Study of Flow Patterns in Two-Stage Mode of Moving Granular Bed Filter

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Abstract

The use of moving granular bed filters (MGBFs) had being growing, and they held an important role in the gasification or combustion of coal or biomass. Furthermore, they had great potential to be developed for the high-temperature gas cleanup of advanced power generation systems. However, the existence of a stagnant zone with defective designs in MGBFs could cause serious damages such as plugging. Therefore, in order to minimize these flow problems, flow-corrective inserts for filter vessels had been researched. Most previous theses used mono-sized filter granules as filter media in a filter vessel. Meanwhile, this study proposed a new method that introduced two filter granule sizes in one filter vessel, called the two-stage filtration mode. Nevertheless, the design theory of a mass flow vessel by Johanson could not be satisfied by using two sizes of filter granules to diminish stagnant zone. The six test conditions of configuration to accomplish the objective were explored in this study. The results included the flow patterns in a two-dimensional and cross-flow moving granular bed with the different geometry designs in a filter vessel. The two kinds of filter granules consisted of coarse and fine silica sands. The findings revealed that the flow pattern profiles of filter granules were influenced by the vessel geometry. The optimal design for two-stage filter granules in a filter vessel was created to diminish the stagnant zone in 165 minutes.

***Keywords**:* Gas cleanup; Flow-corrective-insert; Stagnant zone; Silica sands.

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INTRODUCTION

In 2013, the International Agency for Research on Cancer (IARC) of World Health Organization (WHO) concluded that outdoor air pollution and one of its components, particulate matter (PM), could cause lung diseases (Sax *et al.*, 2013). The PM in air pollution, water resources, soil, and plant contamination, could cause environmental impact and human well–being (Chen *et al.*, 2009; Al-Naiema *et al.*, 2015). In order to decrease the level of PM released to environment, the few filtration methods and specific techniques (Artun *et al.*, 2017) were adopted. Coal-fired power plants (CFPPs) which burned fossil fuel such as coal to produce electricity discharged PM as well. While, It was forecasted that oil, as a source for heat and electricity, would decline in the next century, but coal would still be used in CFPPs for over a hundred years. Pressurized fluidized bed combustion (PFBC) and the integrated gasification combined cycle (IGCC) were notable techniques in the application of CFPPs since the 1970s which were a great source of PM (Li *et al.*, 2016) such as SO_X and NO_X (Baba *et al.*, 2010) at high-temperature gas stream (> 450 °C). Furthermore, PM (e.g. fly ash) would also cause a damage to the blades of a gas turbine. Therefore, to extend the blade-life and reduce contamination of the air, it was necessary to filter fly ash out before they enter the gas turbine. Ceramic barrier filters were one of the possible solutions for particulate removal in high-temperature conditions. However, implementing Ceramic barrier filters had encountered with some typical problems including: discontinuous operation, expensive consumables (rigs), frangible ceramic surfaces, need for back-pulsing, creeping and bending (Saxena *et al*., 1985; Zevenhoven and Kilpinen, 2001). Therefore, the alternative technology of moving granular bed filters (MGBFs) had been studied and developed (Mizukami *et al*., 1987; Jung and Tien, 1991; Jung and Tien, 1992; Brown *et al*., 2003; Stanghelle *et al*., 2007). From these references, the collection particulates of MGBFs were effective and reliable in hot gas cleanup environments.

Granular bed filters have been used in the following modes of operation: fixed bed, intermittent, continuous moving bed, and fluidized bed. They have the advantages of low-cost filtration media, high temperature stability, continuous processing (besides fixed bed), and circulation of filter granules (Kuo *et al*., 1998). The principle of filtering in a MGBF system used bulk solids such as silica sands or limestone to retain particulates as they flow downward from the top of the filter bed. When particulates from the gas flow penetrated the deep-packed granular bed they were retained in the bed and do not plug its surface (Ives, 1975). This principle could also be applied to the filtration of liquids. During the process, plugging problems frequently occurred in moving granular beds (Ives, 1975). Therefore, it was necessary to develop new geometry design in filter systems which were suitable for mass flow rate that kept the filter granules flowing downward in the vessel. Thus, the plugging problems or stagnant zone would be avoided.

Jenike (1964), Amold *et al*. (1980), and Robert (1995) identified that corresponding flow patterns were considered as mass-flow. The mass-flow pattern could be created by smooth, steep bins. Inside these bins, dead region or stagnant zone could be avoided by an obstacle or a flow-corrective insert. Kuo *et al.* (1998) and Hsiau *et al*. (1999, 2000, 2001) found that the flow patterns and velocity profiles of granular flow were influenced by the louvered configuration in the Dorfan Impingo filter system and in different louvered designs of the symmetrical louver-walled moving-bed system. These flow behaviors and velocity profiles were found not only during experimental tests but had also been simulated by Chou *et al*. (2000). In further research, Hsiau *et al*. (2008) and Smid *et al*. (2009) successfully developed and optimized a moving granular bed with a louver-sublouver system to diminish most stagnant zones. However, only mono-sized coarse sands were focused as the filter granules in studies mentioned above.

Some scholar proposed a two-stage filtration mode (Chyou *et al*., 2011). A multi-stage filtration process could provide about 90% to dust capacity with 20% acceptable increasing pressure drop (Yang and Zhou, 2007). It used two kinds of silica sands (fine and coarse) as filter granules with the new configuration of a moving granular bed. This filtration mode called the “two-stage filtration” due to its two granule sizes, which were placed in two different vertical layers. As shown in Fig. 1, the coarse sands were placed in the first stage of filter granular bed, and the fine sands were placed downstream of the coarse sands as the second stage. Thus, the larger particulates in the syngas flowing through the first layer of coarse sands were caught. Then the remaining smaller particulates were captured in the second layer by the fine sands. Therefore, most of the particulates would be retained in the two-stage bed and that the total filtration efficiency would be enhanced corresponding to the decrease in fly ash. This two-stage filtration mode would be applied in the basic setup of two-dimensional thin slice panel system with flow-corrective insert design by Smid *et al.* (2012). Moreover, this design equipped with flow corrective elements could solve the plugging problems caused by the stagnant zones of filter granules. The test of this newly designed apparatus was first reported in this study. Besides, our study essentially helped the development of a moving granular bed filter that could be applied to the removal of dust particulates in IGCC and PFBC systems.

EXPERIMENTAL METHODOLOGY

Apparatus and materials

The MGBFs were a kind of cross-flow filter systems. The filter granules moved downward and were exited from the bottom of the vessel. The syngas passed horizontally through the granular layer forming a cross-flow section as shown in Fig. 2. In present study, a two-dimensional model of the experimental moving bed was shown schematically in Fig. 3 (Smid *et al*. (2012)). Its dimensions were 1160 mm height, 380 mm width, and 50 mm depth. A flow-corrective insert with symmetrical/asymmetrical galvanized plates was placed in the middle position of the moving bed. The parameters of the flow-corrective insert were designed using Johanson's theory (Johanson, 1966; Johanson and Kleysteuber, 1966; Johanson, 1967/1968), as shown in Fig. 4. The flow-corrective insert was characterized by angle $\theta_{1C} = \theta_{1F} = 20°$, $\theta_{2C} = \theta_{1F} = 20°$ for Test 1 to 5, and $\theta_{1C} = \theta_{2C} = 20°$, $\theta_{1F} = \theta_{2F} = 15°$ for Test 6. The insert in a critical placement could diminish the stagnant zone. Following Johanson's theory, $\alpha_{c.r.}$ could be obtained equal to 45°. The vertex of the flow-corrective insert was determined by a line having an angle of $\pi/2–\alpha_{c.r.}–\theta_{2C} = 25°$ as it crossed the center line, where the slope of the angle was measured from the horizontal under Test 1 to Test 5. For Test 6, the vertex of flow-corrective insert was changed due to an angle of $\theta_{1F} = 15°$ and the angle of $\pi/2–\alpha_{c.r.}–\theta_{2F} = 30°$. The length of the flow-corrective insert L was calculated from Johanson's equation, with the help of the angle α_C and angle α_F. In order to investigate the flow patterns of the two sands, which could be affected by the flow-corrective insert, six experiments were designed.

For Test 1 to Test 3, the same symmetry system was used as shown schematically in Fig.

5(a). Test 1 to Test 3 had the same angles, θ_{1C}, θ_{2C} = 20° and θ_{1F}, θ_{2F} = 20° and the same length of the flow-corrective insert L = 142 mm. For further observation of the diminishing stagnant zone, Test 1 and Test 2 were filled with fine sands, coarse sands, respectively. And Test 3 was filled both coarse and fine sands in a vessel as a two-stage filter.

Hsiau *et al*. (2008) and Smid *et al*. (2009)'s researches pointed out that the geometry of flow-corrective insert could influence the various stagnant zones. Furthermore, there was stagnant zone found in Test 3 as a two-stage filter. In order to diminish the stagnant zone, the asymmetrical systems of Test 4 to Test 6 were developed as shown in Fig. 5(b) to Fig. 5(d). Both of Test 4 and Test 5 had the same angles θ_{1C}, θ_{2C}, θ_{1F}, and θ_{2F} of 20°. And for the purpose of diminishing stagnant zone, the length of flow-corrective insert was extended to 147 mm and 192 mm in Test 4 and Test 5, respectively.

Considering that the physical properties of two kinds of sands were different, the configuration of Test 6 was changed. As shown in Fig. 5(d), the vertex of the flow-corrective insert was determined by angle of $\pi/2-\alpha_{c.r.}-\theta_{2F} = 30°$. And the angle of θ_{1C}, θ_{2C} = 20°, θ_{1F}, θ_{2F} = 15° was used. Due to the vertex of the flow-corrective insert shifted, the length L was modified to 169 mm and 173 mm by the angle of α_C and α_F too.

The granular particles were placed between the front and rear glass of the filter vessel and were introduced into the filter vessel from an upper hopper with a rectangular discharging slot. In order to reduce the wall friction effect of flowing granular particles, the front and rear glass were cleaned carefully before each experiment. Near the bottom of the filter vessel, a moving conveyer belt was controlled by a variable-frequency-drive motor at a flow rate of 330 ± 3% g/min. This flow rate was measured by the average weight value of per minute of discharged filter granules using an electronic balance (Precisa 30000D), which had a resolution of 0.1 g. The particles of coarse sands ranged from 2 to 4 mm, whereas the fine sands were around 0.2 mm. The sands consisted of 95% silicon dioxide and 5% other chemical compositions as the flowing granular solids in this experiment. The friction between the sands and wall were measured using a shear tester (Jenike, model FT-5STEH). The friction angles of the coarse and fine sands with the wall were 15.78° and 20.9°, respectively.

Experimental procedure

The experimental tests consisted of two parts as shown in Fig. 6. In the first part, the tests were started to fill the coarse and fine colored sands (the originals were a light brown color) into filter vessel. In this two-stage case, it was difficult to approach clear patterns while filling two kinds of filter granules at the same time. At the beginning, the bin was filled with colored coarse sands as shown in Fig. 6(a) and 6(b). After the first part, the tests started to run circulation and to introduce colored fine sands downstream of the colored coarse sands as the second stage as shown in Fig. 6(c).

The second part was the circulation of the filter vessel to reach the steady-state flow conditions (in Fig. 6(d)). After three hours, the bulk density of moving sands was the steady-state condition, because the weights of sands from vessel outlet were more homogeneous. To record and to observe the colored stagnant zone of whole granular bed as a second part of experimental test, a digital video camera (Sony, DCR-TRV 900) was used. The camera was mounted on the cradle head of an aluminum tripod to get clear video quality and was activated before the filter granules flowed in the filter vessel. The captured videos were stored on a personal computer and further processed as the flow patterns shown in the results.

RESULTS AND DISCUSSION

Flow patterns

In this study, there was no gas flow passing through filter vessel. Generally, in a moving bed design, the horizontal gas flow did not have a significant effect on the gravity flow of filter granules because of its low velocity. For an IGCC system, the gas flow rate had to be limited in a filtration mechanism with a low pressure drop. This was different from a fluidized bed, where the gas flow had to overcome the minimum velocity of fluidization. Therefore, a moving bed filter could be controlled in a low pressure drop condition.

Fig. 7 showed the flow patterns of the colored filter granules for 300 minutes in 15 frames under Test 1 (Fig. 5(a)) conditions. The beginning stage of the experiment was illustrated in Frame 1. The number shown below each frame corresponds to the time in minutes. The time interval between each frame was 10 min over a period of 0 to 60 min. From 60 to 300 min, the time interval between frames increased to 30 minutes to investigate the changes. Three regions in these flow patterns were identified as follows: (1) stagnant zone, which was the residual area of coarse and fine filter granules left in the original filter vessel, near the flow-corrective insert and convergent part of the vessel. As shown in Fig. 7, a short while after the experiment had begun, the patterns of the stagnant zone were quite clear in the period between 30 and 60 min. The development of this zone diminished progressively after the experiment had operated for 300 minutes, as shown in Fig. 7. (2) Left and right free surface regions. These free surfaces were characterized by a minimum angle of repose and a maximum angle of free surface stability. Hsiau *et al*. (2000) indicated that the angle of free surfaces of granules normally oscillated between a minimum angle and a maximum angle above. During the flow downward to the filter bottom, the granules avalanched frequently over the free surfaces. When the angle of the free surface was smaller than the minimum angle of repose, the new granules would roll down over the free surface until the maximum angle of free surface stability was renovated.

In Test 1 to Test 5, flow-corrective inserts were designed to situate at the same horizontal level. However, Test 6 was optimized, which shifted the flow-corrective inserts upward for proper flow ability according to the theoretical angle ($\pi/2 – \alpha_{c.r.} – \theta_{2F}$) for fine sands (Hsiau *et al*., 1999). The test conditions for Test 1 to Test 3 were different: fine sands were used in Test 1, coarse sands were used in Test 2, and both fine and coarse sands were used in Test 3. The filter setups for Test 1 to Test 3 used the same geometry design which was calculated from Johanson's theory according to the conditions of coarse sands. As shown in Fig. 8, the flow histories of the colored sands under Test 2 condition were recorded. In Test 2, the two above-mentioned flow regions were found. The similar flow patterns and the stagnant zone were found not only in Test 1 but were also observed in Test 2. For example, the diminishing of the stagnant zone above the flow-corrective insert (the 40-min frames in both Test 1 and Test 2) and the residual colored filter granules of stagnant zone (see 90 min in both Test 1 and 2) on the convergent part of the filter vessel were all very similar to those patterns in both test conditions. Even if the flow patterns of Test 1 were similar to those of Test 2, there were some differences within the results of the two tests. Thus, the diminishing time of stagnant zone along in Test 1 was smaller than that in Test 2. The results showed that this angle of the flow-corrective insert configuration was a better situation for the fine sands of Test 1 than for the coarse sands of Test 2. By comparing the diminishing time (240 min in Test 1 vs. 210 min in Test2) of the stagnant zone around the convergent part of the filter vessel wall, the time in

Test 2 was shorter than in Test 1.

For the purpose of controlling the particle size and concentration at which flue gas flowed through the filter, both coarse and fine sands were placed in the same filter to achieve two-stage filtration in Test 3 to Test 6. Fig. 9 showed the flow history of the colored sands under Test 3 conditions. Similar flow regions were observed as in Test 1 and Test 2. According to the results in the Test 3 conditions, the flow patterns showed significant change from 40 min to the end of the experiment. First, it should be noted that the plug flow in central area downward to the outlet of filter flowed even faster in 50 min than in Test 1 and Test 2. Moreover, the fine sands behind the right side of the filter vessel wall formed a larger stagnant zone than Test 1 in the 90-min frame with the same sands. This phenomenon indicated that the setup of Fig. 5(a) was no longer suitable when two kinds of filter granules were flowing in this configuration. The results also revealed that coarse and fine sands did affect the each other's flow pattern. Generally, the bulk density of coarse sands were different from that of fine sands making the inner pressure distribution of coarse and fine sands in the filter vessel was also different. In this case, the existing stagnant zone on the right side wall might be caused by internal friction of the coarse sands. The stagnant zone of sands behind the right side of filter wall was diminished in the end.

Johanson (1966; 1967/1968) and Johanson and Kleysteuber (1966) indicated that the configuration and placement of the insert was sensitive to the flow pattern behavior. Meanwhile, a stagnant zone was developed when the wall and insert in the filter vessel were not smooth or steep enough for it to diminish. The research of Hsiau *et al*. (2001) with velocity filed analyses also pointed out that the angle of insert should be small to develop mass flow. In order to decrease the stagnant zone in Test 3, the length of the right plate of the flow-corrective insert was extended by 5 and 50 mm in Test 4 and Test 5, respectively. Fig. 10 and Fig. 11 showed the flow history of colored filter granules with an asymmetrical configuration setup. However, the resulting flow patterns in Test 4 were very similar to those in Test 3. The diminishing time from 90 to 240 min in the two tests showed no significant change with the flow patterns. Compared with Test 3 and Test 5, there were some obvious changes that should be noted. First, the flow area above the insert on the fine sands side moved slower than in any of the previous experiments. This area between the right plate of the insert and right wall of the filter vessel became a narrow flow region because of the 192-mm long plate. This was because the filter granules flow with more difficulty thought the narrow region. Thus, the filter granules moved more slowly in the beginning. Then, in Test 5, after 40 min, a plug flow occurred in the convergence area between the right plate of the insert and the filter wall. This was a result of the fast movement of filter granules in the vertical direction, and low horizontal dispersion. In addition, the plug flow in this area might also have been caused by the extended plate. Next, a stagnant zone occurred above the right plate of the flow-corrective insert. Comparing the stagnant zone in Test 5 to that of Test 3 and Test 4 (90 min in Test 5 vs. 60 min in Test 3 and Test 4), the stagnant zone in Test 5 was more difficult to diminish. For the optimal design of a filter vessel, a long-lasting stagnant zone around the insert should be avoided if gas flew through this zone. Such a zone might cause plugging problems above the insert region; thus, the filtration efficiency would decrease when dusted flue gas flowed through it. This also meant that an existing stagnant zone would increase the refreshing rate of filter granules. Despite the foregoing problem of an existing stagnant zone, the stagnant zone of colored filter granules displayed a better diminishing time in the end.

Considering the experimental results from Test 1 to Test 5, the geometry of the filter vessel or the configuration of the flow-corrective insert could not achieve the goal of mass flow conditions. Thus, the filter vessel and insert were redesigned according to Johanson's theory, as shown in Fig. 5(d). Fig. 12 showed the flow history of colored filter granules in an asymmetrical configuration set up with different angles of θ_1 and θ_2 in Test 6 conditions. The flow behavior of coarse sands was not much different in comparison with Test 3 to Test 5. Nevertheless, the flow behavior of fine sands showed a distinct change with a trending uniform mass flow (20 to 40 min) after the modification. The stagnant zone around insert was also removed quite quickly by virtue of the theoretical angle for fine sands. The steeper right plate of the insert and wall of filter vessel also helped to meet the mass flow condition. In the asymmetrical configuration design of Test 6, the result showed a faster refreshing rate of filter granules removing in 165 min. Furthermore, the refreshing rate could be determined by the time needed to replace the whole filter vessel completely with a new batch of purified filter granules. The high granules refreshing rate might keep the pressure drop remain at a relatively lower level across the filter vessel (Kuo *et al*., 1998).

Stagnant zone time

Fig. 13 showed the operation of experiments for Test 1 to Test 6 with stagnant zone reduction during outflow. The equation for the stagnant zone percentage was described as

$$\text{Stagnant zone percentage (\%)} = A_R/A_A \quad (1)$$

Where A_R was the stagnant zone of colored filter granules, and A_A was the total area of filter granules in the filter vessel. A comparison of the experimental results of flow patterns from Test 1 to Test 6, including both coarse and fine sands, with the stagnant zone percentages was shown in Fig. 13. Under Test 6 conditions one recycle exchange of all filter granules was achieved in 165 minutes, and good results were accomplished. At the same time as the filter granules in Test 6 outflowed, the stagnant zone percentage (colored filter granules) under the other test conditions remained around 10%. This indicated that the refreshing rate in the Test 6 condition had performed efficiently. The stagnant zone percentages under the two-stage filter granules state were shown as Fig. 14 to Fig. 17 for the Test 3 to Test 6 conditions. From the results, the diminishing time in cases with a stagnant zone of coarse sand was lower than in cases with fine sand. Therefore, the refreshing rate was inefficient due to the stagnant zone of fine sands.

The fine sands outflowed successfully under Test 6 conditions; therefore, the stagnant zone percentages of fine sands accomplished 0% even earlier than the coarse sands. Fig. 17 also revealed that the right side of Test 1 and the left side of Test 2 in comparison with Test 6. The results showed the larger stagnant zone of fine sands than coarse sands before 90 min, and the larger stagnant zone of coarse sands than fine sands after 90 min. Compare to Test 1, Test 2, and Test 6, the geometry design and the parameters of Test 6 obtained a better flow behavior remaining. Fig. 18 showed that the ratio of stagnant zone percentage of coarse and fine sands in the Test 6 condition. The equation of the ratio was given as

A_{RC}/A_{RF} = stagnant zone of coarse colored filter granules / stagnant zone of fine colored filter granules (2)

Where A_{RC} was the stagnant zone of coarse colored filter granules, and A_{RF} was the stagnant zone of fine colored filter granules. The subscript R stands for residual stagnant zone, and the subscripts C and F stands for coarse and fine sands, respectively. The ratio of the Test 3 to Test 5 conditions showed that their tendencies were similar, decreasing over time. This explains how the diminishing rate of coarse sands was faster than that of the fine sands and furthermore that the smaller stagnant zone of coarse sands compared with that of the fine sands. In the Test 5 condition, the above-mentioned tendency dropped sharply because of the inefficiency of extending the 192 mm plate length of the insert setup. This was because the excessively long plate obstructed the fluency of flow of the fine sands. After around 60 min of experimental time in Test 3 to Test 5, the tendencies dropped more slowly until the tests finished. This indicated that most of the residual coarse sands had been cleared from the filter vessel, especially in the area along the left side of the insert plate. In the Test 6 condition, as shown in Fig. 18, the tendency dropped at the start of 50 min. However, it started to rise rapidly during 60 to 90 min period. This result represented a totally different situation compared with the other tests. According to the flow patterns in Fig. 12, it could be explained that the fine sands flowed more fluently than the coarse ones. Furthermore, the flow of fine sands under the insert space was similar to having a mass flow condition, which explained why the tendency rose in the Test 6 condition. In this condition, the entire colored stagnant zone diminished after 165 minutes. These results revealed that the optimal asymmetrical design for a two-stage filter vessel offered a clear benefit.

CONCLUSIONS

This paper analyzed the flow patterns in a two-dimensional, cross-flow moving granular bed with the different geometry designs in a filter vessel. The two kinds of filter granules consisted of coarse and fine silica sands. The results revealed that the flow pattern profiles of filter granules were influenced by the vessel geometry, and the optimal design for two-stage filter granules in a filter vessel was created to diminish the stagnant zone.

Six configuration setups of moving granular beds with two-stage filter granules were tested. The length L, angle of θ_{1C}, θ_{2C}, θ_{1F}, and θ_{2F} were adjusted in order to obtain an optimal design. According to the results, both of the filter vessel and flow-corrective insert in an asymmetrical design might solve the plugging issues reported in several advanced research works during tests. This study showed that the more suitable flow pattern results in the optimal design of Test 6, demonstrated that the negligible stagnant zone diminished almost completely under this condition with good flow behavior of the filter granules. Thus, the configuration of Test 6 had been chosen for the development of a three-dimensional model of a MGBF with two-stage filter granules. The current study could provide the industry with the important parameters for a filter system with multi-stage process.

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NOMENCLATURE

L	Left/right plate length of flow-corrective insert.
A_R	Residual stagnant zone of colored filter granules.
A_A	Total area of filter granules.
A_{RC}	Residual stagnant zone of coarse colored filter granules.
A_{RF}	Residual stagnant zone of fine colored filter granules.

Greek symbols

$\alpha_{c.r.}$	Critical angle obtained from Johanson's theory.
θ_{1C}	Filter slope angle of coarse sands on left side of granular bed.
θ_{2C}	Insert slope angle of coarse sands on left side of granular bed.
θ_{1F}	Filter slope angle of fine sands on right side of granular bed.
θ_{2F}	Insert slope angle of fine sands on right side of granular bed.