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Classification of particles in particle-laden stream through a stainless steel fibrous filter

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Abstract−This investigation experimentally explores the penetration curve of particles shot onto a stainless steel fibrous filter or a flat surface. The effect of the pore size of the stainless steel fibrous filter, with or without an oil coating, on the particle penetration was examined at various flow rates, nozzle diameters and dimensionless particle diameters, Sqrt(Stk). The penetration of the flat surface by particles was also determined for comparison. Experimental results demonstrate that oleic acid particles larger than $Sqrt(Stk)_{50}$ are collected on the stainless steel fibrous filter with a low penetration, while smaller particles stay in the particle-laden stream with high penetration. The penetration of potassium chloride particles exceeds that of oleic acid particles, because potassium chloride particles bounce off the stainless steel fibrous filter and the flat surface. Particles bounce off the metal filter less easily than the flat surface. Coating the stainless steel fibrous filter with oil effectively reduces problems of particle bounce. The potassium chloride particles sucked the coated oil forming a small mountain on the surface. When the loaded particle mass on the coated stainless steel fibrous filter ranges between 0.4 and 2.3 mg, $Sqrt(Stk)_{50}$ is a constant 0.35.

Key words: Classification, Penetration, Particle, Stainless Steel Fibrous Filter, Particle-laden Stream

INTRODUCTION

Particulate matter has caused several environmental and health problems in recent years. Small particles can penetrate the human pulmonary system and induce respiratory diseases such as bronchitis, emphysema and lung cancer. Furthermore, small particles remain in the atmosphere for a period scattering and dissipating sunlight [1]. Accordingly, the removal of particulate matter from a gas stream from either industrial or mobile sources is very important [2]. Stainless steel fibrous filters have been adopted to separate particulate matter from a particle-laden stream. The particles can be removed by passing a particle-laden stream through the stainless steel fibrous filter [3], or shooting the particle-laden stream onto a stainless steel fibrous filter from a circular jet [4,5].

Heikkinen and Harley [3] experimentally studied the particle penetration characteristics of a stainless steel fibrous filter. The results revealed that stainless steel fibrous filters are useful in the size-selective filtration of particles. Stainless steel fibrous filters have high mechanical strength and chemical stability; they are cleanable, reusable and electrically conductive [3,5,6]. They have the advantage of being usable in separating particles at high temperature or in corrosive environments [7]. The stainless steel fibrous filter is also employed in many industrial applications, including retaining catalysts and chemical and high-temperature gas purification [6,8,9]. Tribolet and Kiwi-Minsker [6] proposed the use of sintered metallic filters as catalysts and supports for the growth of carbon nanofibers. Their results demonstrated that the metallic filters had uniform size on the micron-scale, large permeability and excellent filtrating characteristics with a low pressure drop during the operation of a reactor. The high thermo-conductivity of the stainless steel fibrous filter is helpful in catalytic applications.

A particle classifier with a collection plate was applied to determine the size distribution of particles in the particle-laden stream [10]. However, a solid particle may bounce off from the collection surface leading to a change of particle size distribution [11]. The application of an oil-coated stainless filter into classifying particles from a particle-laden stream has been investigated [12,13]. Their results indicated that the use of a sintered stainless steel substrate impregnated with oil could prevent particle bounce. The effect of the pore size of the stainless steel fibrous filter on the particle penetration was not reviewed. Recently, the effect of porosity and surface roughness of an uncoated stainless steel fibrous filter on the particle collection efficiency has been experimentally investigated by using liquid particles. The results indicate that larger pores and rougher stainless steel fibrous filters are associated with smaller cut-points and less sharp collection efficiency curves [5]. The influence of the loaded particle mass on the stainless steel fibrous filter on the penetration of solid particles has hitherto been ignored. When the particles in a particle-laden stream are loaded on the filter fibers, the filter structure might be changed [14]. Consequently, for a high particle loading of the stainless steel fibrous filter, the performances of the particle classifier need further investigating.

This work experimentally examines the penetration of particles fired onto a stainless steel fibrous filter or a flat surface from a circular jet. The effect of the pore size of the stainless steel fibrous filter on the penetration of particles was studied at various flow rates, nozzle diameters and Reynolds numbers. Additionally, the use of a coated stainless steel fibrous filter with various pore sizes was established to prevent particle bounce. Finally, the penetration of a coated flat surface and a stainless steel fibrous filter with various loaded particle masses was examined.

EXPERIMENTAL

This investigation experimentally determines the classification

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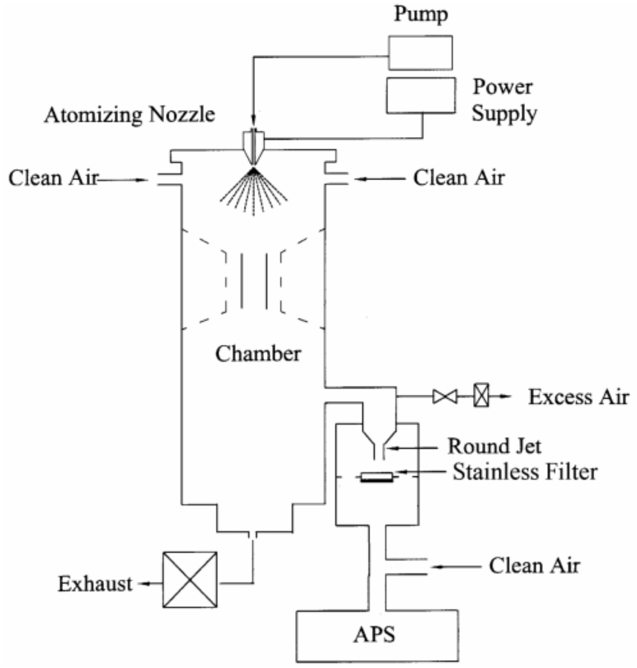

Fig. 1. Experimental setup for particles impinging on a stainless steel fibrous filter.

of particles in a particle-laden stream that discharges on a stainless steel fibrous filter or a flat surface. Fig. 1 schematically depicts the experimental setup. Both oleic acid and potassium chloride particles with the diameter ranging from 1 to 10 μm were generated by using an ultrasonic atomizing nozzle (Ultrasonic nozzle, Model 8700, Sono-Tek Inc., NY, USA). The particles were dried by mixing with clean air and were further neutralized by utilizing a charge neutralizer. Potassium chloride particles were employed to test if particle bounce occurs on the stainless steel fibrous filter or the flat surface and whether the loaded particle mass on the coated surface affects the penetration of solid particles. The stainless steel fibrous filter was coated with a silicone oil of about 70 mg in mass for preventing particle bounce. Oleic acid particles were also tested as liquid particles for comparison. An aerodynamic particle sizer (APS, TSI Model 3310A) was utilized to measure the particle number concentrations at the inlet and outlet of a test sampler containing a circular jet and a stainless steel fibrous filter to determine the penetration of particles. The test chamber was made of acrylic material. The outside diameter is 40 cm and the total height is 230 cm. In the sampler, a particle-laden air is passed through a circular jet and directed against a stainless steel fibrous filter or a flat surface. Stainless steel fibrous filter made by Mott Metallurgical Corp. (Farmington, CT, USA) was 0.317 cm in thickness, 1.2 cm in diameter and 100, 40, 20 and 5 μm in pore size. The circular jet was 0.26 and 0.36 cm in diameter. Aluminum foil was also employed as a flat surface to compare the penetration of particles with the stainless steel fibrous filter. Particle wall loss in the inner wall of the test sampler was measured by using monodisperse oleic acid particles, and it was found to be less than 4%. Since particle wall loss is small, it is not expected to affect the penetration measurement.

The inlet particle concentration was measured as the particles passed through the jet, while the outlet particle concentration was measured after the stainless steel fibrous filter was put into the test sampler. The sampled inlet flow rate ranged from 1.5 to 2.5 L/min without the stainless steel fibrous filter being installed in the sampler first. An additional 2.5-3.5 L/min of clean air was added to make the total flow rate of 5.0 L/min for the APS. The outlet particle number concentration was determined by the APS when the stainless steel fibrous filter was put in place in the sampler by using the same sampling flow rate as the inlet concentration measurement. The duration of each sampling was maintained at 20 seconds, and a wait of 10 seconds was required before the downstream concentration was measured when the stainless steel fibrous filter was inserted. After the outlet concentration had been measured, the inlet concentration was measured again to check the steadiness of particle concentration. The steadiness of the generated particle concentration was found to be within 5%. One data point at a particular test condition and particle size is the average of six measurements. The penetration of particles was determined as the rates of the outlet particle concentration divided by the inlet particle concentration. Dimensionless parameters such as Stokes number, Stk, and Reynolds number, Re, were used to present the penetration of particles of the stainless steel fibrous filter at various conditions and were defined as:

$$\mathrm{Stk}=\rho_p \mathrm{C} dp^2 \mathrm{U}/9\mu \mathrm{D}_n \quad (1)$$

$$\mathrm{Re}=\rho \mathrm{U} \mathrm{D}_n/\mu \quad (2)$$

where ρ_p represents the particle density, dp is the particle diameter, C is the slip correction factor, ρ is the air density, U is the air velocity, μ is the air viscosity and D_n is the diameter of the circular jet. The square root of the Stokes number, Sqrt(Stk), represents the dimensionless particle diameter. $\mathrm{Sqrt(Stk)}_{50}$ is defined as the cut-point of the stainless steel fibrous filter as the penetration of particles is 0.5. In the loading test of potassium chloride particles, the loaded mass of particles, Lm, on the stainless steel fibrous filter was determined as:

$$\mathrm{Lm}=\sum_j^m \sum_i^n \mathrm{C}_{i,j}(1-\mathrm{P}_{i,j})\rho_p \pi dp_i^3/6 \quad (3)$$

where $C_{i,j}$ and $P_{i,j}$ is the particle number and penetration for the ith particle diameter and the jth minute, respectively.

THEORETICAL

To calculate the penetration of particles impinging onto a finite surface from a circular jet, a theoretical model originally developed by Huang [15] was used. In this model, the flow field was simulated by solving 2-D Navier-Stokes equations in cylindrical coordinates, and the fluid flow was assumed to be steady, incompressible and laminar. The air was assumed to be at 20 ℃ and 1 atm. After the flow field had been obtained, the particle motion equations were solved numerically to obtain the particle trajectories and the penetration curves. Other details of the theoretical model for particles impacted onto the finite surface can be found in Huang [15].

RESULTS AND DISCUSSION

1. Particle Penetration

Fig. 2 reveals the penetration of potassium chloride and oleic acid particles that impinge on the flat surface or the stainless steel fibrous

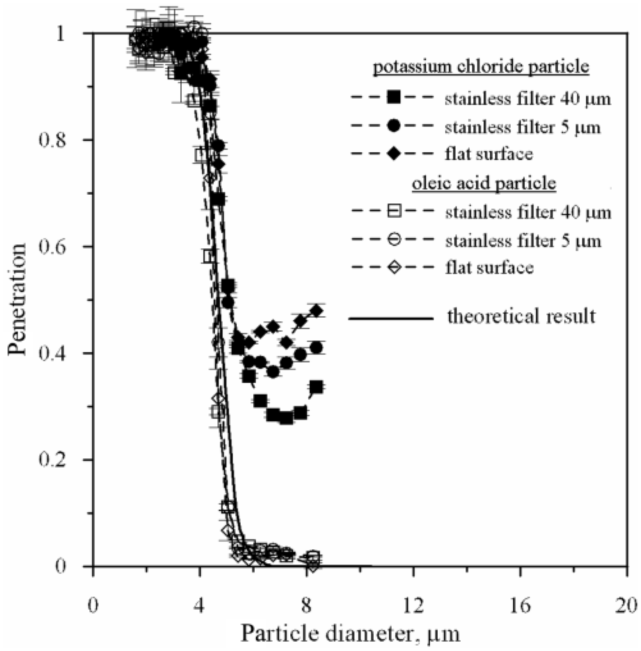

Fig. 2. Potassium chloride and oleic acid particle penetration for flat surface and stainless steel fibrous filters with nozzle diameter of 0.26 cm, flow rate of 1.5 L/min and Reynolds number of 811.

filters with various pore sizes for a nozzle diameter of 0.26 cm and flow rate of 1.5 L/min. For oleic acid particles, the larger particles deposited on the flat surface and the stainless steel fibrous filter resulting in a low penetration, while the smaller ones remained in the particle-laden stream with a high penetration. The figure also displays a comparison of the experimental data of the oleic acid particles with those from the theoretical model. The results show that the penetration of the oleic acid particles is close to the theoretical result. However, the figure indicates that the penetration of potassium chloride particles of the stainless steel fibrous filter or the flat surface was higher than that of oleic acid particles for larger particles. For example, for the stainless steel fibrous filter of 5 μm pore size, when the particle diameter was increased from 4.7 μm to 7.2 μm, the penetration of potassium chloride particles dropped from 0.79 to 0.38, whereas it fell from 0.42 to 0.02 for oleic acid particles. This phenomenon can be explained by the bounce off of potassium chloride particles from the stainless steel fibrous filter or flat surface, which leads to a higher particle penetration than that of oleic acid particles [11]. As particles were smaller than 4 μm, the penetration of potassium chloride particles was close to that of oleic acid particles. The figure also shows the penetration of potassium chloride particles of the stainless steel fibrous filter was different from that of the flat surface. In addition, the penetration of potassium chloride particles of the stainless steel fibrous filter with a pore size of 5 μm was higher than that of 40 μm pore size. It is probably because the larger pore size and increased roughness of the stainless steel fibrous filter, compared with the flat surface, may elevate the difficulty in the particle penetration for potassium chloride particles.

2. Effect of Pore Size

The influence of the pore size of the stainless steel fibrous filter

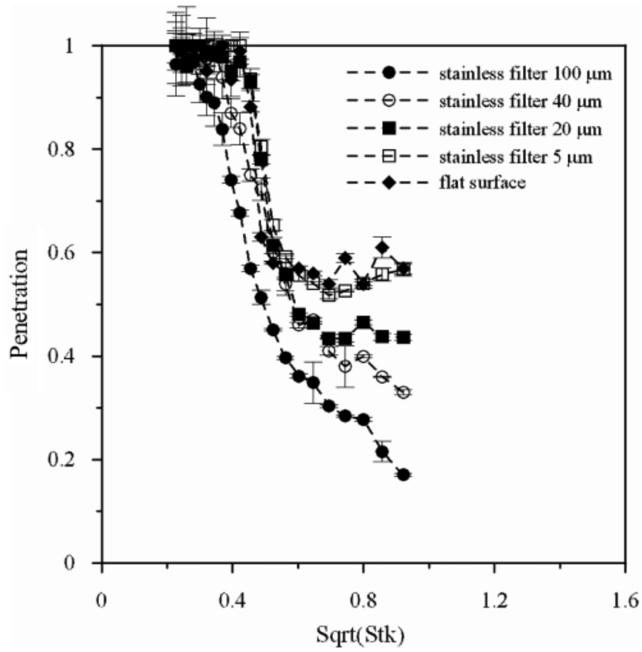

Fig. 3. Influence of pore size on potassium chloride particle penetration at flow rate of 2.5 L/min, nozzle diameter of 0.26 cm and Reynolds number of 1353.

on the penetration of potassium chloride particles is shown in Fig. 3 for a flow rate of 2.5 L/min, nozzle diameter of 0.26 cm and Reynolds number of 1353. The figure demonstrates that the penetration of potassium chloride particles of the stainless steel fibrous filter was lower than that of the flat surface because the former exhibited less particle bouncy characteristics than those of the latter. Moreover, the particle penetration dropped with an increasing pore size for

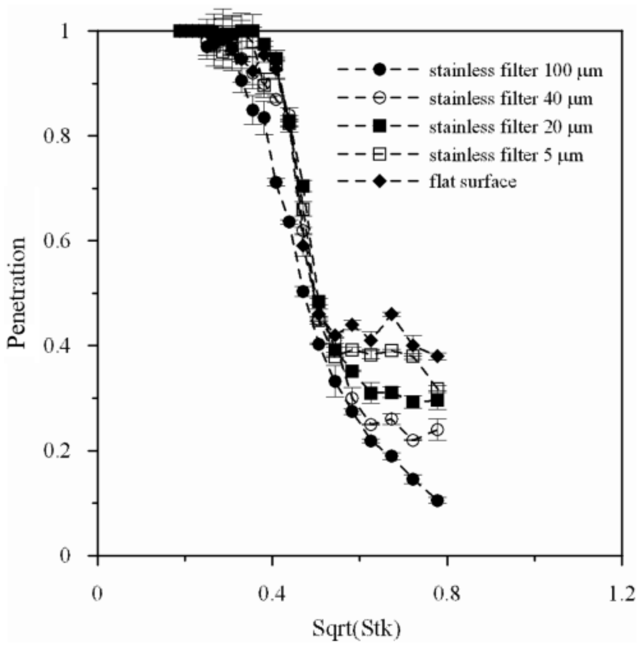

Fig. 4. Influence of pore size on potassium chloride particle penetration at flow rate of 2.0 L/min, nozzle diameter of 0.36 cm and Reynolds number=782.

the stainless steel fibrous filter. The larger pore structure of the stainless steel fibrous filter may reduce some of particle bounce problems and therefore increase the collection efficiency of the potassium chloride particles. Compared to the flat surface, the penetration of potassium chloride particles of the stainless steel fibrous filter with 100 μm pore reduced by 21-40% and it was by 11-24% for those with 40 μm pore at Sqrt(Stk)=0.60-0.92.

Fig. 4 presents the penetration of potassium chloride particles of the stainless steel fibrous filter with various pore sizes for flow rate of 2.0 L/min, nozzle diameter of 0.36 cm and Reynolds number=782. The results indicate that as the flow rate falls, the penetration of potassium chloride particles decreases. For example, the penetration of potassium chloride particles was 0.28 at Sqrt(Stk)=0.74 for the flow rate of 2.5 L/min (Fig. 3), while it was 0.15 at Sqrt(Stk)=0.72 for the flow rate of 2.0 L/min (Fig. 4). High flow velocity upon the stainless steel fibrous filter causes a higher kinetic energy of the accelerated particles. Hence, the particles are more likely to bounce off from the collection surface. However, a lower sampling flow rate or a larger pore size cannot eliminate particle bounce problems completely. When a particle is smaller than the cut-point of the stainless steel fibrous filter, Figs. 3 and 4 show that the penetration of particles of the stainless steel fibrous filter with 100 μm pore size is lower than the others. This is due to the particle penetration into the stainless steel fibrous filter resulting in the increased collection efficiency.

3. Coated Filter

Fig. 5 displays the penetration of potassium chloride particles of the stainless steel fibrous filter at various pore sizes, with or without an oil coating, for a nozzle diameter of 0.26 cm, flow rate of 2.0 L/min and Re=1082. Compared to the case without the oil coating, the particle penetration is higher than that of filters with oil coating for larger particles. The results show that the coated stainless steel fibrous filter is effective in reducing particle bounce problems. The influence of the pore size on the penetration of the particles could be neglected when the stainless steel fibrous filter was coated with the oil. For uncoated filters, the penetration of potassium chloride particle of the stainless steel fibrous filter with 100 μm pore size was about 0.24 for the flow rate of 2.0 L/min and the nozzle diameter of 0.26 cm at Sqrt(Stk)=0.77 (Fig. 5), and it was 0.11 for the flow rate of 2.0 L/min and the nozzle diameter of 0.36 cm (Fig. 4). The flow velocity of the stream increases with a decreasing nozzle diameter at a fixed flow rate. As stated earlier, increasing flow velocity leads to lower collection efficiency because the particles are more apt to bounce off from the surface.

4. Mass Loading

Fig. 6 shows the penetration of potassium chloride particles of the flat surface and the stainless steel fibrous filter with or without oil coating at particle loaded mass of 0.24 mg for the nozzle diameter of 0.26 cm and the flow rate of 2.0 L/min. The figure indicates that the differences between the penetration curves for the uncoated flat surface, coated flat surface, and uncoated stainless steel fibrous filter are not obvious. This may be attributed to the characteristics of the adhered particles on the surface being similar under slight mass loading, and they behave as another obstacle for capturing incoming particles. The penetration of particles of the coated stainless steel fibrous filter was lower than that of the coated flat surface. Because the amount of the coated oil on the flat surface is unable to reach the surface, particle bounce or re-entrainment will happen again when the particle mass is loaded. But no such phenomenon was observed for the coated stainless steel fibrous filter. The coated oil would be sucked and absorbed by particles leading to reduction of particle bounce off or re-entrainment from the filter.

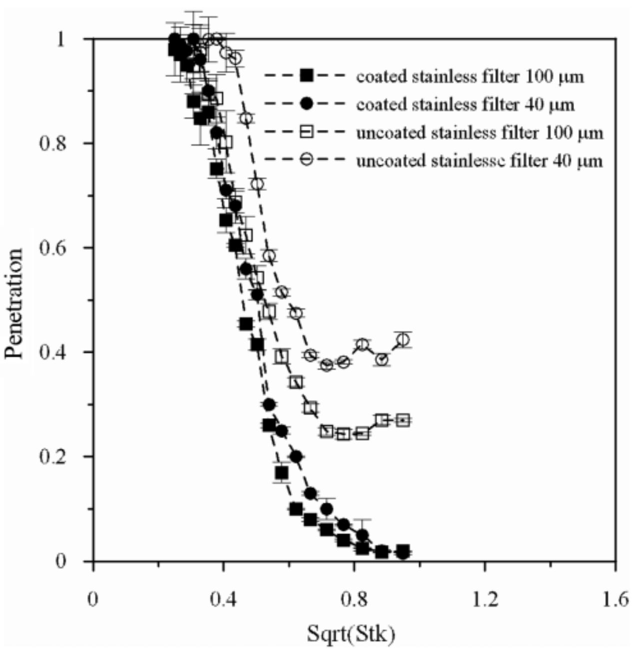

Fig. 5. Particle penetration of coated and uncoated stainless steel fibrous filter with different pore size for nozzle diameter of 0.26 cm, flow rate of 2.0 L/min and Reynolds number=1,082, at no loading mass.

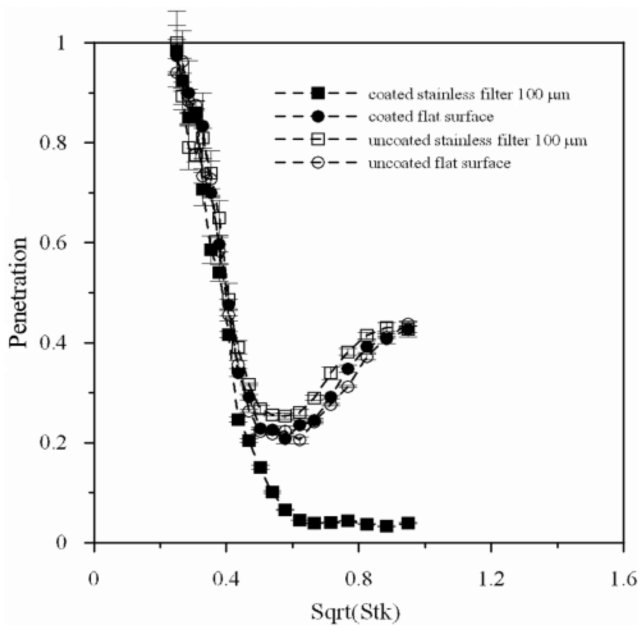

Fig. 6. Particle penetration of flat surface and stainless steel fibrous filter with or without the coating oil for nozzle diameter of 0.26 cm, flow rate of 2.0 L/min and Reynolds number=1,082, at loading mass of 0.24 mg.

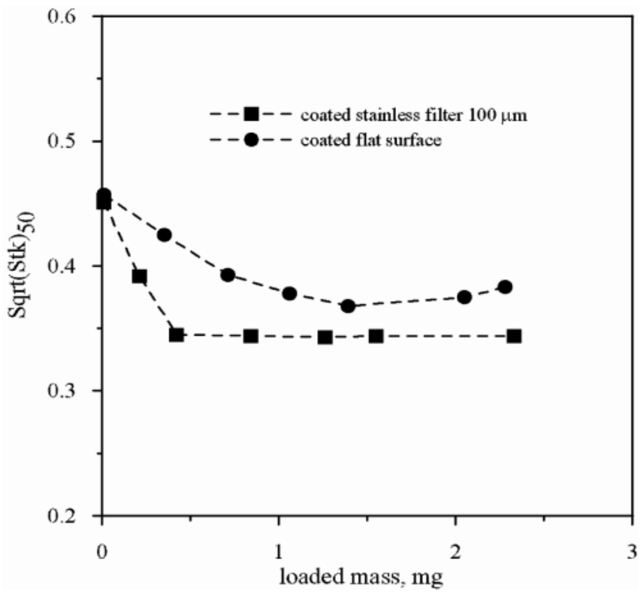

Fig. 7. Influence of loaded mass on cut-point of particle penetration for coated flat surface and stainless steel fibrous filter.

Fig. 7 displays the cut-point of penetration of particles as a function of the loaded mass for a coated flat surface and stainless steel fibrous filter at a nozzle diameter of 0.36 cm, flow rate of 2.5 L/min and Re=977. Results demonstrate that the cut-point decreased gradually with an increasing loaded mass of particles and then reached a constant value for the stainless steel fibrous filter. The steady value of the cut-point for the coated stainless steel fibrous filter was 0.35 as a loaded mass is about 0.4-2.3 mg. When the particle loaded mass increased, the coated oil was sucked by the particle to form a small mountain on the collection surface; therefore, the air flow pattern near the surface was changed. The gradually formed hillock on the surface causes the particle collection efficiency to increase. After forming a mound, the particle continues sucking the oil because of the capillarity effect [12]. The particle bounce or re-entrainment problems are reduced and the cut-point does not change obviously. For the coated flat surface, a small mountain was formed gradually on the surface as the loaded mass of potassium chloride particles accumulated, which caused the dropping of particle penetration. However, as the particle loaded mass was greater than 1.4 mg, particle re-entrainment would arise such that an increasing cut-point was observed. The cut-point of the coated flat surface for particles was higher than that of the coated stainless steel fibrous filter. One likely reason was the rougher surface of the coated stainless steel fibrous filters associated with smaller cut-points. Another one was that there was negligible particle bounce or re-entrainment for the coated stainless steel fibrous filter with increasing mass loading.

CONCLUSIONS

The particle separation characteristics of a particle-laden stream that impinges on a stainless steel fibrous filter or a flat surface from a circular jet were experimentally investigated. When the dimensionless diameter of the particles exceeded $Sqrt(Stk)_{50}$, the oleic acid particles penetrated less than the potassium chloride particles for the flat surface or uncoated stainless steel fibrous filter, because the potassium chloride particles might be bouncing off from the stainless steel fibrous filter or the flat surface. Coating the stainless steel fibrous filter with oil markedly improves the collection efficiency of potassium chloride particles. When the loaded particle mass on the coated stainless steel fibrous filter was approximately 0.24 mg, the particle penetration was as low as 0.02 when Sqrt(Stk)>0.8. The penetration of the uncoated stainless steel fibrous filter or the flat surface by the particles is much greater. The capillarity effect causes the coated oil to be absorbed onto the deposited particle layer to prevent the potassium chloride particles from bouncing, and therefore increases the particle collection efficiency. A hillock slowly formed on the coated stainless steel fibrous filter would decrease the particle penetration. Once a mound had been formed, the value of $Sqrt(Stk)_{50}$ remained almost constant.

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