Effect of operation parameters on the performance of hot gas clean-up technology with a moving granular bed filter

Yi-Shun Chen[1], Shu-Che Li[2], Yau-Pin Chyou[1,*], Jhe-Yu Lin[1] and Hung-Te Hsu[1]

[1] Chemistry Division, Institute of Nuclear Energy Research, Longtan, Taoyuan 32546, Taiwan (R.O.C.)
[2] Department of Mechanical Engineering, National Central University, Chung-Li, Taoyuan 32001, Taiwan (R.O.C.)
*e-mail: ypchyou@iner.gov.tw

Abstract

Hot gas clean-up is important in the integrated gasification combined-cycle (IGCC) and advanced pressurized fluidized-bed combustion (PFBC) technologies, which exhibit higher efficiency and benign environmental impacts. Dust particulates must be removed before the raw gas is burned in the gas turbine to protect the turbine blade and to control particulate emissions, since syngas from coal gasification or flue gas from combustion contains dust particulates. A syngas cleaning technology of dust particulates has been under development at the Institute of Nuclear Energy Research (INER) since 2010. The present work attempts to provide a general understanding of granular bed filters, which is regards as a promising technology for hot gas clean-up. An experimental method was established to investigate the filtration processing of dust particulates.

This study implements a newly developed moving granular bed filter (MGBF) system to remove the dust particulates at the high-temperature conditions. The experimental facilities include an air fan, the ducts, the heaters of gas and filter granules, a screw feeder of dust particulates, a measurement system for size distribution of dust particulates, a filter granules supply device, a rotary valve, and a granular bed filter filled with filter granules. The filtration technology of an MGBF was employed to demonstrate the performance for collection efficiency, between room temperature and 500℃, under different filtration superficial velocities, mass flow rates of granular media, and fixed dust concentration. The variations of the outlet concentration and size distribution of dust particulates were measured to evaluate the dynamic characteristics of the process. In addition, important design constraints were identified for the successful operation of the proposed MGBF. The results of this study indicate that this type of method could be useful in application of different cross-flow filter systems for gas clean-up.

The focus in the current study is essentially the development of a moving granular bed filter that could be applied in near-industrial environment. The results are expected to serve as the basis for future research.

Keyword: Hot gas clean-up; Dust particulate; Moving granular bed filter (MGBF); High temperature.

1. Introduction

Hot gas cleaning is mainly used in an attempt to obtain clean hot gas, so that its thermal energy can be effectively utilized. For example, in integrated gasification combined-cycle (IGCC) and advanced pressurized fluidized-bed combustion (PFBC) [1], gases generated from coal must undertake cleanup processes, preferably without cooling the gases, prior to expansion via a gas turbine, to protect the downstream heat exchanger and gas turbine components against fouling and erosion. Particulates can be removed from a hot gas stream through cyclones, ceramic candle filters, or granular bed filters. Among the available approaches for hot gas clean-up, ceramic candle barrier filters and granular bed filters are most promising [2]. Granular bed filters have greater advantages over ceramic candle type, as the former could employ low-cost refractory filter for a very high temperature. Granular bed filters can be classified as fixed bed, fluidized bed or moving bed. The first one is very efficient, but the pressure drop can increase significantly over time. In addition, the fluidized bed and moving bed have advantages over the fixed bed as they could be continuously operated and regenerated at lower pressure drop. The configurations of the granular bed filters could be co-current, counter-current or cross-flow. In the co-current mode, gas typically enters the bed at the top and flows from the cleanest granules to the dirtiest granules, whereas in the counter-current filter gas flows from the dirtiest to the cleanest granules. In a cross-flow granular filter, gas perpendicularly flows through the downward flowed moving bed. Different configurations of the moving bed granular filters have different advantages and disadvantages and a lot of research efforts have been carried out on these filters.

Filtration of gas by granular filters was investigated by Paretsky et al. [3], Payatakes et al. [4], Payatakes et al. [5] and others. Gutfinger and Tardos [6] introduced a mathematical model for the calculation of granular bed filtration efficiency. Tien & Payatakes [7] and Gutfinger et al. [8] studied the clogging process in granular filters. A study by Brown et al. [9] concluded that filtration efficiency improves with granular flow rate while other studies have reported that increasing granular flow rate decreases filtration efficiency [10, 11], presumably due to disturbances of the dust cake in the filter, as granules are more rapidly conveyed through the filter. Yang et al. [12] concluded that granular flow rate has little effect on filtration efficiency. Zevenhoven [13] studied the removal of particulates from gas in coal-fired power plant using a counter-flow moving bed granular filter in conjunction with the use of an electrostatic precipitator for improving the collection efficiency. The efficiency of the filter was 80-98% when operated at 850 ℃ and 10 bar, while it decreased with gas pressure. Brown et al. [14] evaluated the performance of a counter-current moving bed granular filter by using similitude theory to devise experiments that were conducted at ambient conditions. They investigated the effect of dust ratio (the ratio of ash flow to the granular filter media flow) and granule size on the performance of the filter. They found that the dust ratio did not influence the performance, but the granule size did. The granule size of 2 mm gave higher collection efficiency and pressure drop than that of 4 mm. They reported that more than 99% collection efficiency could be achieved.

In 2007, Bai et al. [15] investigated the performance of a circulating cross-flow moving bed granular filter with conical louvre plates in terms of the collection efficiency and pressure drop by varying the mass flow rate and the size of the filter media as well as the dust/collector particle types. They reported the maximum collection efficiency of 99.5% when applying cyclone as the dust/collector particle type. They also reported that the dust collection efficiency was related to the effects of the solids mass flow rate, the collector particle size, the separator type and pressure drop. El-Hedok et al. [16] evaluated the effect of granular flow rate on the performance of a counter-current moving bed granular filter designed for hot gas filtration of fine char particles produced during fast pyrolysis of biomass. They concluded that when increasing the granular flow rate or decrease the residence time of the granular filter media, the hold-up of char in the filter could be reduced. All of the previous works showed that the gas flow rate, the granular filter size and granular mass flow rate influenced the collection efficiency of the moving bed granular filters. Nevertheless, the effect of the number of filtration stages, which is another important process parameter, on the performance of a moving bed granular filter is not well-understood, especially in a cross-flow one.

Therefore, the current work aims to elucidate the effect of the number of filtration stages as well as the temperatures and mass flow rate of granules on the collection efficiency in a moving bed granular filter. The filtration of the fly ash is a dynamic process since the fly ash captured by the filtration media is collected from the bed. The results obtained from this work would be beneficial to optimizing the parameters of the filter applied in the hot gas clean-up technology.

2. Experimental apparatus and procedures

2.1 Materials and apparatus

The dust particulates were taken from a coal-fired power plant in Taipei, Taiwan. The original size distribution of dust particulates ranged from 0.23 to 120.67 μm with a Gaussian distribution. The mass median aerodynamic diameter of the dust particulates was 69.24 μm. In addition, silica sand, with a particle size ranging from 2 to 4 mm, was used as the filter granules.

Tests of hot model were performed in a moving granular bed filter (MGBF), as illustrated in Fig. 1. The system consists of a trommel screen system, an air fan, two-stage gas heaters, a screw feeder, a sampling probe, a filter granule heater, and a filter granule supply device. The trommel screen device includes a trommel body, conveyors, a shield board, and a tilt control member. Trommel screen system is illustrated in Fig. 2 and will be utilized in future work to *"regenerate"* the particulate-laden granules, from which the reusable granules could be recycled back to the filtration system. The dust particulates and filter granules passed through the feeding hopper to the trommel body, where undersized of dust and oversized of filter granules were separated using the screen meshes of trommel screen system.

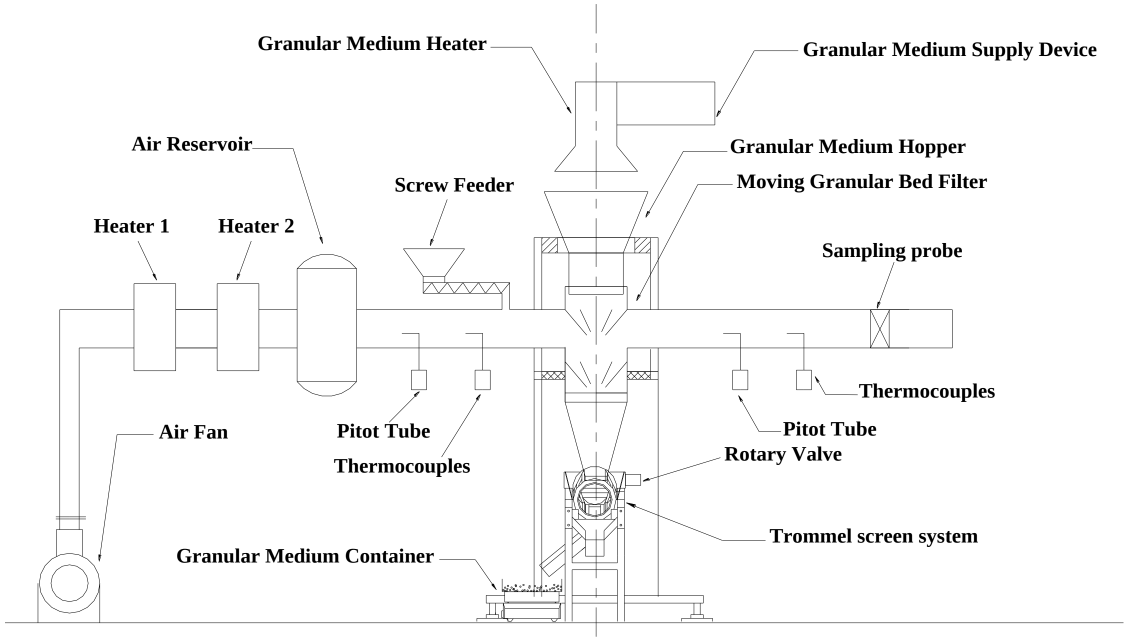


Fig. 1. Schematic diagram of the current experimental moving granular bed filter (MGBF) apparatus.

Fig. 2. Trommel screen system

In the MGBF, gas flowed horizontally from a dirty gas plenum through the vertically flowing filter granules, which intercepted the dust particulates, until finally exited the vessel and went into a clean gas plenum. Filter granules flowed downward through the system via a channel with louvers and sublouvers. The clean filter granules were turned into the filter granules with dust particulates due to the collection of dust particulates in the filter granules. Then, the filter granules with dust particulates discharged from the filter system were transported to the trommel screen system by means of the feeding hopper. The dust particulates were then separated to regenerate the filter granules. The mass flow rate of the filter granules was controlled by a rotary valve underneath the granular bed. The mass flow rates were 300 and 600 g/min, respectively.

Based on the quasi-2D design of Hsiau et al. [17], a modified granular bed filter was adopted for collecting dust particulates. Tests of the filtration of dust particulates using the cold model of moving granular bed technology was performed by Chen et al. [18]. This system was essentially the basis for developing the hot model of moving granular bed filter that has been commissioned for the present study. The filter bed had the following dimensions: 1070 mm in height, 380 mm in width and 200 mm in depth. The filtration superficial velocity during filtration was 35 cm/sec, which was controlled at the inlet of the filter system by an air fan. During the heating processes, the temperature of inlet gas was heated by the first- and second-stage gas heaters. The operation temperatures of inlet gas were 20, 100, 200, 300, 400, and 500℃, respectively. The screw feeder at the entrance to the inlet of filter system controls the flow rate of dust particulates. The dust concentration was 7500 ppmw (7.276 g/m^3). A sampling probe is installed at the outlet pipe to measure the dust mass behind the filter system. In this study, the outlet concentration of the filter system is determined with a real-time process particle counter (PPC). The PPC utilizes two monochromatic laser beams passing perpendicular to the gas stream to count the number and size of particles. A particle supply device continuously fed fresh and clean filter granules from the upper hopper to ensure that the amount of filter granules in the filter system remained the same.

2.2 Experimental procedure

Prior to the experiments, the particles and the inlet gas were heated. Then, the silica sand was placed in the granular bed. The mass flow rate of filter granules was measured by collecting the discharged filter granules in a bucket and then weighing them with an electronic balance. In this study, to simplify the experimental set-up, the silica sand was not reused; instead, fresh silica sand was continuously fed from the upper hopper so that the same amount was maintained in the bed. The test procedure could be divided into two stages, namely the fixed-bed mode and the moving-bed mode.

Using the silica sand supply device, clean filter granules were continuously fed into the filter system. Dust-laden gas was filtered from the inlet feed pipe to the outlet of the filter system where the gas passed through to the outlet pipe, and the dust particulates remained on the filter granules. The filter system offers a reasonable resistance to the flow of gas and dust particulates, having to work with different filtration conditions. In the fixed-bed filter, an air fan and a screw feeder were used to mix the gas and the dust particulates, which entered the filter bed through the inlet feed pipe. More and more dust particulates became trapped by the filter granules. After the depth filtration process, a dust cake built up along the surface of the filter granules at the inlet of the filter system (surface filtration), with relatively little dust penetrating the granules themselves. When the achievement stage of cake formation finished, the device was switched from the fixed-bed mode to moving-bed mode. In the moving-bed mode, the mass flow rate of the filter granules was controlled by a rotary valve. The outlet dust concentration was simultaneously measured by the sampling probe. The collection efficiency can be calculated using Eq. (1) from the dust concentrations at the inlet and outlet of filter system.

The performance of particulate filters is often expressed in terms of particulate collection efficiency η

$$\eta = 1 - \frac{C_{out}}{C_{in}}, \qquad (1)$$

where C_{in} and C_{out} are the dust concentrations at the inlet and outlet of the granular bed filter, respectively.

In this study, the dust particulates follow the curvilinear path of gas motion and tend to move along the gas streamlines until deposited on the filter granules. The collection mechanisms considered include inertial impaction and diffusion.

3. Results and discussion

3.1 Collection efficiency of dust particulates under various mass flow rates

To understand the mechanisms of the moving granular bed filter (MGBF) in removing dust particulates through the relationship between mass flow rates of filter granules and collection efficiency, the collection mechanisms of filter system, including inertial impaction and diffusion, were considered. Figure 3 shows the variation of the collection efficiency with different mass flow rates of filter granules, but at the fixed filtration superficial velocity of 35 cm/sec and temperature of 500℃. It can be seen that as the filtration time increased, the amount of dust particulates accumulated in the filter bed also increased, and hence so did the collection efficiency. This phenomenon held true for different mass flow rates. The higher mass flow rate led to more dust particulates being attached to the filter granules leaving the moving granular bed filter, because the effect of inertial impaction and diffusion was higher. Thus, a higher mass flow rate of filter granules led to better dust particulate capture efficiency. According to Ghadiri et al. [19], a reduction in the collection efficiency would occur if fewer dust particulates were retained in the filter system. Since the overall porosity of filter granules was higher with higher mass flow rate, it was relatively easy for the flue gas to pass through the filter granules to the outlet of the filter system. Thus, it is found that the outlet dust concentration would be higher if the mass flow was too high. The best filtration performance was not obtained.

On the other hand, in the granular bed using a lower mass flow rate, part of dust particulates did not pass through the dust cake to the filter granules, which caused the dust packing on the inlet of filter system. Hence, in this work, although the test showed that using a lower mass flow rate led to a lower dust concentration in the outlet of the filter system, the dust particulates were still not fully removed by the filter granules. Moreover, when the filtration time exceeded 90 min, because of the higher kinetic energy of gas with the dust particulates, it was relatively easier for the dust particulates to pass through the dust cake and the filter granules, to reach the outlet pipe, causing decreased collection efficiency. Besides, in this work, the collection mechanisms of inertial impaction and diffusion had an insignificant influence on the collection efficiency. In this study, the experimental results showed that the collection efficiency was better when the mass flow rate of filter granules was 600 g/min.

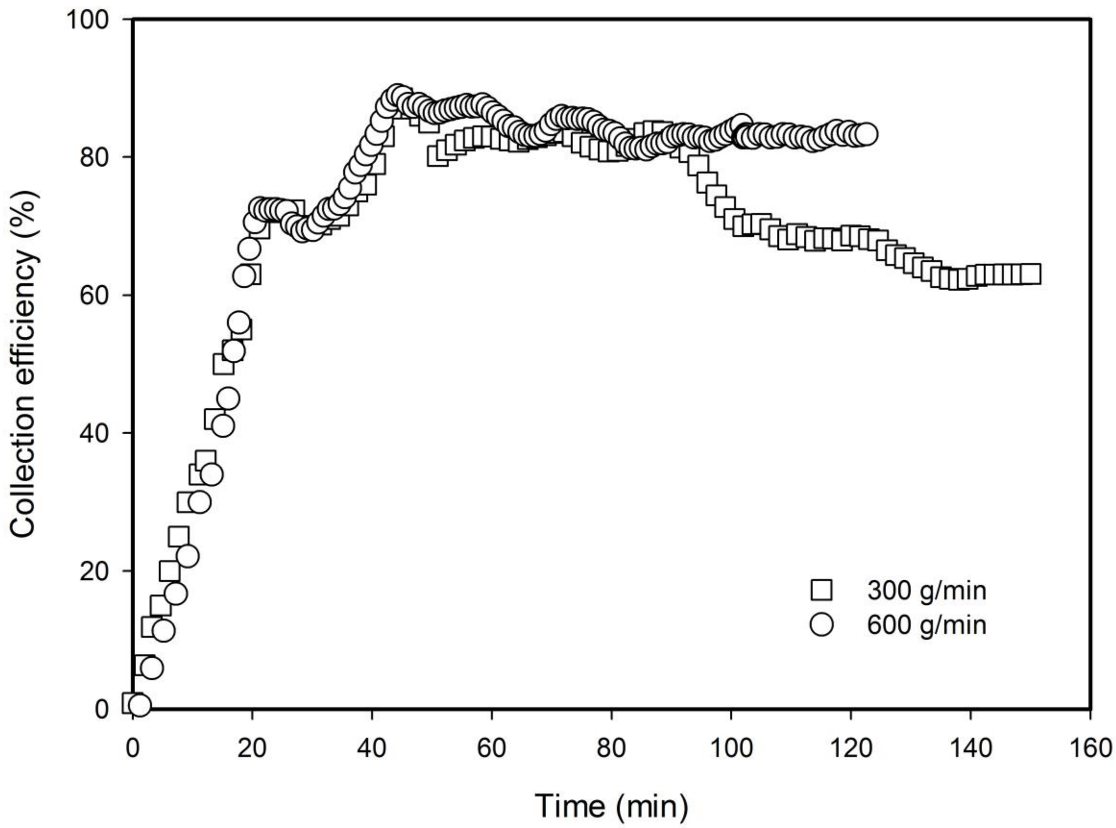


Fig. 3. Variation of the collection efficiency with filtration time for different mass flow rates of 300 and 600 g/min, with the fixed filtration superficial velocity of 35 g/min and room temperature of 500 ℃.

3.2 Collection efficiency of dust particulates under various operation temperatures

For the tests of the overall collection efficiency, the feeding rate was held constant for different runs, so a steady inlet concentration was achieved. The inlet concentration was derived from the air flow rate and the feeding rate of the dust particulates under temperature of 20, 100, 200, 300, 400, and 500℃, respectively. The outlet concentration was determined by sampling at the exit. Figure 4 presents the results of the test performance of the filter system, showing the variation in the collection efficiency with different operation temperatures and mass flow rate of filter granules, but using a fixed filtration superficial velocity of 35 cm/sec and dust concentration of 7500 ppmw (7.276

g/m^3). The collection efficiency decreased gradually as the bed temperature increased from 20 to 500℃. The experimental results showed that the overall porosity of the filter granules was smaller at lower temperature, leading to a higher filter resistance; hence, it resulted in the higher collection efficiency of the filter system in comparison, when the operation temperature was lower. When considering the influences of temperature, the viscosity of gas increases with higher temperature. Then, the Stokes' number of fly ash becomes smaller, so lower capture efficiency could be expected because of the inertial impaction caused by increasing viscosity. However, this trend does correspond to the results of Fig. 4.

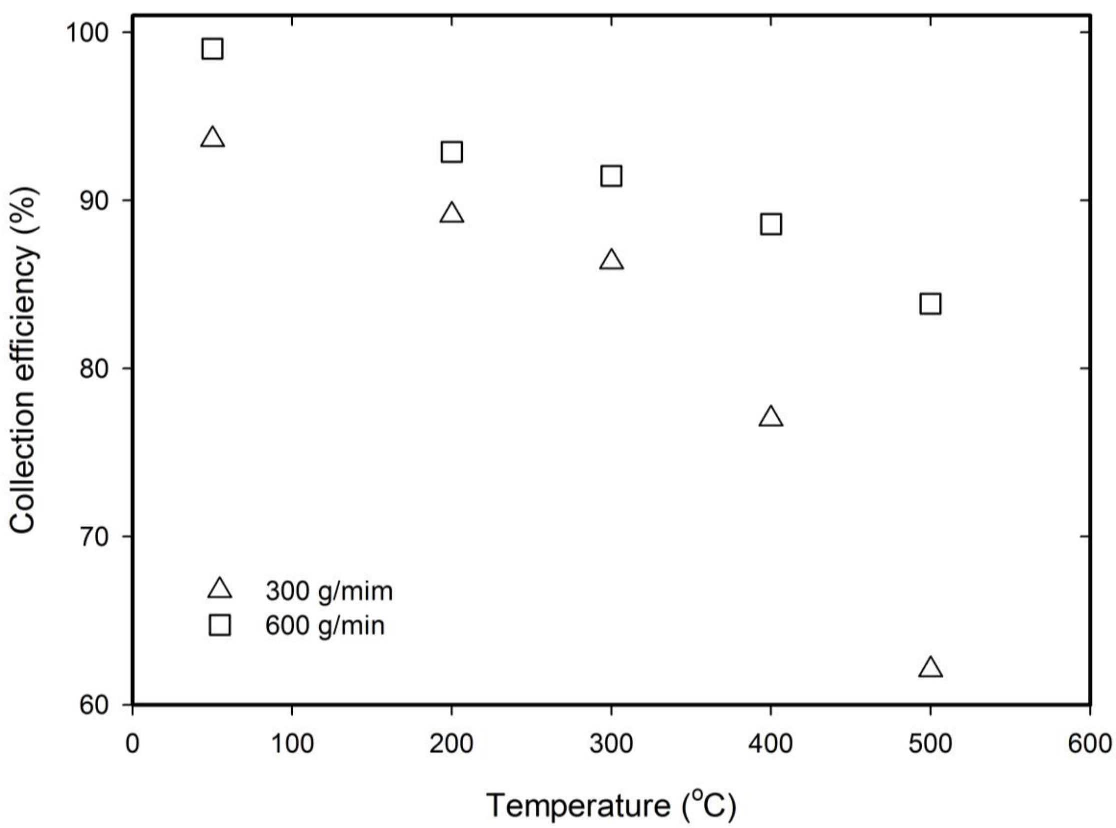
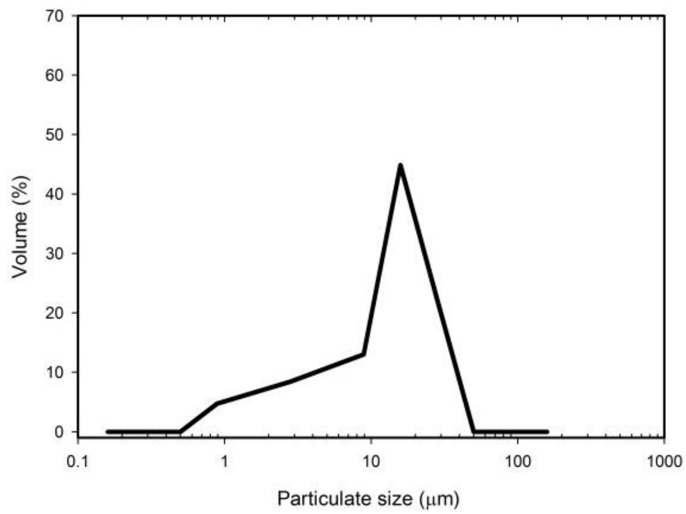


Fig. 4. Variation of the collection efficiency with different operation temperature and mass flow rate, with the fixed filtration superficial velocity of 35 cm/sec.

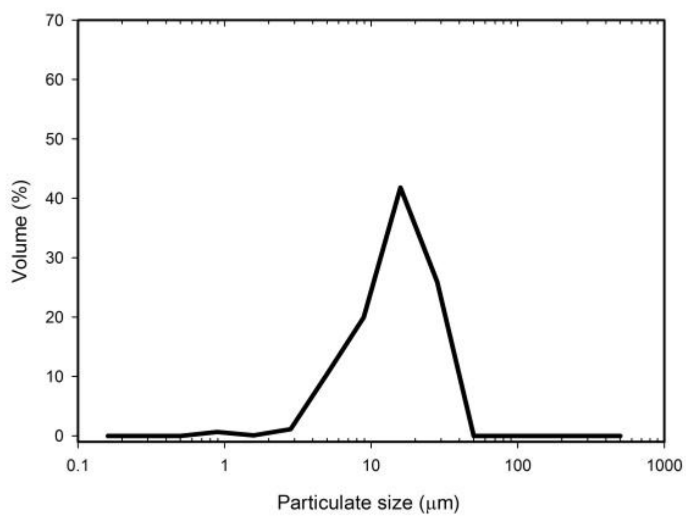
On the other hand, when temperature increases, the diffusion coefficient and viscosity increase, meaning that the diffusion could increase the collection efficiency of fly ash at high temperatures. Therefore, diffusion deposition would be one of the main mechanisms when MGBF is controlled at high temperature, especially for submicron particles. Nevertheless, the dominant mechanism for removal of fly ash at high temperatures would still be inertial impaction. This trend is consistent with our experimental results, especially for MGBF, of which the efficiency at high temperature could significantly decrease. In addition, for the mass flow rate of filter granules at 600 g/min, the collection efficiency decreased less noticeably than the counterpart with a lower mass flow rate of 300 g/min, when the temperature increased from 20 to 500℃. The outcome was due to the fact that the effects of inertial impaction and diffusion were relatively higher for the case with a higher mass flow rate of filter granules at 600 g/min.

3.3 Size distribution of dust particulate exiting the moving granular bed filter

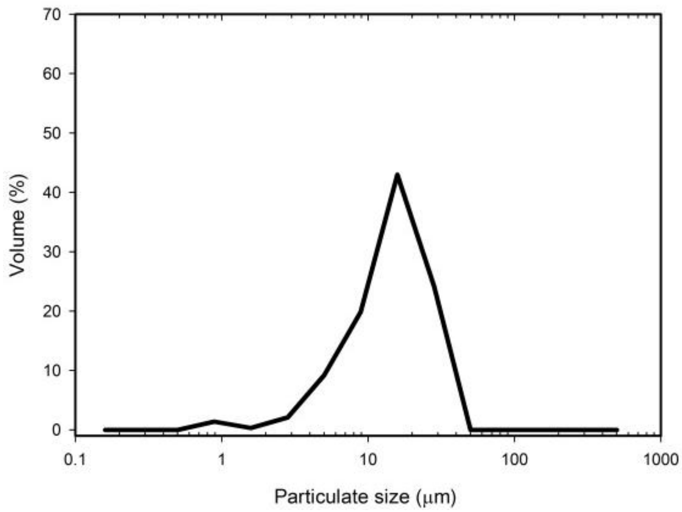
Figure 5 depicts a series of the size distribution of dust particulates collected from the outlet of the filter bed under various operating conditions, i.e., mass flow rates of 600 g/min, filtration superficial velocity of 35 cm/sec, and test temperatures of 20, 100, 200, 300, 400, and 500℃, respectively. The size distribution of these dust particulates exhibited similar characteristics with a Gaussian distribution. On the whole, the size distribution of dust particulates of all runs are smaller than that of dust particulates at inlet, which means that size distribution of dust particulates tends to finer particulates after flowing through the MGBF. When the operating temperature was increased, the overall porosity of the filter granules and diffusion coefficient were increased, meaning that the size distribution of dust particulates could be increased. Figure 6 shows the measurement results indicating variation of the mass median aerodynamic diameter of dust particulates with operation temperature for different mass flow rates of filter granules. The decrease of mass flow rate causes an increase in the size distribution of dust particulates. When the operation temperature was 500 ℃ and mass flow rate of 600 g/min, the mean diameter of dust particulates at the outlet (41.57 μm) was smaller than that at the mass flow rate of 300 g/min (43.5 μm), meaning that more larger-sized dust particulates were removed (i.e., removal effectiveness had increased). In the granular bed using a lower mass flow rate of filter granules, because of the relatively higher kinetic energy of gas with the dust particulates, part of larger-size dust particulates penetrated through the filter granules to the exhaust pipe of filter system, causing the higher size distribution of dust particulates during the collection process. The results indicate that the mean diameter of dust particulates at high temperature is larger than that at room temperature, which means that room temperature environment can enhance the removal of lager-size dust particulates. Consequently, in this work, the corresponding operation conditions at room temperature in the filter system caused the better collection efficiency and the smaller-sized distribution of dust particulates in the outlet of filter system.

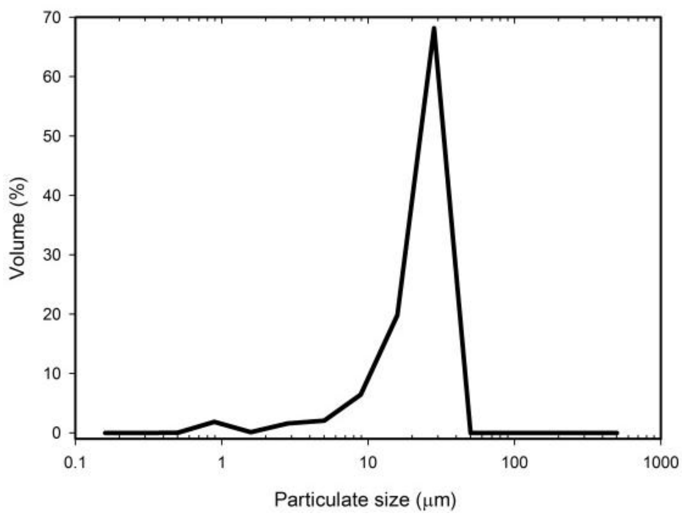


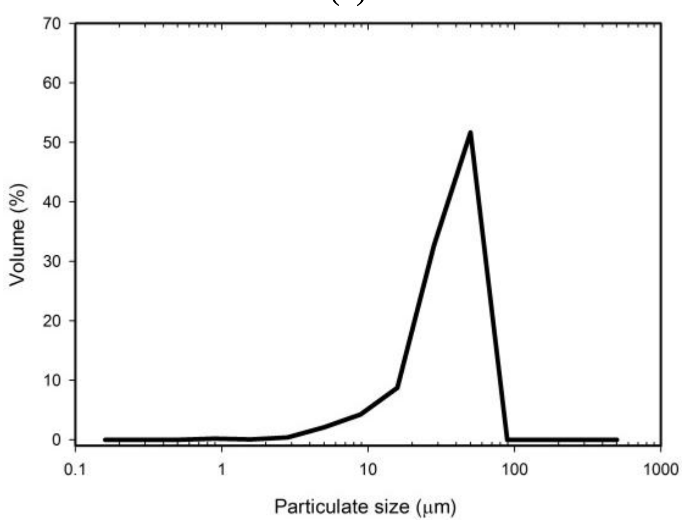
(a)

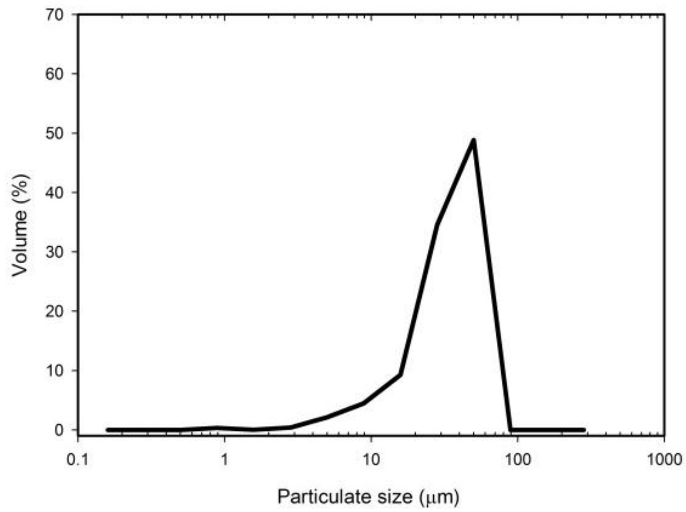


(b)


70
60
50
40
30
20
10
0
Volume (%)
0.1
1
10
100
1000
Particulate size (μm)
(c)


70
60
50
40
30
20
10
0
Volume (%)
0.1
1
10
100
1000
Particulate size (μm)
(d)


70
60
50
40
30
20
10
0
Volume (%)
0.1
1
10
100
1000
Particulate size (μm)
(e)



(f)

Fig. 5. Size distribution of the dust particulate exiting the moving granular bed filter bed for operation temperatures of: (a) 20 ℃, (b) 100 ℃, (c) 200 ℃, (d) 300 ℃, (e) 400 ℃, and (f) 500 ℃, with a fixed filtration superficial velocity of 35 cm/sec and mass flow rate of 600 g/min.

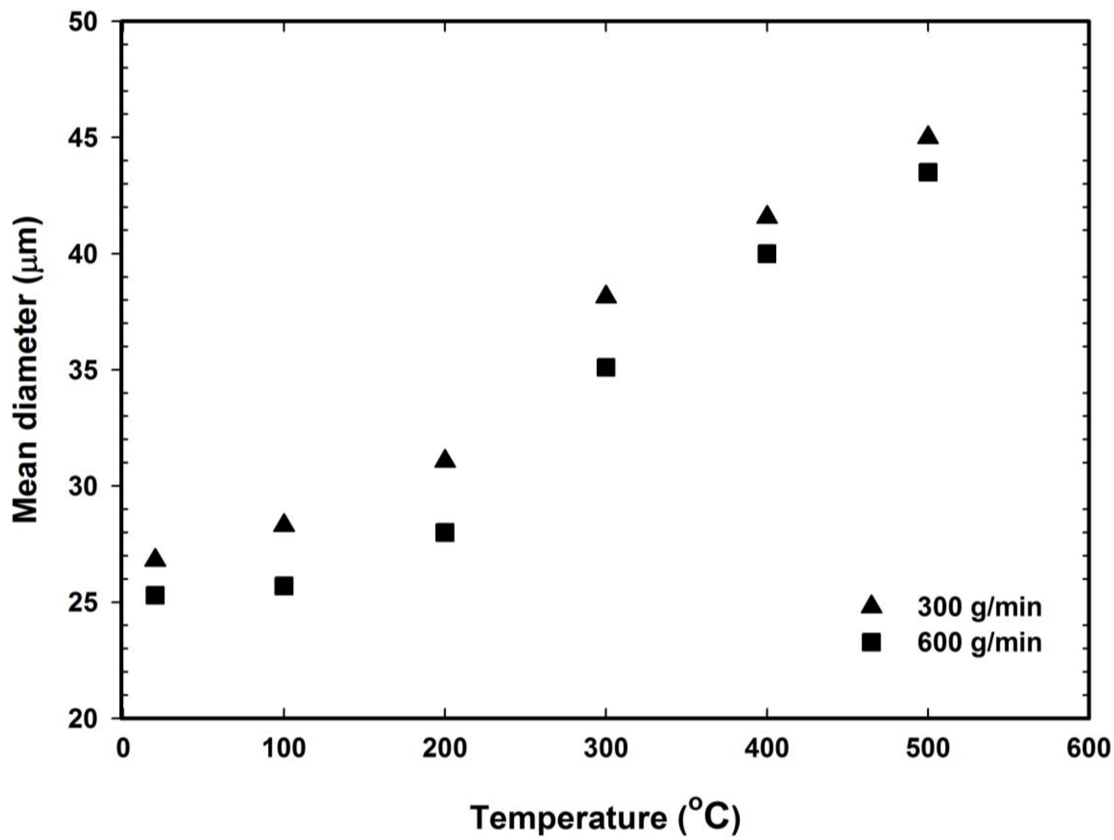


Fig. 6. Mean diameter of the dust particulate at outlet filter system under various operating conditions.

4. Conclusions

Tests with the hot model of moving granular bed filter (MGBF) designed in this study successfully achieve the required tasks. It is shown that the mass flow rate and the test temperature affected the removal efficiency of dust particulates. The results indicate that the highest collection efficiency and the smaller-sized distribution of dust particulates occurred when the mass flow rate was 600 g/min, and at room temperature. Based on the results, it is hoped that the design rules for a commercially viable moving granular bed filter can be developed. The current results are also very important to establish a database of operating parameters for a moving bed filter system. Furthermore, this is an important step towards the future development of a high-temperature gas clean-up system for advanced coal-fired power generation systems.

Acknowledgements

This study is part of the "Clean Carbon as Sustainable Energy (CaSE)" program, supported by the governmental R&D budget allocated to the Institute of Nuclear Energy Research (INER), under the framework of National Energy Program (NEP) of Taiwan, ROC.

References

[1] Y. Takashi, F. Shinji, M. Tomoaki, Application of the severity parameter for predicting viscosity during hydrothermal processing of dewatered sewage sludge for a commercial PFBC plant, Bioresource Technology 101 (2010) 2043-2045.

[2] J. Stringer, A.J. Leitch, Ceramic Candle Filter Performance at the Grimethorpe (UK) Pressurized Fluidized Bed Combustor, Journal of Engineering for Gas Turbines and Power 114 (1992) 371-379.

[3] L. Paretsky, L.Theodore, R. Pfeffer, A.M. Squires, Panel bed filters for simultaneous removal of fly and sulfur dioxide. Journal of Air Pollution Control Association 21 (1971) 204-209.

[4] A.C. Payatakes, C. Tien, R.M. Turian, A new model for granular porous media: Part I. Model formulation, AIChE Journal 19 (1973a) 58-67.

[5] A.C. Payatakes, C. Tien, R.M. Turian, A new model for granular porous media, Part

II. Numerical solution of steady state incompressible Newtonian flow through periodically constricted tubes. AIChE Journal 19(1973b) 67-76.

[6] C. Gutfinger, G. Tardos, Theoretical and experimental studies on granular bed filtration, Atmospheric Environment 13 (1979) 853-867.

[7] C. Tien, A. C. Payatakes,.Advances in deep filtration, AIChE Journal 25 (1979) 737-759.

[8] C. Gutfinger, D. Pnueli, M. Fichman, Effect of particle loading on granular bed filtration — extension of the CEF model to polydisperse systems, Journal of Aerosol Science 19 (1988) 443-450.

[9] R.C. Brown, H. Shi, G. Colver, S.-C. Soo, Similitude study of a moving bed granular filter, Powder Technology 138 (2003) 201-210.

[10] T.W. Kalinowski, D. Leith, Aerosoll filtration by a concurrent moving granular bed: penetration theory, Environmental Science and Technology 17 (1983) 20-26.

[11] Y. Otani, K. Miyajima, H. Emi, Collection performance of moving granular bed filters, Proceedings of the International Aerosol Conference 1990, p. 733.

[12] W.C. Yang, R.A. Newby, T.E. Lippert, D.L. Keaims, D.C. Cicero, Moving granular bed filter concept for particulate removal at high temperatures and high pressures, dagineering Foundation 1992, p. 703.

[13] C.A.P. Zevenhoven, Particle Charging and Granular Bed Filtration for High Temperature Application, Chemical Engineering, Delft University of Technology, Netherlands, 1992, p. 288.

[14] R.C. Brown, H. Shi, G. Colver, S. C. Soo, Similitude study of a moving bed granular filter, Powder Technology 138 (2003) 201–210.

[15] J.C. Bai, S.Y. Wu, A.S. Lee, C.Y. Chu, Filtration of dust in a circulating granular bed filter with conical louver plates (CGBF-CLPs), Journal of Hazardous Materials 142 (2007) 324-331.

[16] I.A. El-Hedok, L. Whitmer, R.C. Brown, The influence of granular flow rate on the performance of a moving bed granular filter, Powder Technology 214 (2011) 69-76.

[17] S.S Hsiau, J. Smid, S.A. Tsai, C.C. Tzeng, Y. J. Yu, Flow of filter granules in moving granular beds with louvers and sublouvers, Chemical Engineering and Processing 47 (2008) 2084-2097.

[18] Y. S. Chen, S.S. Hsiau, H.Y. Lee, Y. P. Chyou, Filtration of dust particulates using a new filter system with louvers and sublouvers, Fuel 99 (2012) 118-128.

[19] M. Ghadiri, J.P.K. Seville, R. Clift, Fluidized-bed filtration of gases at high-temperatures, Chemical Engineering Research & Design 71 (1993) 371-381.