\text{m}$  helped the dust cake formation in the granular bed. While the cake would be destroyed by high tangential gas flow from the cyclone shell. By adjusting the exhaust gas reflux volume ratio, the performance advantages of the purifier became more apparent based on the corresponding operating conditions. This is also the reason why it is necessary to conduct pilot-scale experiments to address the equipment operating characteristics, thus bridging the critical knowledge gap between laboratory findings and industrial process scalability.

As discussed above, the efficiency contribution of the centrifugal separation was improved by increasing the inlet gas volume. The calculated results were illustrated in Fig. 12(a)–(e). Because of this phenomenon, the dust particles that escaped from the centrifugal separation were weakened. Changes in bed porosity and dust cake in the granular bed were slight, the filtration efficiency

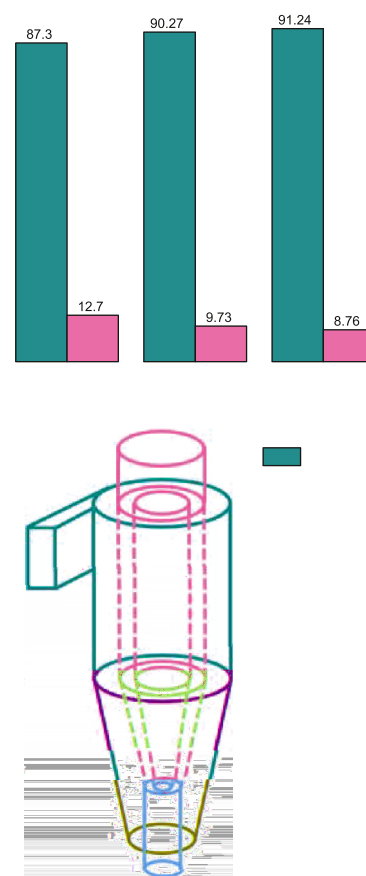


Fig. 12. The contribution ratio of the cyclone and the moving bed with different inlet gas volume and reflux volume ratios. (a)  $RV = 0\%$ , (b)  $RV = 25\%$ , (c)  $RV = 50\%$ , (d)  $RV = 75\%$ , (e)  $RV = 100\%$ .

decreased with increasing inlet gas volume. From the perspective of pressure loss, the variation of the moving bed filtration pressure induced a limited impact on the overall pressure loss. It appears that the gas volume from the exhaust consistently had a positive effect on dust particle collection. While the fine dust particles were separated more efficiently at a high reflux volume ratio.

In addition, the outlet size distribution with different inlet concentrations and reflux volume ratios was also presented in

Fig. 13. The median size remained almost unchanged when the reflux volume ratio was greater than 0%. Compared to  $RV = 0\%$ , the median size decreased from  $1.67 \mu\text{m}$  to  $0.82\text{--}1.04 \mu\text{m}$  with a narrower size range. Thanks to the dust cake enhancement and the swirling flow strengthening, the dust particles

exhaust gas purification and recovery technology for a closed-loop gas purification process. For technology providers, the CFPCS opened a collaborative path to innovate and deliver solutions that

Methodology, Investigation, Funding acquisition, Conceptualization. **Xin-Lei Li**: Formal analysis, Data curation. **Yu-Qin Han**: Formal analysis, Data curation. **Yi-Ping Fan**: Validation, Supervision. **Chun-Xi Lu**: Validation, Supervision.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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