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DEPOSITION-DEPENDENT PARTICLE COLLECTION EFFICIENCY OF MODEL FILTER FIBERS IN PARALLEL ARRAYS

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ABSTRACT

In depth filtration, pressure drop and filter efficiency of fibrous filter media both show a strong dependency on the particle mass accumulated on the individual filter fibers. In this work, the efficiency of individual model fibers in arrays was measured online as a function of particle load using a customized scattered-light device. Experiments with arrays composed of parallel steel fibers were conducted at different flow velocities. These arrays were loaded progressively with mono-disperse solid aerosol particles of varying diameter and material. Results were compared qualitatively to models for isolated single fibers by Kasper et al. 2009 [1].

KEYWORDS

Gas Filtration, Fibrous Media, Single Fiber Efficiency, Particle Deposition, Dust Loading, Light Scattering

1. Introduction

Filtration properties of dust loaded depth filters differ considerably from those of unloaded filter media. The pressure drop of filter media is frequently correlated with the accumulated particle mass. In order to predict the accumulation of particle mass, it is necessary to have reliable functions of filtration efficiency with dust load. One possible approach is to describe these changes based on the progression in single fiber efficiency with accumulated particle volume or mass.

Measurements have recently been published by Kasper et al. [1] for the collection efficiency increase of particle-loaded isolated fibers. It turned out however, that these are not sufficiently representative for fibers inside a filter matrix. Particle collision and the drag forces on particle structures are highly dependent on fiber orientation and distance, because the flow field around a fiber is massively influenced by neighboring fibers.

In this work, the collection efficiency of individual fibers in the regime of dominant inertial deposition was measured as a function of particle velocity and accumulated particle mass per unit fiber length at different particle diameters.

Kasper [1] proposed an empirical fit model for the single fiber collection efficiency over particle mass for *isolated* fibers.

$$\frac{\eta}{\eta_0} = 1 + b \cdot M^c \qquad (1)$$

Where η denotes the single fiber collection efficiency, η_0 the initial efficiency of an unloaded fiber and M the accumulated particle mass per unit fiber length. b and c are empirical fit parameters. These parameters were calculated based on experimental data obtained with measurements mostly on isolated fibers.

2. Measurement of single fiber efficiencies

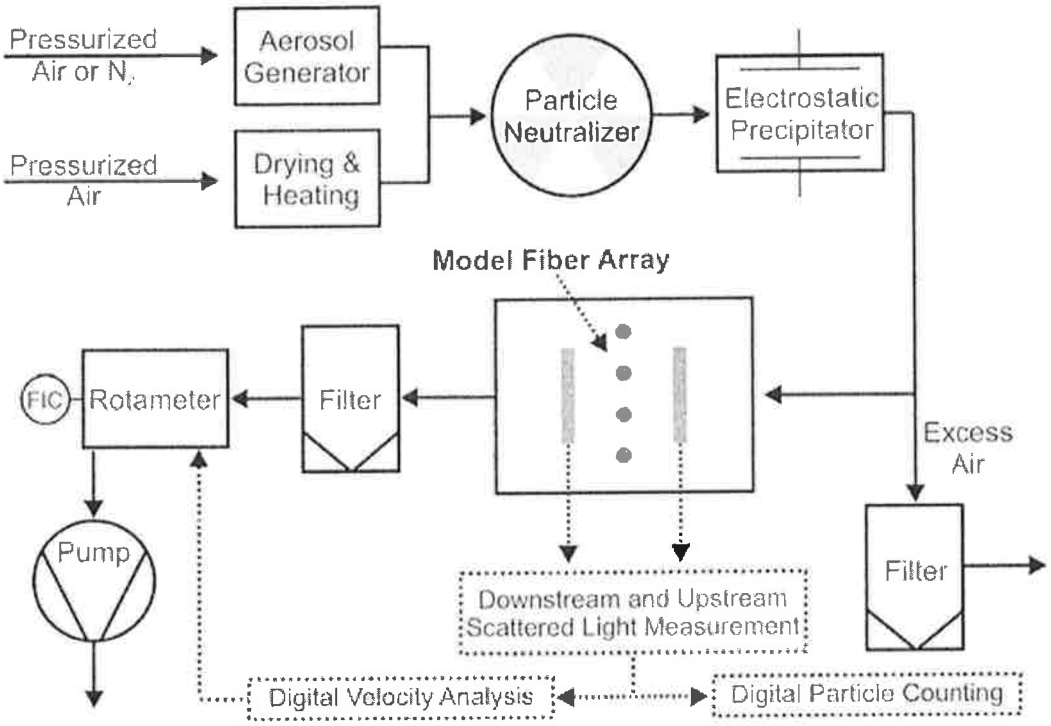

Figure 1 – Process Flow Chart

The experimental setup specified in Figure 1 allows for the measurement of single fiber efficiencies of both isolated fibers and fibers in parallel arrays. Various particle sources can be applied, such as spray atomizers for particle suspensions or Sinclair-LaMer-type aerosol generators. Airborne particles are neutralized and, if necessary, charged particles are precipitated in order to avoid significant influence of electrostatic forces on the collection efficiency. Afterwards the aerosol passes through a customized scattered light measurement chamber which contains two independent measurement zones for particle counting at a distance of 500 µm. The examined single fiber or array of model fibers is placed between these zones after being mounted and tensioned on sawtooth-shaped microstructures (fig. 2). The system offers several degrees of freedom: particle and fiber diameter, gas velocity, fiber distance, particle material and particle concentration.

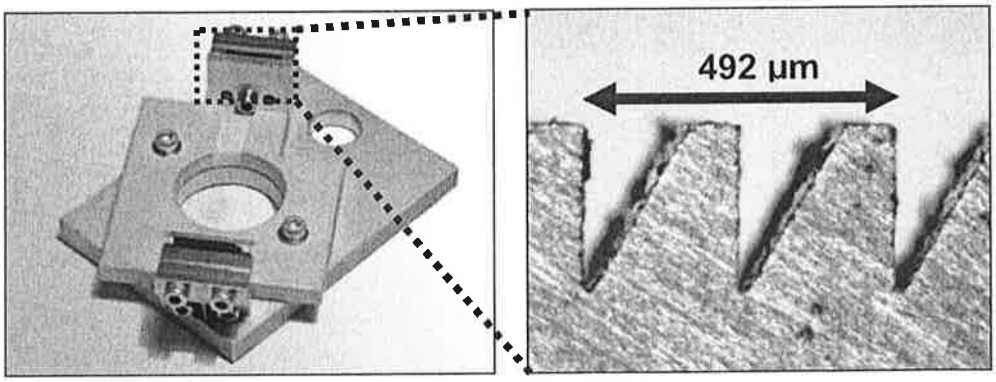

Figure 2 – Steel fiber array (l.) and magnified fiber comb (r.)

The single fiber efficiency η is obtained by counting pulses in both measurement zones:

$$\eta = \frac{N_A - N_B}{N_A} \cdot \frac{A_{SL}}{A_F} \tag{2}$$

where N_A and N_B are the numbers of particles counted upstream (A) and downstream (B) of the fiber array. A_{SL} and A_F are projected areas in the direction of flow of the scattered light measurement zone and the fibers, respectively.

Using a refined method of online data recording, the reproducibility of measured results could be raised significantly compared to former concentration based counting methods. This was accomplished through an extensive analysis of the individual voltage signal induced by each particle. Apart from just counting the particles separately in each measurement zone, the customized post-processing software allows for extensive visual error analysis, depending on signal shape and coincidence of signals.

When $N_{A,i}$ denotes the total number of particles counted in a time interval *i*, then the total number of deposited particles $N_{D,j}$ after *j* samples is calculated by

$$N_{D,j} = \frac{A_F}{A_{SL}} \cdot \sum_{i=1}^{j} \eta_i \cdot N_{A,i} \tag{3}$$

In case of mono-disperse particles, the accumulated particle mass is then computed by multiplying $N_{D,j}$ by the mass of a single sphere M_S. For better comparability $N_{D,j} \cdot M_S$ is then divided by the length of the fibers covered by the measurement zones.

3. Results

Figure 3 shows exemplary initial collection efficiencies for polystyrene particles (particle diameter d_p = 2.4 µm) plotted over the Stokes number St

$$St = Cu\,\frac{\rho_P d_P^2 v_\infty}{18 \mu_g d_F} \tag{4}$$

where Cu represents the Cunningham slip correction factor, ρ_P the particle density. d_P and d_F denote the particle and the fiber diameter, respectively. v_∞ denotes the approaching velocity and μ_g and dynamic viscosity of the gas.

The distinct maximum of this initial fiber efficiency plot is based on two opposed effects. While higher velocities lead to a higher collision frequency, particle accumulation is reduced by particle bounce in the regime of high Stokes numbers.

Figure 4 contains exemplary data of measurements for polystyrene mono-spheres. The model arrays were created by mounting 25 parallel steel fibers of diameter 20 µm at a distance s_F of 246 µm. Due to the stochastic character of the deposition process and the consequential effects on the shape of particle structures on the fiber, measured collection efficiencies show stronger variations with increased loading.

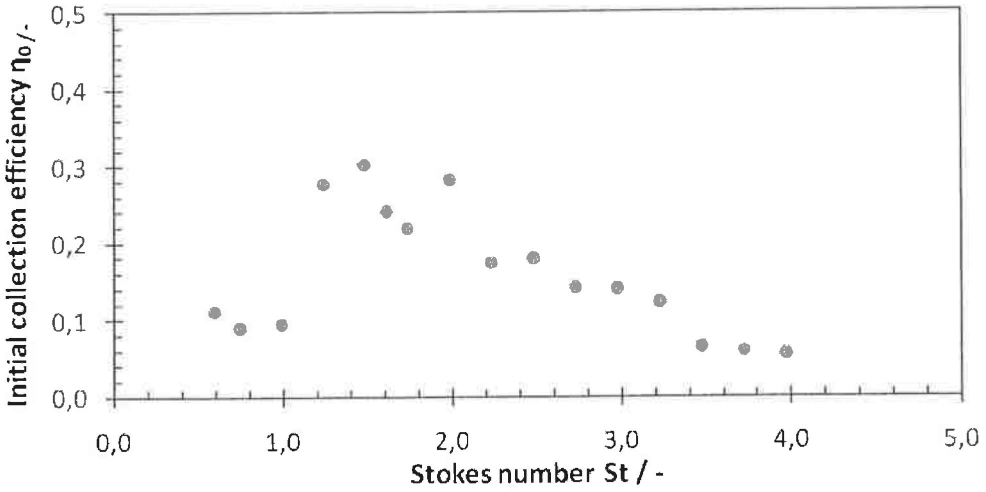

Figure 3 - Initial fiber collection efficiency vs. Stokes number
(25 parallel steel fibers; v = 1.25 m/s, d_f = 20 μm, s_f = 246 μm, d_p = 2.4 μm)

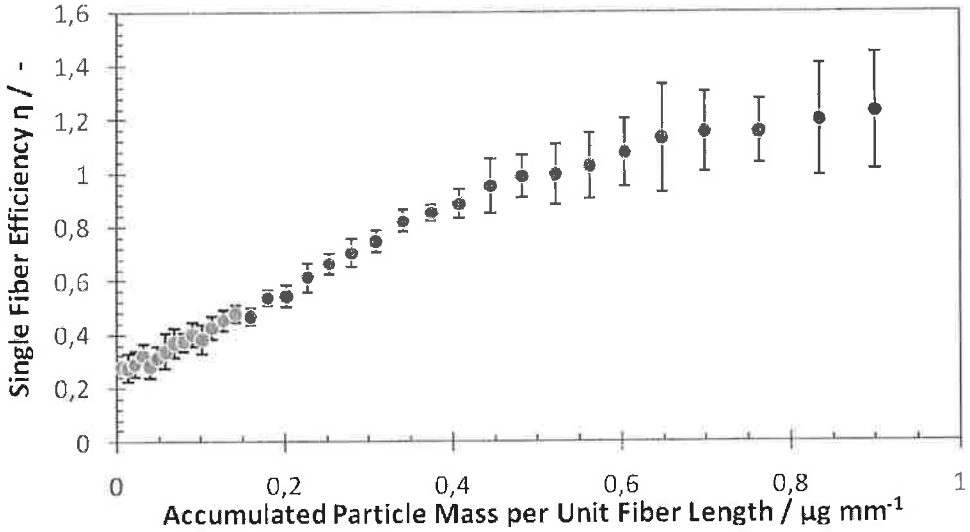

Figure 4 – Single fiber efficiency vs. accumulated particle mass;
Data points represent mean values from 3 measurements ± one standard deviation;
(25 parallel steel fibers; v = 1.25 m/s, d_f = 20 μm, s_f = 246 μm, d_p = 2.4 μm)

As figure 5(a) and (b) point out, the available flow area is reduced significantly by accumulated particles. Thus, continuous particle deposition causes an increase in gas velocity between the fibers. Simultaneously, fluid drag forces on accumulated particles increase due to higher velocity gradients. These forces may induce detachment and re-entrainment of relatively large particle agglomerates (figure 5(c)), especially at high approaching velocities. As mass and position of detached particle structures can't be determined in-situ, particle detachment leads to an undefined state of particle loading. This delimits utilizable data for η over M (figure 6). Consequently, acquiring reliable data at high particle load and at high velocities requires higher effort.

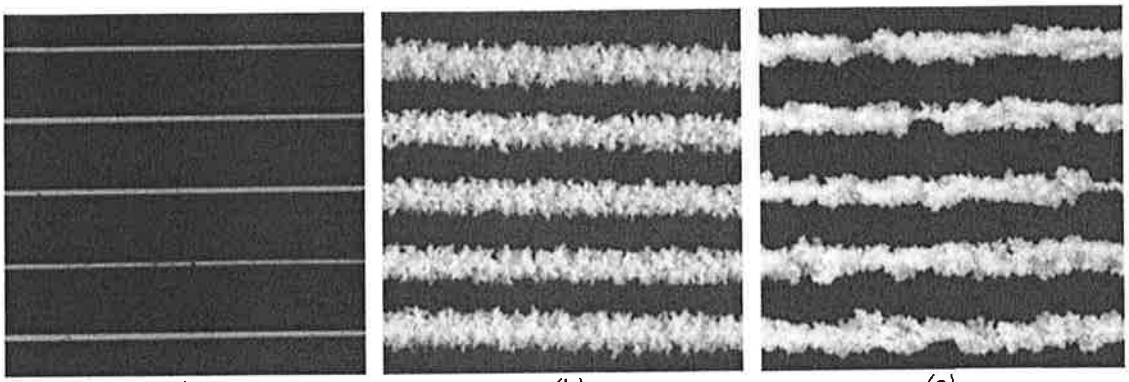
(a) (b) (c)

Figure 5 – Macroscope images of parallel steel model fibers; d_f = 20 µm; s_f = 246 µm; polystyrene mono-spheres, d_p = 2,4 µm

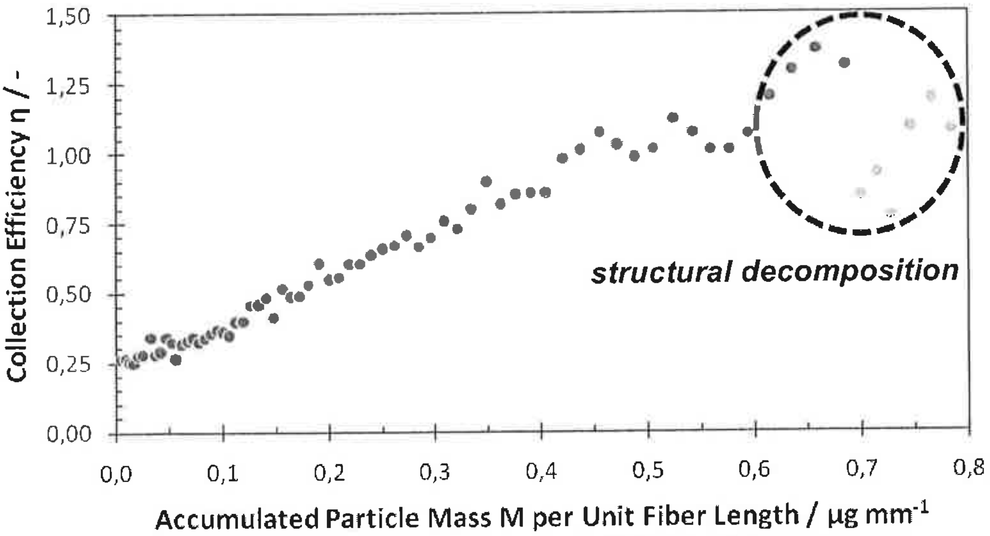

Figure 6 – Fiber efficiency vs. accumulated particle mass; v = 1.25 m/s, d_f = 20 µm, s_f = 246 µm, d_p = 2.4 µm

Qualitatively, the evolution of empirical fit parameters b and c in equation (1) for arrays was found to show good accordance with those Kasper et al. [1] suggested for isolated single fibers, although absolute values differed expectedly. Figure 7 shows plots for the two fitting parameters b and c over characteristic dimensionless numbers for the inertial impaction on fibers.

$$R = \frac{d_p}{d_F} \qquad Re_F = \frac{\rho_g d_p v_\infty}{\mu_g} \qquad (5)$$

Kasper described the empirical fit parameter b as a 2nd order function in St/R for isolated single fibers. Figure 7 shows the evolution of b when b is fitted to fiber array data. For low values of the fiber Reynolds number Re_F, parameter c approaches unity, thus unifying equation (1) and a linear approach suggested by Kanaoka et al. [2]. For high Re_F, tendencies towards a constant value for c are discernable. However, there is still a substantial lack of data for higher Stokes and Reynolds numbers in order to predict the evolution of both parameters reliably.

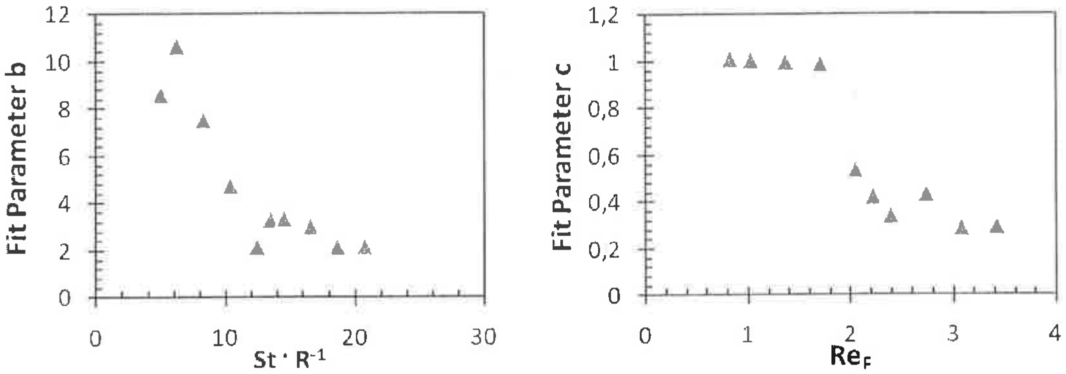

Figure 7 – Empirical fit parameters b and c from Eq. (1) derived from data of the deposition-dependent single fiber collection efficiency for parallel arrays, d_p = 2.4 µm

4. Summary

The collection efficiency of a single steel fiber of 20 µm diameter within an array of 25 parallel fibers was measured as a function of accumulated particle mass. The experiments were performed with an improved experimental set-up in combination with better data recording and analysis giving better reproducibility of obtained results. First results reported here show good agreement with an empirical model suggested by Kasper et al. [1].

5. Acknowledgement

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6. References

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