THE INFLUENCE OF PARTICLE REBOUND ON THE COLLECTION PROCESS ON SINGLE FIBERS

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ABSTRACT

When fibrous gas filter media are operated at high volumetric flow rates, the impaction velocities of dust particles on individual fibers are also high. In that case, particles can rebound off the fiber surface and are re-entrained in the gas flow. By means of applying a thin film of liquid on the fibers, particle rebound can be reduced significantly. In this paper we intend to demonstrate the influence of particle bounce using results from micro-scale single fiber experiments conducted with bare fibers and fibers coated by thin films of oil.

KEYWORDS

Gas Cleaning, Filter Media, Nonwovens

1. Introduction

Many fractions of standard test dusts (e.g. ISO-coarse, ISO-fine) used for the characterization of fibrous filter media are rather coarse. Their mass-inertia leads to high impaction velocities on the fibers inside the fiber matrix, causing bounce and thereby a shift in dust distribution along the depth of the filter media. Today, one target in filter development is to predict the behavior of filter media for the whole operating time. Deposited dust influences the evolution of pressure drop, fractional efficiency and clogging properties. That is why local dust mass distribution inside the fiber framework becomes more and more of interest.

As the computation power available for engineering applications increases steadily, modern CFD software gradually allows for micro-scale simulation of filtration processes with fibrous media. Flow fields around resolved filter fibers are calculable nowadays. Particle deposition is computed directly by calculating particle trajectories. In order to consider particle rebound effects correctly, collision models have to be applied for each particle-fiber and particle-particle contact. The adhesion probability h for particles on fiber contact approaches 100% for low impaction velocities or very fine dusts (<< 1 µm). However, even in case of low filter face velocity, higher gas velocities can occur locally inside the media due to inhomogeneity.

Hence, the major objective of the presented studies is to obtain experimental data for the validation of contact models and parameters. Single fiber experiments are a fast and conclusive method for identifying and quantifying fundamental changes in filtration behavior caused by fiber surface modifications.

Individual fibers inside the filter matrix act as collectors of airborne particles. Hence, a common approach for describing the fractional efficiency of fibrous media is based on the collection efficiency of single fibers and geometric properties of the filter medium. In order to be precipitated, particles must meet two conditions. First, they have to collide with either a fiber or previously deposited particles. Then, they must adhere permanently to the contact surface. Consequently, the single fiber efficiency η can be described as the product of the impaction probability φ and the adhesion probability h.

$$\eta = \varphi \cdot h$$

η was determined for polystyrene mono-spheres on bare steel fibers using single fiber efficiency experiments (*paragraph 2*). Furthermore, when the evolution of φ versus the Stokes number is known, h can be calculated. If we assume, that a film of liquid on a fiber can suppress particle bounce completely, the adhesion probability h is 100%. Thus, the impaction probability φ can also be directly measured employing the same method as in the case of single fiber efficiency, provided the liquid film is very thin and does not change the effective fiber diameter substantially. In our studies, we used a penetrating lubricant (WD-40, WD-40 Company Ltd.) for fiber coating (*see paragraph 3*).

2. Single fiber efficiency measurement method

Single fiber efficiency is measured using the online counting method depicted in *Figure 1*. Parallel fiber arrays are positioned between two independent scattered light measurement volumes. These are defined optically by two sets of blinds each, one in the optical path of the light source and one at the 90° position. Single fiber efficiency η is calculated using the number of particles counted upstream and downstream, respectively (N_{Up} , N_{Down}), and the fraction of the scattered light measurement area covered by fibers $\mathrm{A_F}/A_{SL}$.

$$\eta = \frac{N_{Up} - N_{Down}}{N_{Up}} \cdot \frac{A_{SL}}{A_F}$$

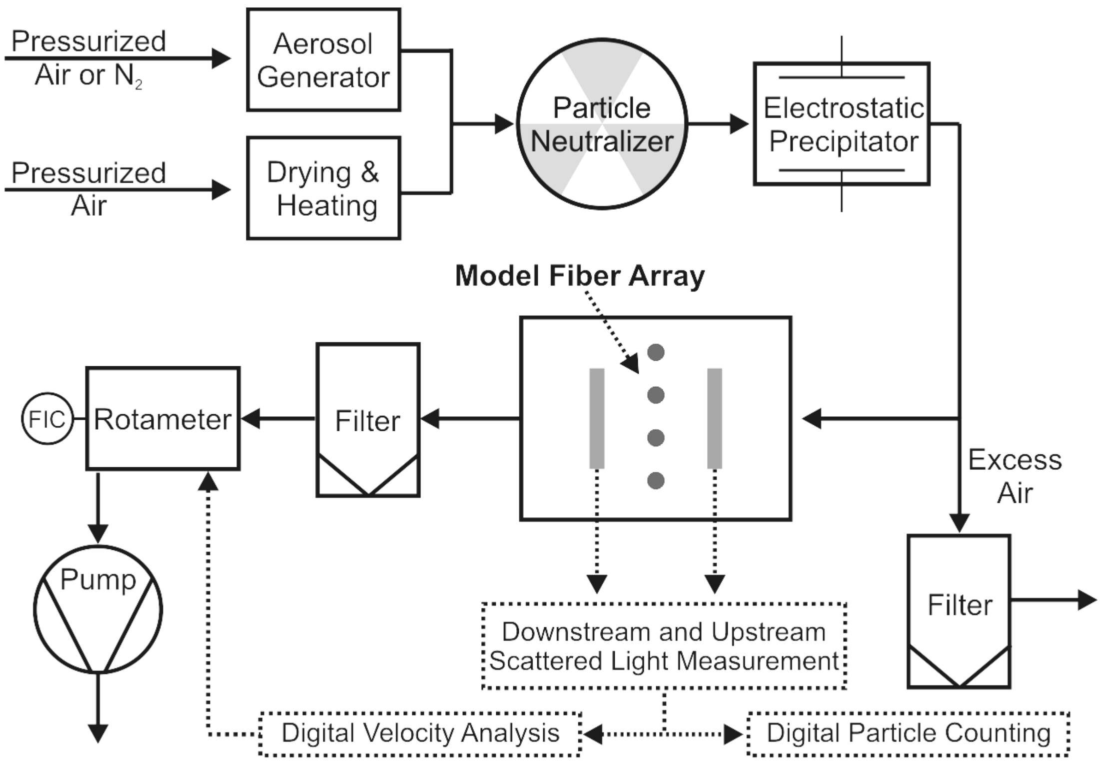

Figure 1 - Single fiber efficiency measurement flow chart

Pulse width analysis allows for calculating the approaching velocity of airborne particles towards the array more precisely than mass or volume flow methods. Time of flight analysis and complex post-processing help to reduce counting errors. Thus, measurement results are highly reproducible.

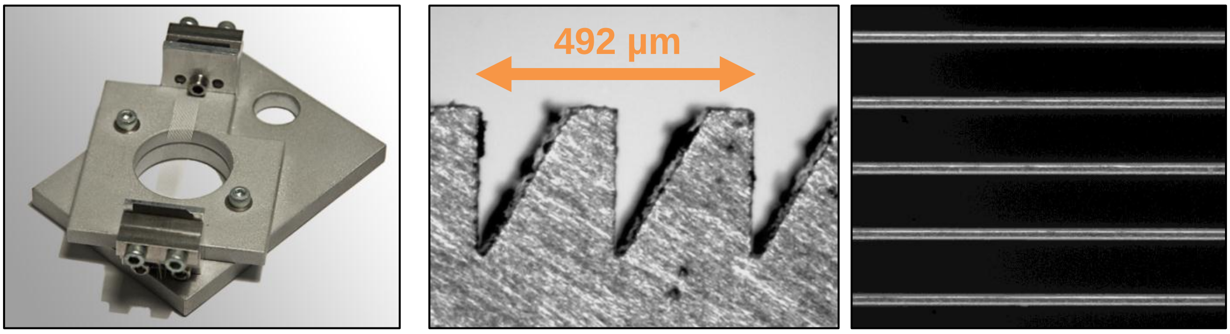

Figure 2 - Left: *Fiber array consisting of 25 parallel stainless steel fibers (ø 20 µm)*
Center: *Detail of sawtooth structure*
Right: *Detail of fiber array*

For efficiency measurements, fibers are mounted horizontally in arrays between a set of sawtooth-shaped microstructures (*Figure 2*). That way, a precisely parallel orientation and sufficient fiber tension is guaranteed.

3. Fiber preparation method

The major objective for the fiber coating process was to cover the fibers with a liquid film. As liquids on fibers frequently form chains of droplets (*Figure 3, top*), a very thin film (and thus very low droplet diameters) is desirable in order to uphold a very narrow effective fiber diameter distribution. Furthermore, the thinner the film, the better the comparability of results obtained using untreated and treated fibers. Larger effective fiber diameter leads to lower Stokes numbers and hence to reduced values of the impaction probability.

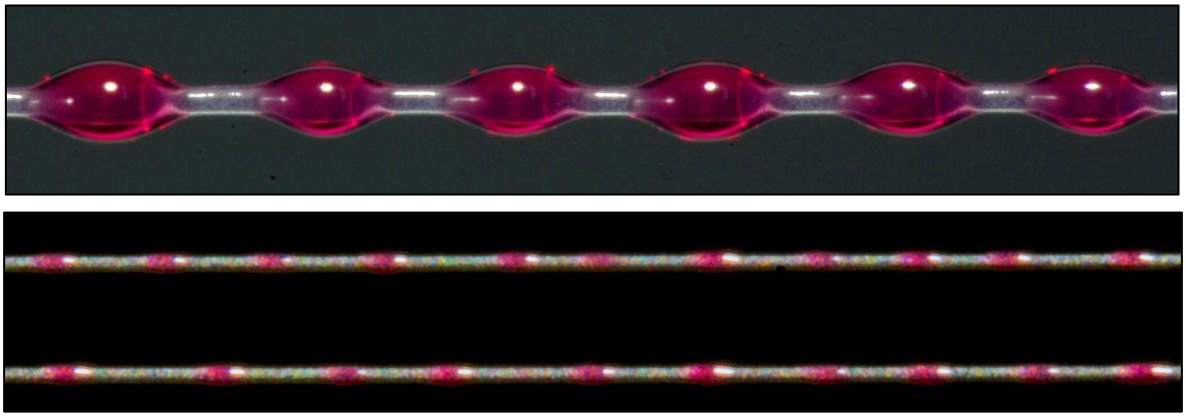

Figure 3 – *Dyed oil droplets (WD-40), connected by a very thin oil film on a fiber.*
Top: *Very high oil mass per unit fiber length in favor of better visibility.*
Bottom: *Oil mass applied for measurements*

Handling oil-coated fibers negatively affects the local distribution of oil on the fiber. Meniscal bridges between neighboring fibers and other kinds of fiber-fiber contact had to be avoided. Therefore, the most viable method was generating an oil aerosol with low mean oil droplet diameter (< 1 µm) using a custom build atomizer and exposing a previously mounted fiber array to a high velocity free jet of aerosol (see *Figure 4*). In that case, oil droplets are collected on the fiber mainly through inertial deposition. Very small amounts of oil can be deposited on the fiber in this fashion (see *Figure 3*, bottom). The overall volume of fiber and droplets was determined using a digital transmitted light bright field microscope and the Mathworks Matlab Image Processing toolbox.

5. Results

Single fiber efficiency measurements were conducted with arrays of stainless steel fibers (ø30 µm) mounted at a distance of 246 µm. Approaching velocities were varied between roughly 0.5 m/s and 2 m/s. Highly elastic polystyrene mono-spheres ("Latex particles", ø3.5 µm) were used. Experiments were repeated after coating the fibers with a thin film of penetrating lubricant (WD-40, WD-40 Company Ltd.).

The observed shape of the single fiber efficiency measured versus the Stokes number plot obtained for bare single fibers was as expected (compare *fig. 5*). Impaction probability φ increases when fibers are exposed to rising velocities. After a certain limit for the impaction velocity is exceeded, particle rebound effects start to take place. When the approaching velocity is raised further, adhesion probability decreases stronger than impaction probability rises, so single fiber efficiency declines towards zero. As shown in *figure 5*, particle rebound could be suppressed effectively by oil coating. Hence, the single fiber efficiency for coated fibers can be assumed to be equal to the impaction probability

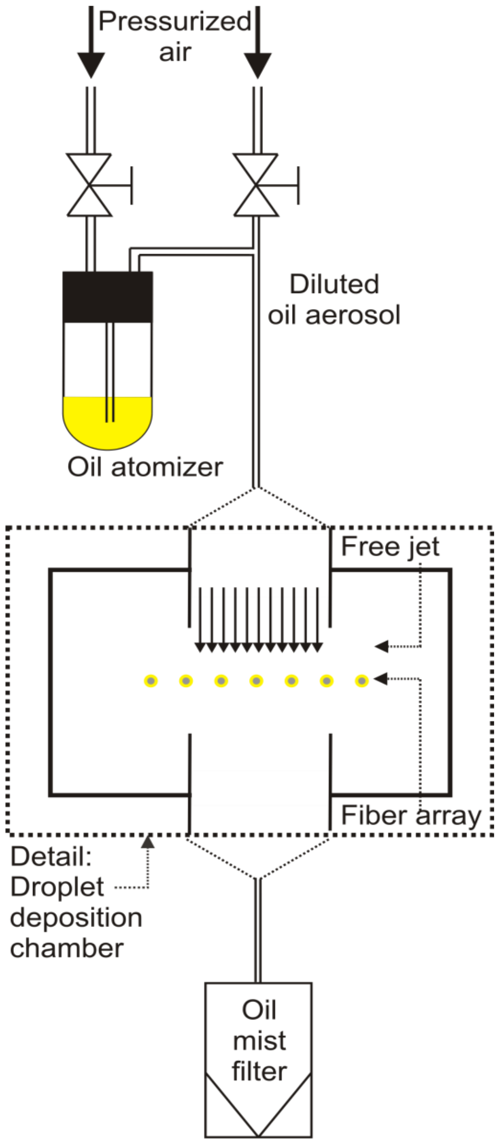

Figure 4 – Flow chart of the fiber coating process including a detail oft he droplet deposition chamber

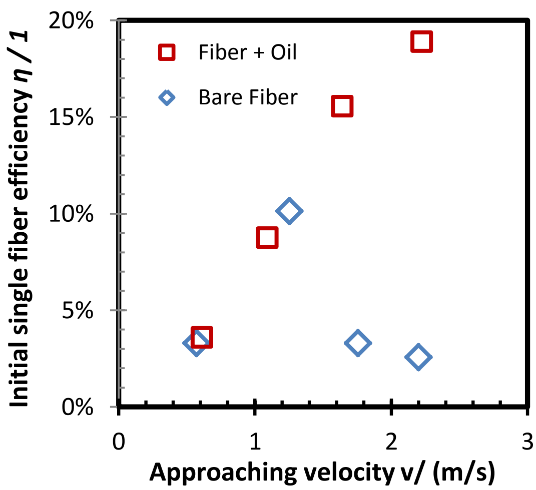

Figure 5 – Single fiber efficiency for bare metal fibers and fibers coated with oil

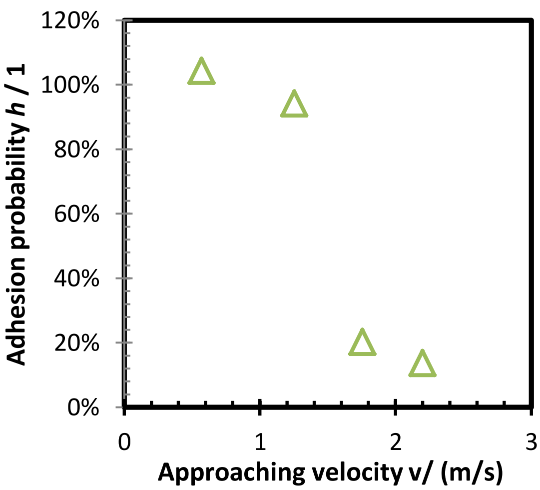

Figure 6 – Adhesion probability for bare metal single fibers

for the bare fibers. After linear interpolation of φ, adhesion probability h was calculated (*fig. 6*). The shape of the curve is plausible, as low impaction velocity positively affects adhesion. However, only few of the empirical model formulations available in literature satisfy the reasonable limit conditions for h, 100% for very low velocities and 0 for high velocities. Two of these are the suggestions by Ptak and Jaroszczyk (PJ) [1] and Kasper et al. [2]:

Ptak and Jaroszczyk: $$h = \frac{190}{(St \cdot Re_P)^{0.68} + 190}$$

Kasper et al.: $$h = \frac{St^{-3}}{St^{-3} + 0.0365 \cdot Re_F^{2.46} + 1.91}$$

Here, the Stokes number St, the fiber Reynolds number Re_F and the particle Reynolds number Re_P are defined as follows:

$$St = \frac{\rho_P d_P^2 v}{18\, \mu_G d_F} \cdot Cu(d_P) \qquad Re_F = \frac{\rho_G d_F v}{\mu_G} \qquad Re_P = \frac{\rho_P d_F v}{\mu_G}$$

ρ_p and d_p are the density and diameter of the fiber, respectively. μ_G denotes the dynamic viscosity of the gas, v the gas flow velocity and d_F the fiber diameter. Cu is the Cunningham correction factor.

Our measurement results don't resemble the models closely (*fig. 7*), although values spread around the Ptak & Jaroszczyk curve. However, as highly elastic particles were used in this study, bounce incidents were expected to occur frequently at high velocities. More experiments with different materials have yet to be conducted in order to evaluate existing models and to provide further experimental validation data for realistic contact models.

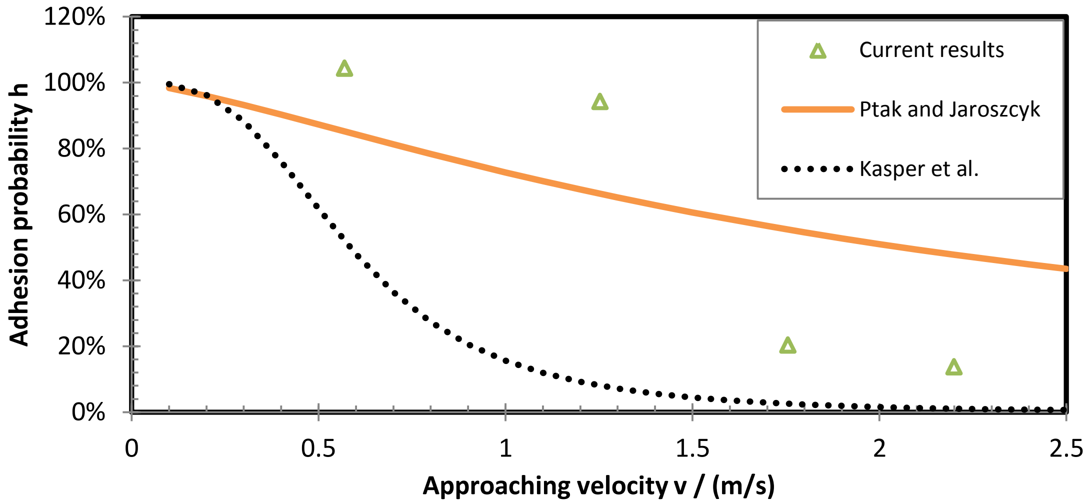

Figure 7 – Current results for the adhesion probability in comparison with two models from literature.

6. Summary

Experiments were conducted in order to demonstrate the influence of particle bounce on the single fiber efficiency. Rebound was reduced by applying a very thin film of oil on the fibers using an aerosol deposition method. That way, the adhesion probability for polystyrene particles of 3.5 µm diameter impinging on steel fibers could be calculated. Measurement data obtained using the presented experimental method can be utilized to evaluate and adjust existing contact models.

7. Acknowledgement

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Literature

1. Ptak, T., Jaroszczyk, T. *Theoretical-Experimental Aerosol Filtration Model for Fibrous Filter at Intermediate Reynolds Numbers*. in *Proceedings of the 5th World Filtration Congress*. 1990.
2. Kasper, G., Schollmeier, S., Meyer, J., Hoferer, J., *The collection efficiency of a particle-loaded single filter fiber.* Journal of Aerosol Science, 2009. **40**(12): p. 993-1009.