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Impact of an oil coating on particle deposition and dust holding capacity of fibrous filters

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ABSTRACT

A light coating of oil is known to increase the dust holding capacity of fibrous filter media. The underlying causes for this effect were investigated by performing filtration experiments with arrays of nylon and stainless steel fibers (diameters of 20, 30, and 44 μm) coated with precisely defined amounts of oil. The single fiber efficiency in the inertial regime (Stokes numbers >0.5) was measured as a function of dust load, using 3.5 μm polystyrene and 2.1 μm silica particles in combination with various types of oils (0W-30, WD-40). Additionally, the influence of an oil film on the growth of particle deposit structures was investigated by optical microscopy.

It was found that dust deposition on oily fibers occurs in two distinct stages: at first particles are immersed in the oil film without any appreciable increase in fiber efficiency. Once the film is saturated with particles, further deposition leads to quasi-normal dendritic growth typical of dust deposition on dry fibers, and a sharp increase in single fiber efficiency. The maximum packing density inside the film which is reached at the transition from particle immersion to regular growth, was approximately 46% by volume, regardless of film thickness. There were no indications of flow-induced particle rearrangement inside the film during the first stage.

Comparative measurements were also made with standard paper media containing varying quantities of oil. The oil caused an increase in dust holding capacity by factors between about 1.5 and 3 compared to dry media, due to a delayed upswing of the filter pressure drop with dust loading. The penetration of dust through the media more than doubled.

We conclude that particle immersion in the oil film is responsible for both the delayed increase in fiber efficiency and fiber drag, and that this delay is roughly proportional to the amount of oil loading.

1. Introduction

The pre-treatment of engine intake air cleaning systems with oil has a long tradition. While being both, chemically stable and innocuous to the engine itself, oil provides a wide range of exploitable features such as better filter cleanability, suppression of solid particle re-entrainment or even the deactivation of bio-aerosols (Pyankov et al. [1]). Since the early 1990s, oil-treated filter media are also used increasingly for disposable intake air filter elements in road applications, especially in Asia, because they offer higher dust holding capacities and accordingly long service intervals. Despite the apparent practical advantages of "pre-oiled" fiber filters, the open literature contains surprisingly little information about the exact reasons for such a performance improvement, or even about how the oil is actually distributed inside the media.

Oil (or any other liquid, for that matter) will spread on wettable fibers to form a thin film, which may break up into droplet chains due to the Plateau-Rayleigh instability, depending on the amount of liquid (see e.g. Mullins & Kasper [2]). In fibrous filters or wire meshes the liquid distribution is less uniform, because liquid tends to aggregate at fiber intersections or other constrictions while those regions actually responsible for particle deposition receive only a thin film (Walkenhorst [3]). It is therefore desirable to limit the amount of oil inside the fiber matrix to prevent excessive closure of interstices associated with a higher pressure drop (Niakan [4]; Mead-Hunter et al. [5]). Thin liquid coats are known to reduce or suppress the elastic rebound of particles on flat surfaces (Davis et al. [6]) as well as on fibers or wires (Walkenhorst [3,7]; Boskovic et al. [8]). The sticking probability of particles impacting on a wet fiber essentially becomes unity for low impaction velocities. However, beyond a critical velocity, particles will nevertheless rebound even from wet surfaces (Davis et al. [6]; Walkenhorst [7]). On dry fibers, reduced particle bounce is known to lead to changes in the way dust deposits build up around the filter fibers with attendant changes in filter efficiency (Kasper et al. [9,10]). Furthermore, an oil film (or the presence of oil droplets on fibers) effectively increases the fiber diameter and this will also have an influence on the collection efficiency. Niakan [4] claims an increased efficiency for pre-oiled automotive filters.

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However, none of the aforementioned effects can readily explain the very striking increase in dust holding capacity (DHC) observed in practice for oily filters. The DHC is defined as the amount of collected dust that leads to a predetermined maximum pressure drop at a given volumetric flow rate. Higher DHC means reaching the critical pressure drop at a later stage of dust loading and represents a substantial benefit to many filter applications. Presumably the increase in DHC is caused by changes in the micromechanical interactions between impacting particles and fiber matrix and/or a more advantageous arrangement of particles around the filter fibers. Brown [11], in his well-known book on filtration and in reference to two papers by Walkenhorst [3,7], suggests that particles in (or on) the oil film may become mobile and be transported to the downstream side of a fiber. Their contribution to the drag force would be far smaller there than on the upwind side where they normally accumulate due to inertial impact (Kasper et al. [10]). Although we were unable to find any information in Walkenhorst's original papers pertaining to particle transport in, on, or by the oil film, Brown's transport hypothesis nevertheless represents a plausible explanation for the advantageous effects of oil on the pressure drop evolution, and hence on DHC. Walkenhorst's work [3,7,12] on particle deposition on wire grids was mostly focused on macroscopic filtration properties, but offers a wealth of other valuable observations on the effects of oil. Apart from the aforementioned report that oil accumulates preferentially at crossing points, he observed that it creeps slowly inside the deposited particle structure but, in case of high particle deposition rates, cannot seep fast enough through the deposit to wet the growing structure exposed to the gas flow. Finally, he noticed a marked change in the deposition behavior of charcoal dust above a particle load of 0.6 g per gram of oil, where the efficiency drops radically due to particle rebound (however at a gas flow velocity of 10 m/s). We shall return to these observations in the discussion of our own results.

The objective of this paper is to sort out the various hypotheses by systematic investigations of particle accumulation on oil coated filter fibers, and to provide a micromechanical explanation for the macroscopically observed increase in DHC. We do this with techniques developed previously for the investigation of particle deposition on individual filter fibers (Kasper et al. [9,10]). These techniques permit the *visualization* of changes in the arrangement of particles around individual fibers due to oil loading, and their correlation with *measurements of the single fiber collection efficiency* as a function of particle load. The experiments were done with particles in the size range of several micrometers (typical of those used in standard filter tests), deposited on metal or polymer fibers in the diameter range of 20 to 44 μm. On the basis of these experiments we provide a qualitative mechanistic explanation for the behavior of the oil–fiber-particle system and derive a value for the dust capacity of an oil film. Finally we compare our observations qualitatively with the behavior of actual filter media coated with oil.

2. Experimental methods

All *single-fiber experiments* presented in this paper were carried out on arrays of 25 parallel, equidistant fibers. The fibers were either of nylon 6,6 or stainless steel (SS), with diameters of 20, 30, or 44 μm and a center-to-center spacing of exactly 246 μm. The fibers were coated with commercial engine oil Castrol Edge 0W-30 or penetrating oil WD-40 (by WD-40 Co.). In some cases the transparent oil was dyed with a red colorant (Sudan III) to help visualize the oil film. More details are given below about how the oil was deposited and how the amount of oil on a fiber was determined.

Fibers were loaded with mono-dispersed particles of either polystyrene (PSL, 3.5 μm) or silica mono-spheres (2.1 μm). Filtration velocities were chosen to ensure predominantly inertial deposition at Stokes numbers above 0.5. In this work, the Stokes number is defined as the particle relaxation time τ_P, nondimensionalized with the ratio of fiber diameter d_F to approaching velocity v.

$$St = \frac{\tau_P \cdot v}{d_F}$$

The collection efficiency of individual fibers in the array was measured continuously as a function of time via an optical real-time technique described in more detail below. Such data also provide quantitative information about the cumulative particle load. The fiber loading experiments were interrupted from time to time to document the evolution of deposit structures photographically with a macroscope. Where necessary, digital image stacking techniques were applied to improve the depth of field at higher magnifications.

A small number of experiments were also performed with *flat sheets of cellulose paper media,* in order to assess the transferability of conclusions from the single fibers to the media scale. The media were treated with oil to varying degrees by essentially the same procedure as for single fibers, and then loaded with test dust (ISO 12103-1 A2 fine) on a standard filter testing rig using state-of-the-art test methods which do not need to be repeated here. Experimental parameters are given in Section 5, alongside the results.

2.1. Procedure for coating fibers with oil and determining the exact amount of oil deposited

Oil was nebulized with a custom-built atomizer to create a fine oil mist with an average drop diameter around 400 nm. These droplets were deposited directly onto the fiber array by exposing it to the aerosol stream at a rather high flow velocity. This ensures a defined and homogeneous distribution of the oil without liquid bridges building up between neighboring fibers.

The exact volume of the oil film on individual fibers was determined by image analysis after each coating step, taking into account its wavy contour of successive drops connected by a film (compare also Fig. 1). For this purpose the local diameter of the combined contour of fibers and oil droplets was derived pixel by pixel from high resolution microscopy pictures and converted into liquid volume assuming a cylindrical symmetry. The accuracy of this method depends on the degree of cylindrical symmetry of the oil film which, among the sample oils tested, was found to be best for WD-40 oil (see Section 3.1). Consequently, all experiments requiring quantitative information about liquid coverage (as detailed in Section 4) were conducted with WD-40.

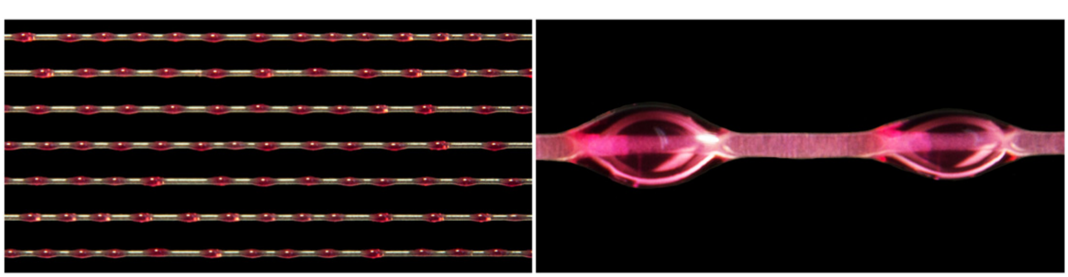

Fig. 1. Micrographs of fibers coated with dyed oil. Left: 30 μm stainless steel fibers in an array coated by WD-40. Right: 44 μm nylon fiber coated with WD-40 showing that droplets are connected by a thin oil film.