Research Progress of the Control Technology of the PM_{10} from Combustion Sources

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Abstract: The particulate and combustion engineering (PACE) group is a vigorous research team dedicated to the study and application of the control technology of the PM_{10} from combustion sources in the Tsinghua University in china. Most of our recent work has been on the filtration and clean of the charged particles. First, different filters were tested systematically in various filtration conditions, including charging the particles as pretreatment. It was found that charged particles slowed the clogging and made increase rate of pressure drop larger than in neutralized cases and the penetration varied a lot. Second, direct observation of particle deposit on a single fiber was conducted to investigate the mechanism of the described phenomena. It was found that when the particles were charged, straight chains or chains with branches on which particles were evenly distributed were formed. Moreover, the discrete element method (DEM) based on JKR theory of adhesive elastic contacts, was used for three-dimensional simulations. A dimensionless adhesion parameter is defined and shown to have a dominant effect on the predicted particle deposition rate. Third, a continuous filtration bench was set up according to VDI 3926 to investigate the differences of cake detachment stresses between charged particle filtration and common filtration. The cake cleaning is carried out under a slowly increased reverse flow, when the overall pressure drop and cake detached is recorded. Primary results show that with the same filter, charged particle cake is harder to remove.

Keywords: PM_{10}, Filtration, Charged Particle, Dust cake, Single Fiber, cake detachment, reverse flow cleaning

1 INTRODUCTION

PM_{10} is one of the most important atmospheric pollutants in many Chinese cities, especially due to emission from combustion sources. Bag filter, which is known as “high efficiency” and “cleanable” filter, is widely used to remove the particulate matters from the flue gas. However, its high pressure drop and high sub-micron particle penetration prevent itself from meeting the increasingly strict emission standard. Some studies have introduced electrostatic effects to enhance the performance of the bag filter. Charged enhanced filtration is a key technology [1]. As there is the Coulomb force between the charged particles, the deposition mechanism of the charged particles in the filter is far different from the uncharged particles. Moreover, the formation and the detachment of the surface cake have also different characteristics.

The research activities in the particulate and combustion engineering (PACE) group are presented here. Fig. 1 summarizes the work. The paper is organized as follows. Section 2 presents the experimental results of the filter filtration[2]. In Section 3, the results of the single fiber filtration experiment and the discrete element method (DEM) simulation are described[3, 4]. Section 4 presents the cake detachment experiment[5]. Section 5 gives the conclusions.

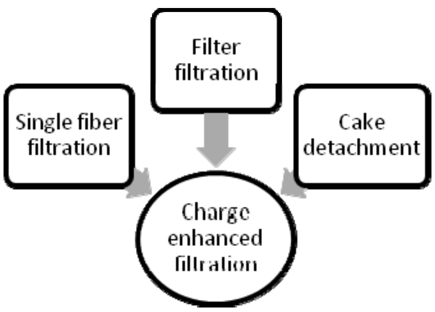

Fig. 1 Filtration research in PACE

2 FILTER FILTRATION EXPERIMENT

A novel experimental setup (Fig. 2) was developed to perform in situ monitoring of pressure drop, aerosol concentration and diameter distribution[2]. In the experiment, different filters were tested systematically in the laboratory in various filtration conditions, including charging the particles as pretreatment.

The test aerosol particle is a kind of Si bead (Fig. 3(a)). The Si bead particles are generated by a rotary brush generator (PALAS RGB2000) with a clean compressed air. Filtration velocity is kept between 2.40 m/min and 2.52 m/min by a mass flow controller. Two filter media, Polypropylene fibrous media A and membrane filter QR 033, are tested. And their SEMs are shown in Fig. 3(b), 3(c).

There are two cases for both A and QR033 filter: the high DC generator charges particles or not. Fig. 4 shows the pressure drop evolutions in all four cases. OnA and OnQR represent the cases that the A and QR033 media filtrate charged particles, respectively, and OffA and OffQR refers to the case that the A and QR media filtrate for uncharged particles. For the fibrous filter media A, there is a few minutes deep filtration first, and then the increase becomes markedly linear. For membrane fibrous media QR033, it is not obvious for the slow increase firstly and gets the markedly linear increase step directly. Fig. 5 are the final surface pattern photoes from the laser displacement sensor (Model LK-081/2101, Keyence, Osaka, Japan) monitoring continuously. These results indicate that there are not cake formed on the surface for fibrous filter media A and the two cases of the QR033 filter begin cake filtration directly. The slope of the OffQR curve is 53 Pa/g m^2 while the OnQR curve 29 Pa/g m^2. It indicates that electrostatics optimizes cake structure to have a lower pressure drop increase.

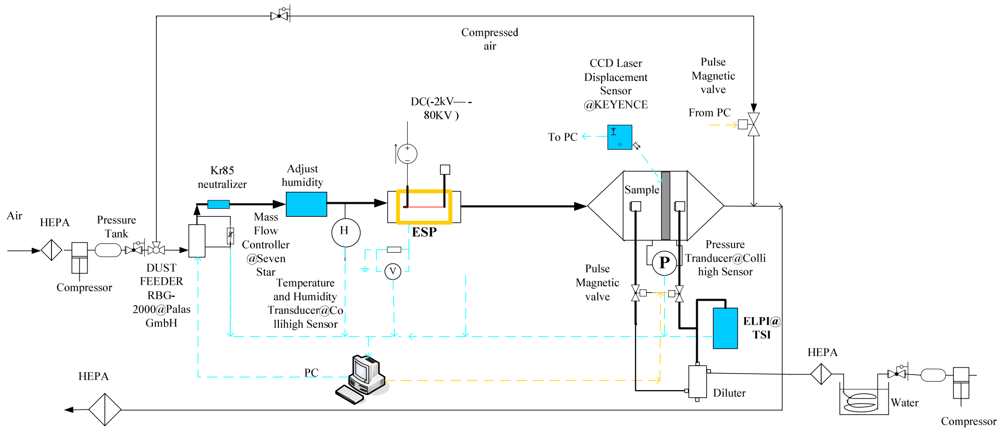

Fig. 2 Filter filtration experimental setup.

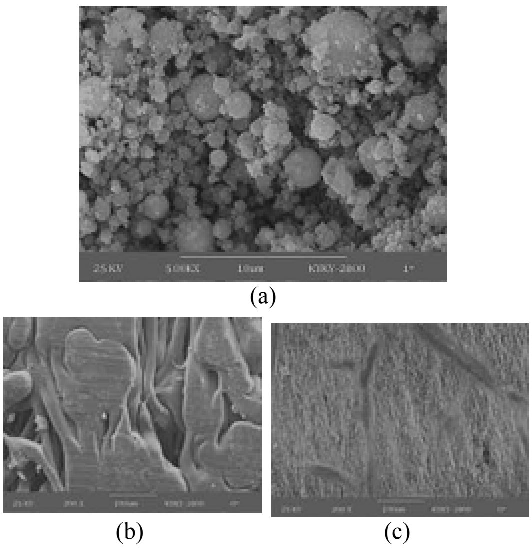

Fig. 3 The Si bead particles and the fibrous filters: (a) The scan electron micrograph of the particles; (b) Polypropylene fibrous filter media A; (c) Membrane fibrous filter media QR033

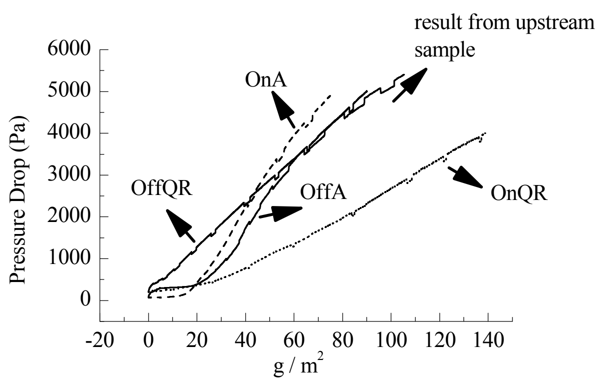

Fig. 4 Pressure drop change curve with mass loading for the four test cases

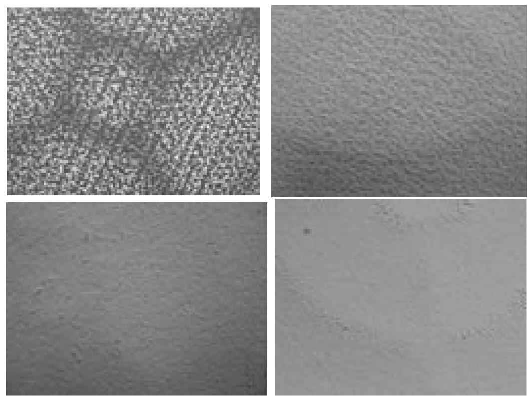

Fig. 5 The photos of the final surface pattern for the four cases (from left to right): OffA case, OnA case, OffQR case and OnQR case

3 SINGLE FIBER FILTRATION EXPERIMENT AND SIMULATION

3.1 Experiment

The experimental setup in Fig. 1 is modified by using a square flow tube (Fig. 6) to replace the filter part. Two sheets of aluminum foil were pasted on the inside walls of the tube as electrodes. A single fiber was fixed across the tube 100 mm beyond the electrodes. A CCD camera (PL-A662, Pixe Like capture, China) was mounted on a 200× microscope (ECLIPSE E600 POL, Nikon, Japan) to observe the process. Two kinds of fly ash particles from a power plant (P1, P2) and two kinds of ceramic particles (P4, P5) were used in the experiment. The P1 and P2 are mainly spherical particles, while the P4 and P5 are highly irregular and flake-like. They are 1.43, 1.72, 1.37, 1.47 μm in VMD and 5.1, 6.1, 4.1, 5.6 μm in standard deviation, respectively. The fiber is a commercial Polypropylene fiber with a 20 μm diameter.

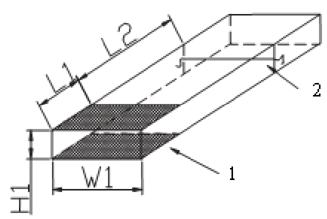

Fig. 6 The square flow tunnel to install a fiber to capture the particles: 1—aluminum foil, 2—fiber

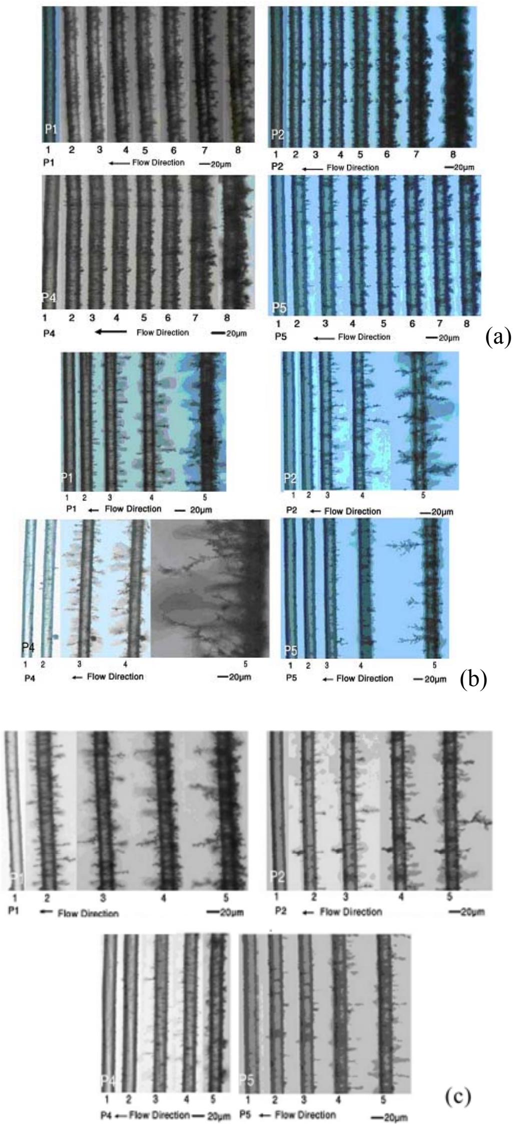

Fig. 7 The photos of the single fiber filtration: (a) the tribocharged particles; (b) the polarized particles; (c) the precharged particles

From the results, the following conclusions can be obtained[3]:

1) The chains formed by the polarized and precharged particles were straight and were dendrites in the tribocharged case. The straight chains in the prepolarized case had uniform space between the chains. But small branches formed on straight chains after chains grew to some length in the precharged case.

2) In prepolarized case, the capturing process had two clear stages: straight chains growth and falling over. The fallen over chains still remained a high capturing ability. In precharged case, the capturing process also had growth phenomena including branch formation, falling over, breakage and collapse. In the tribocharged case, the capturing process had three distinct stages: captured by the fiber only, captured both by fiber and dendrites, captured by the dendrites only.

The pre-treatment conditions, particle shapes and particle diameters affected the chain binding intensity on the fiber for the prepolarized particles. The chains were more intense in the prepolarized case than in the parcharged case. In the prepolarized case, the larger spherical fly ash particles produced higher chain binding intensity than the smaller particles. However, for the irregular ceramic particles, the effect of particle diameter was opposite to that of the spherical particles. In the precharged case, for both the spherical fly ash particles and the irregular ceramic particles, the larger particles were, the higher the chain binding intensity was.

3.2 Discrete Element Method Simulation

To study the mechanism of the single fiber filtration, the discrete element method (DEM), based on JKR theory of adhesive elastic contacts, is used for three-dimensional simulations of micro-particle deposition and aggregation on an individual fiber of an array[4]. The fluid flow domain consists of a two-dimensional periodic array of cylindrical fibers (Fig. 8(a)), with *x*-coordinate in the streamwise direction and *y*-coordinate in the cross-stream direction. And the simulation of particle dynamics is performed on a three-dimensional rectangular domain with a fiber located at the center, as shown in Fig. 8(b).

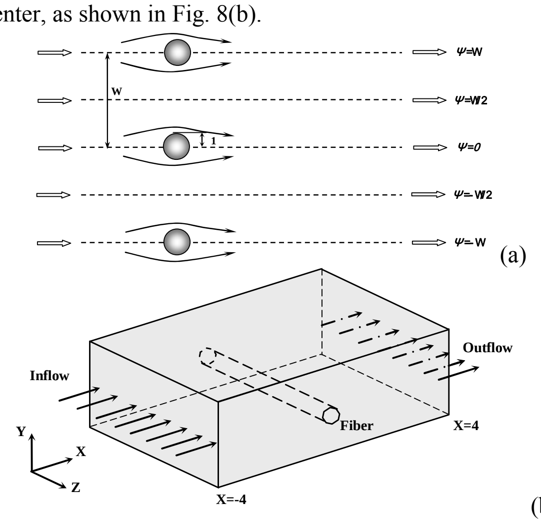

Fig. 8 Schematic of flow configuration: (a) domain of fluid simulation; (b) domain of particle simulation

Fig. 9 illustrate particle build-up on the front face of a fiber in the *X*-*Y* and *X*-*Z* views, respectively. The Fig. 9 show only particles in a slice of width 0.2 about the $Z = 0$ plane (in Fig. 9(a), 9(b)) or the $Y = 0$ plane (in Fig. 9(c), 9(d)), where the slice thickness is twice the particle diameter. Both figures show results from two calculations, one with $W = 4$ and the other with $W = 8$, and both cases have $\mathrm{Re}_F = 0.178$, $St = 0.21$ and $\phi = 1000$. The upstream particle concentration is set to $c_0 \equiv 0.0044$ for both cases by adjusting the particle injection rate at the inlet boundary in proportion to the area of the inlet plane. Compared with the *W=8* case, the more compact fiber array with $W = 4$ significantly accelerates the particle deposit rate for an identical inlet particle concentration. This occurs because the $W = 4$ array has lower permeability than arrays with a larger value of *W*.

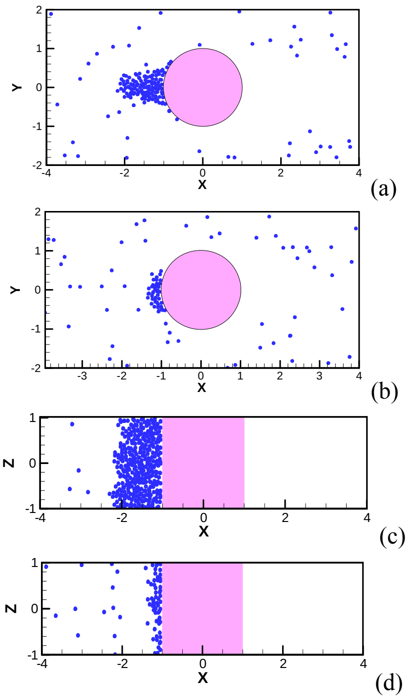

Fig. 9 View of particle deposition on a fiber (T=500), for (a, c) W=4.0 and (b, d) W=8.0

The maximum length of the captured particle dendrites attached to the fiber can be used as a key parameter that connects simulated results and experiments. A comparison between the experimental data for particle dendrite length and the DEM predictions under conditions of $\phi = 1000$, $U_0 = 0.26$ m/s and $W = 8$ is shown in Fig. 10.

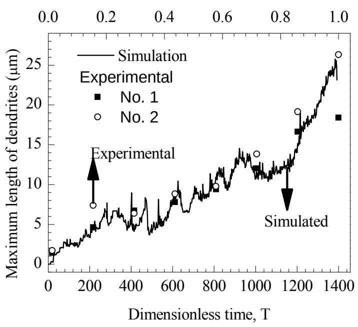

Fig. 10 Qualitative comparison between the DEM predictions (line) and scaled experimental data (symbols)

4 CAKE DETACHMENT EXPERIMENT

Experiments were conducted to calculate cake detachment stress in both cake filtration and electrostatic enhanced cake filtration[5]. Generally, two methods were used to measure cake detachment stresses, including reverse flow and acceleration[6]. It is concluded that cakes formed with finer particles and higher filtration velocity will need higher stress to be successfully detached[6,7]. However, very few experiments were reported to analyze how the force varied when the cake was formed by charged particles[8]. So a bench for continuous charged particle filtration with online reverse pulse-jet cleaning was set up according to VDI 3926, adding a line-plate particle charging section just before the fabric filtration. The system was also modified to conduct reverse flow detachment stress test conveniently. The whole system is shown in Fig. 11 and operation parameters in Table 1.

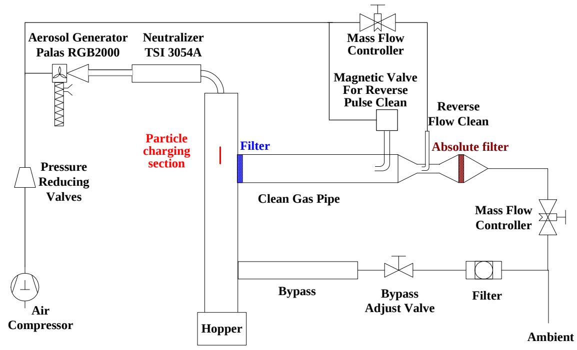

Fig. 11 The schematic of experiment set-up

To find the influence of charged particle on the filter online cleaning and followed filtration, two new filters were used to conduct common filtration and charged particle filtration respectively. After pulse-jet cleaning the filter for the 4th time, the filtration cake formed in followed filtration was used to measure the cake detachment stress. An extra cake was formed on the charged particle filtration filter after it was cleaned and halted 24hrs to discharge, and the cake was detached to see the detachment stress difference of the cake structure only on the nearly same filter surface condition. Cake detachment test results are shown in Fig. 12 and the cake properties formed in the two filtrations are listed in Table 2.

Table 1 Operation parameters of common and charged particle continuous filtration

	Common Filtration	Charged particle filtration
Filter	membraned terylene fibrous filter	
Particle	selected fly ash, $d_{0.5}{}^3$= 3.31 □m, σ= 2.55	
Filtration velocity	1.125m/min	
Particle concertrationa	4.86g/m^{3*}	19.5g/m^3 (before ESP)*
Pulse-Jet cleaning	triggered at 1000Pa, pressure 5 bar, pulse duration 80ms	
ESP line-plate distance	55.5mm	
ESP Charge Voltage	-	-14 ~ -16 kV
ESP current	-	1 ~ 2 mA
ESP efficiency	-	~ 90%**

*Particle concentration was calculated from feed rate and air flow.
**ESP efficiency was estimated from the pressure drop increasing rate compared with common filtration.

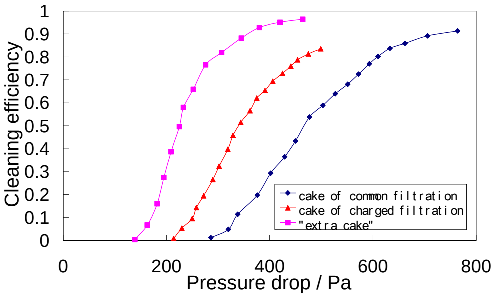

Fig. 12 Detachment stresses of different filtration formed cakes

From Fig. 12 it was found that cake formed in common filtration needed higher detachment stresses to clean. However, if the surface status was the same, as a result of comparing the "extra cake", that is cake formed with uncharged particles on the cleaned filter performed charged particle filtration as mentioned in measurement introduction, with the charged particle formed cake, the charged particle formed cakes needed higher detachment stress. After examining the filter after clean, it was found that the filter conducted common filtration has a rougher surface, as more particles has penetrated into the filter, which might be caused of the high particle concentration at cleaning. If the surface was the same, charged particles form a much loose structure as listed in Table 2, and in the detachment test, the detachment was harder to extend as much smaller fragments are formed in the cleaning, which can also seen from the cleaning pictures.

Table 2 Cake structure properties formed in different filtrations

	Common Filtration	Particle charged filtration
Cake weight	3.4 g	3.1 g
Cake load	192 g/m^2	175 g/m^2
Cake pressure drop	900 Pa	900 Pa
Cake thickness	380 mm	460 mm-480 mm
Cake porosity	0.80	0.85

5 CONCLUSIONS

PACE group in Tsinghua University has done a lot of research on the filtration. Especially, the electrostatic effects on particle filtration and on cake detachment have been investigated. It is found that the electrostatics makes it easier to clog for fibrous filter media and has a more quick pressure drop increase. The electrostatic positive effect for filter filtration is to form looser cake which decreases the increase rate of pressure drop increase and enhances initial filtration efficiency. But for the fibrous filter, the electrostatics has much negative affection on pressure drop and efficiency. The electrostatics has also strong effect on the particles deposition on the fiber. The chains are straight when the particles are polarized or precharged. For the same filter, charged particles form a much loose structure, but the detachment was harder to extend as much smaller fragments are formed.

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REFERENCES

1. Bin Huang. Study on the effect of electrostatics in fibrous filtration of PM10, PhD dissertation, Tsinghua University, 2005.
2. Bin, H., Qiang, Y., Hai-wei, X., Zheng-wei, L., and Shui-qing, L. Evolutions of Pressure-drop and Penetration for Pre-charging and neutral Particles on Fibrous and Membrane Filter. International Conference & Exhibition for Filtration and Separation Technology, Wiesbaden-Germany, 2005. 45-50.
3. Bin Huang, Qiang Yao, Shui-Qing Li, Hai-LiangZhao, Qiang Song and Chang-Fu You. Experimental Investigation on the Particle capture by a Single Fiber using Microscopic Image. Powder technology Technique, 2006, 163: 125-133.
4. S. Q. Li, J. S. Marshall. Discrete-element Simulation of Micro-particle Deposition on a Cylindrical Fiber in an Array, Journal of Aerosol Science, 2007, 38: 1031-1046.
5. Xu Haiwei, Xiong Gang and Yao Qiang. Experimental study of cake detachment in cake filtration and electrostatic enhanced cake filtration, World Filtration Congress/ Exhibition, April, 15-18, 2008.
6. D. Koch, J. Seville, R. Clift. Dust cake detachment from gas filters. Powder Technology, 1996, 86(1): 21-29.
7. C.R.N. Silva, V.S. Negrini, M.L. Aguiar, J.R. Coury. Influence of gas velocity on cake formation and detachment. Powder Technology, 1999, 101(2):165-172.
8. K. Morris and R.W.K. Allen, The influence of dust and gas properties on cake adhesion in fabric filters. Filtration and Separation (1996 (April)), 339–343.