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Removal mechanisms of particulate contaminations from polymer woven filter media

Caroline Weidemann [*], Nicole Barkholz, Hermann Nirschl

Institute of Mechanical Process Engineering and Mechanics, Karlsruhe Institute of Technology (KIT), Campus Sued, Strasse am Forum 8, D-76131 Karlsruhe, Germany

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ABSTRACT

This study deals with cleaning of particle-loaded filter media by means of continuous and pulsed flows of water. Earlier studies have shown that the detachment of particulate impurities from filter media is influenced by time. Thus, the fraction of particles successfully removed by the flow initially increases with the period of exposure to the flow, reaching a constant level only after some time. The detachment mechanisms occurring in this phase, for instance, include rolling, slipping, or direct detachment of particles normal to the contact radius. These mechanisms are a function of the particle position on the filter medium. Particles not removed immediately but first rolling or slipping over the surface will be removed after a sufficiently long period of exposure to the flow. In this study, the individual mechanisms of particle detachment under continuous and pulsating flow through the filter media are shown experimentally. In addition to critical cleaning spots of the fabric, changes in position were detected and analyzed as a function of filter geometry. For this purpose, the filter medium was subdivided into four segments, and their cleanability was examined. It was seen that the critical sites are located at the highest points in the fabric. There is also a connection between the degree of cleaning of the respective segment and the reposition of particles within the segment.

1. Introduction

The detachment of particulate impurities from surfaces is of great interest to many industries. In the pharmaceutical and food industries, for instance, this concept is important, among other things, in connection with cleaning plants and plant components. The purpose of the exercise is to detach all particles from the surface. In order to intervene positively in the cleaning process, it is important to understand the mechanisms of detachment of particulate impurities from surfaces. Three types of detachment mechanisms are known in the literature: Immediate detachment caused by direct buoyancy forces; particle detachment by first rolling; detachment by the particles slipping over the surface. Rubin [1] was one of the first authors to describe the initial resistance and buoyancy coefficients of stationary spherical particles in a laminar boundary layer close to the wall. He used experimental measurements of the flow forces for calculation. He varied the diameters of spheres between 1000 and 3000 μm, the flow rate between 0.1 and 35 cm/s, and the viscosity of the flowing fluid between 1 and 14 cm^2/s.

Masironi and Fish [2] were the first authors to observe the mechanisms of particle detachment directly (on line) under a microscope. They saw a combination of particle motion (rolling and sliding) along the surface and immediate particle detachment (without motion) normal to the surface.

Many measurements also indicated that detachment does not occur immediately but within a certain period of time (see, e.g., [3]). This phenomenon is assumed to be attributable to an irregular flow pattern of the fluid near the surface [4]. For this purpose, quantitative measurements were performed by Kline et al. [5] which showed flow movement in the laminar boundary layer to occur as a function of space and time. The flow is permanently interrupted by turbulent shocks resembling miniature tornados. These shocks cause a brief rise in buoyancy force, which gives rise to particle detachment. Cleaver and Yates [6] developed a model in which the possible buoyancy force acting on a particle can be predicted.

Hubbe [7] presented theoretical models of the detachment of colloidal particles from solid surfaces in a shear flow. The models mainly refer to hard and round particles small enough to fall in the range of Brownian motion. He showed that the hydrodynamic force component acting parallel to the wall in most cases is many times higher than the buoyancy force. The different types of motion of the particles (rolling, sliding, direct detachment) can

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* Corresponding author. Tel.: +49 721 608 44833; fax: +49 721 608 42403.
E-mail address: caroline.weidemann@kit.edu (C. Weidemann).

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be distinguished by their dependence on shear stress. He experimentally and theoretically studied the detachment of colloidal particles from flat surfaces exposed to shear flow [8,9]. He showed that rolling was the dominant detachment mechanism causing the release of particles from flat substrates subjected to turbulent flow. He reported an increase in colloids released with time, which was attributed to variations in local shear rates. Hubbe also observed, that some particles during the exposure to the flow moved across the surface from positions upstream.

Reeks et al. [10] developed a new approach to resuspending particles entering a turbulent flow from a solid surface. Unlike the customary balance-of-forces models, this model takes into account the turbulent energy transferred from the flow to the particle. The approach in this case implies that the particle is detached from the surface as soon as it experiences a sufficiently high vibration energy. Wen and Kasper [11], in their study, presented a kinetic model of particle detachment, comparing it with data from industry and experiments conducted with particles in a size range between 0.4 and 1 μm. Wang [12], in a theoretical approach, studied the initial types of motion in particle detachment from surfaces. He found detachment to be caused more easily by rolling rather than by sliding or direct particle detachment. These findings had been shown before experimentally by Masironi and Fish [2]. Soltani and Ahmadi [13] developed two theoretical models of particle detachment based on turbulent flow patterns near the wall. One of these models covers detachment by rolling, the other one detachment by slipping along the surface. Both models include flow effects caused by the production of turbulent eddies and shocks favoring particle detachment. Ibrahim et al. [14] studied particle detachment in turbulent air flows caused by air intake through a fan. In addition to direct particle detachment (normal to the surface, no rolling) they also observed particle motion (rolling or sliding) prior to detachment. There are also several publications dealing with particle detachment from surfaces under a laminar flow or covered by a flow of fluids. Burdick et al. [15] showed that it is possible to predict the detachment of a particle when the adhesive force between the particle and the surface and the mechanical force applied during cleaning are known. His model system were polydisperse polystyrene particles adhering to a quartz surface. He exposed the adhesive partners to a laminar transverse flow in an aqueous solution. For the model, he used a critical particle Reynolds number to define the force criterion for particle detachment.

Beck et al. [16] studied a variety of parameters (e.g. roughness, surface energy, surface anisotropies, detergents) influencing cleanability of real surfaces. Bode et al. [17] worked about cleaning technical surfaces. In addition to soluble impurities they also employed a particulate impurity. The focus of their study was on cleaning surfaces of different roughness structures. Only Stahl et al. [18] in 2013 dealt with cleaning complex structures (in this case, woven metal fabrics). However, they studied high flow rates (0.5–1 m/s) and only a very short time span (10–30 s) in which it was not possible to show any significant influence.

This paper is to continue the work by Stahl by studying in more detail the influence of time on cleaning, determining and comparing the cleanability of a fabric in various filter segments, and making particle motion visible during cleaning. The paper deals with the mechanisms of detachment of particulate impurities on filter fabrics by means of a continuous (steady over time) flow. The fluid used is fully demineralized water. Unlike the publications referred to above, the flow entered on the filtrate side while the impurity was located on the top of the filter on the side facing away from the flow. This made it impossible to obtain an on-line view of particle detachment. For this reason, a method was developed allowing detachment mechanisms to be observed off line, i.e. is after each cleaning step.

2. Materials and experimental procedure

2.1. Filter media, particles and cleaning fluid

Because of the complicated experimental procedure and evaluation, the studies were performed on one type of filter fabric only. The filter fabric used has been employed in earlier investigations as well [19]. It is a monofilament polymer fabric made of PET with PRD (plain reverse Dutch) weave and a filter fineness of 22 μm. The impurities used were monodisperse fluorescent melamine resin particles with a particle diameter of 10 μm made by Microparticles GmbH, Berlin. The particles emitted light in the wavelength range of 429 nm (blue fluorescence), the fluorochromes being homogeneously distributed inside the particles, which is why the surface properties are not changed by the fluorescent labeling.

The cleaning fluid, which was used for all experiments, was demineralized water with an electrical conductivity of 10 μS/cm.

In literature [20] it was found that the PET-surface have a negative surface charge and Zetapotential measurements of the particles in demineralized water showed, that the surface charge of the particles is positive charged.

2.2. Contamination of the filter medium

Before a cleaning experiment can start the filter medium has to be contaminated. Therefore a defined contamination of the filter media is necessary to make the experiment reproducible. The contamination is to be made with fluorescent particles described in Section 2.1. The requirements to be met by contamination in this case are outlined below:

- Uniform distribution of the particles emitting blue on the filter medium (after all, the removal mechanisms between single particles and the filter surface, not between agglomerates and the filter surface, are to be studied).
- No contact of the contaminated particles; particles are to be present as single particles.
- The reverse side of the filter medium must not be covered with particles in order to prevent particles getting from the reverse side to the front side during cleaning, which would also be evaluated in that case and could falsify the result.

For contamination, the filter medium was put into a contamination cell consisting of two cylindrical PET tube sections screwed together. The filter medium to be contaminated was put between the PET cylinders. Two stoppers used for test tubes allowed the two cylindrical tube sections to be joined tight. The filter medium was inserted in the section and the lower half of the cylinder had been filled with fully demineralized water. After the two cylindrical tube sections had been connected, and the top part had been filled up with 10 ml of fully demineralized water to which 10 μl each of the particle suspension emitting blue (5% [m/m]) had been added, it was necessary to run the cell in a rotator for a defined period of time at a specific speed. This allowed a homogeneous distribution of the particles on the filter surface to be achieved. The cell was discharged quickly by turning it upside down and removing the plug. After removal, the filter medium was dried for 30 min at 30 °C. This procedure was necessary to achieve a level of contamination meeting the requirements outlined above.

As the cleaning technique used here always implies fluid flow through the fabric, it is impossible to take pictures on line during the cleaning process. For this purpose, the microscopic images must be taken off line, i.e. after each cleaning attempt. After each experiment, the fabric is carefully removed from the filter mount,