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Pressure drop and liquid transport through coalescence filter media used for oil mist filtration

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ABSTRACT

A phenomenological model is presented to explain the increase in pressure drop (Δp) of air filters during steady operation with oil mist. It is based on (currently) semi-quantitative conclusions obtained from measurements of liquid distribution patterns in the media associated with the transport of coalesced liquid by the flowing air. Correlation of these patterns in space and time with the evolution of the pressure drop suggests that the over-all increase in Δp (the "wet" pressure drop) is governed by two distinctly different liquid transport mechanisms:

A steep Δp *jump* is required to overcome the capillary exit (or entry) pressure and pump liquid into non-wettable, or out of wettable fibrous matrices. It is associated with the formation of a thin liquid film covering almost the entire front (or rear) face of the respective media. With the help of a polymerization technique to "freeze" the liquid distribution, the film is shown to be confined to the outermost surface without entering the media while the aerosol flow is on.

Liquid transport inside the media is shown to occur in multiple parallel channels spanning almost the entire thickness of a filter. The *channel* Δp associated with this transport mechanism increases linearly with media thickness. Wettable media form numerous fine channels which feed a liquid film on the rear face by which drainage takes place. Non-wettable media form fewer, relatively wide channels ending in large drops on the rear face, through which drainage takes place during steady operation.

Sandwiched combinations of wettable and non-wettable media show the same combination of features in their respective Δp curves. There are separate Δp jumps and channel regions for each media type. In case of a transition from wettable to non-wettable media, the combined exit and entry Δp jump takes place at the internal interface.

1. Introduction

Coalescence filters are widely used to remove droplet aerosols such as oil mist from air. They typically consist of multiple layers of fibrous media, which can be wettable ("oleophilic") or non-wettable ("oleophobic"). Oil mist is emitted by air compressors and engine crankcases in the size range of about 0.1–1 μm. The aerosol is removed quite efficiently by such filter media, often within the first few layers, and collects on the fibers, where it coalesces with time into much larger drops (Yarin et al., 2006). With growing size these drops are entrained by the air flow. Coalesced liquid is thus transported from the front most layers of a filter to its rear surface, where it must drain due to gravity. (Media are installed vertically in many oil mist filters, i.e. with a horizontal air flow.) After some time of operation, which depends on the rate of aerosol arrival, the filter reaches a steady state where the rate of oil accumulation equals drainage. Coalescence filters operate in this mode for almost their entire useful life.

A large body of theoretical and practical knowledge has been accumulated on the functioning of air filters in general (e.g. Davies, 1973; Brown, 1993). As long as a filter is dry, this knowledge can be used to estimate its pressure drop and efficiency of aerosol deposition, regardless of whether the arriving particles are solid or liquid. However, once aerosol has accumulated to an appreciable degree, a filter will behave very differently with respect to the two types of aerosol: While solid "dust" remains on the fibers (e.g. Kasper et al., 2009, 2010) until the filter clogs and forms a cake (Walsh, 1996), liquid accumulating in a coalescence filter does not stay where it is first deposited due to forces such as gravity of friction from the air flow. These subsequent processes of liquid redistribution and transport inside the media are complex and still poorly understood, in some regards not even qualitatively, because they depend on numerous parameters such as media structure, fiber wettability and capillary effects, fluid viscosity, as well as the interaction of the coalesced liquid with the air flow. Unfortunately these processes are also critical for the evolution of pressure drop and efficiency,

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the most important performance criteria of any filter. Hence there is a growing need to understand them better in order to optimize coalescence filters.

Static saturation and liquid uptake by porous capillary systems *in the absence of an air flow* have been researched extensively (e.g. Dullien, 1979; Schubert, 1982), including the wetting of fiber arrays (Princen, 1969) and filter materials (Gillespie, 1959; Marmur and Cohen, 1997; Mullins et al., 2007). Static or quasi-static treatments do not suffice to describe the dynamic liquid distribution in coalescence filters, especially not inside media that are not wettable.

The *dynamic saturation S* of fibrous media (measured either under conditions of a stationary aerosol flow or, more often, by first saturating the media and then "blowing them out") generally shows an inverse dependence on the flow velocity, which can be expressed as saturation $S \sim (Ca)^{-\alpha}$. $Ca = \mu v/\sigma$ is the capillary number, i.e. the ratio of flow induced shear driving the liquid out of the medium to the surface tension force retaining it. (With μ the dynamic viscosity, v the filtration velocity, and σ the surface tension.) Reported values for the exponent α vary between about 0.2 (derived from Frising et al., 2005a; for a very low flow velocity), 0.5 (Liew and Conder, 1985; at rather high flow velocities) and 1 (Mead-Hunter et al., 2013; for intermediate velocities most typical for oil mist filters). This is evidence for the internal "rearrangement" of liquid due to the air flow, but also for a mechanism akin to the inverse relationship between capillary rise and static pressure head observed in porous media (Mullins and Braddock, 2012). However such relationships do not explain the dynamic saturation profiles commonly observed inside thick coalescence filters (which are by no means uniform), nor can they describe the complex pressure drop dependence of such filters, which is the main subject of our paper.

Publications surrounding coalescence filtration fall mostly into one of two major categories: There are studies involving flat media or even entire filter elements (e.g. Raynor and Leith, 2000; Contal et al., 2004; Mölter-Siemens et al., 2012) which describe the increased pressure drop of wet filters with its attendant decrease in filter efficiency in terms of classical filtration theory, or investigate the effects of inclination and combinations of different media types on efficiency and drainage (Agranovski et al., 2001a,b). Although this macroscopic approach provides a useful framework for predicting filter behavior within a narrow parameter range, it typically cannot establish a satisfactory causal relationship between saturation and wet pressure drop. – The other category of studies addresses the forces of interaction between individual droplets and single fibers. With obvious advantages and drawbacks to either approach.

At the single-fiber level, quite a number of investigations describe the forces acting on drops attached to fibers due to shape, capillarity and contact angle (Carroll, 1976; Quéré, 1999; McHale and Newton, 2002; Shin and Chase, 2004), as well as their motion along fibers due to air friction and gravity (Mullins et al., 2005; Dawar and Chase, 2008) or by active intervention with AFM techniques (Mead-Hunter et al., 2010). Such techniques and observations provide valuable input to the numerical simulation of droplet transport in fibrous systems (King and Mullins, 2011), without however being able to describe the kinetics of real filter behavior with sufficient realism, as shown first by Agranovski and Braddock (1998a,b). Several years ago a video was taken in our lab (www.mvm.kit.edu/gps.php) to illustrate how fine water mist accumulates on steel fibers, coalesces into mm-size drops forming a "string of pearls", and then drains periodically under the influence of gravity, sweeping away and collecting smaller drops in the process (an image also evoked in a conference paper by Andan et al., 2008) This video provides a sense of the discontinuous and distributed nature of liquid transport in a fibrous matrix. The challenge remains to translate those mechanistic pieces of the puzzle into a coherent transport model at the scale of a typical fibrous filter medium.

At the *level of filter media or entire elements*, one key challenge, addressed in our paper, is to explain (and then minimize) the dramatic rise in pressure drop with increasing oil load. For oleophilic media, the type investigated almost exclusively in the literature, the "wet" pressure drop typically rises modestly at first until just before reaching steady state, where it makes a rather steep jump and then levels off. This trend has been described frequently for various (wettable) filter media, e.g. by Walsh et al. (1996), Contal et al. (2004) and Frising et al. (2005a). Contal et al. attribute it qualitatively to several stages of clogging – an expression borrowed from dust filtration – starting with gradual coalescence of drops on individual fibers (to which the slow part of the Δp increase is ascribed), followed by internal rearrangement of liquid due to air flow and/or capillary forces (not accessible to observation) and ending with the formation of a dense liquid layer visible across much of the filter surface[1]) which clogs the filter and is presumed to cause the final, dramatic jump in Δp before reaching steady state. The layer-by-layer saturation profiles measured during these four stages (Contal et al., 2004) show a liquid front progressing through the filter until the oil distribution in steady state becomes completely flat, suggesting that the oil is rearranged internally until the entire filter is filled uniformly from front to back. Based on this interpretation, the semi-empirical pressure drop model proposed by Frising et al. (2005a) assumes that successive layers are filled to equal levels of saturation, first in the form of a liquid film around the fibers and then with additional coalesced liquid. The resulting pressure drop model curve indeed becomes steeper with oil load, but does not emulate the sharp jump actually observed before the on-set of drainage in steady state. Generally, both the models developed by Raynor and Leith (2000) and Frising et al. (2005a) do not represent the actual liquid distribution inside the filter well (Mullins and Kasper, 2006). We shall return to these references in discussing our own results.

Work has also been done for relatively coarse droplet separators where *gravity induced flow* plays a significant role, such as in wire meshes (e.g. Laminger and Höflinger, 2011), demisters (El-Dessouky et al., 2000) and packed columns (Ellman et al., 1990; Nguyen et al., 2005). The role of gravity seems to depend strongly on the density of the fibrous matrix. While it is an important factor for widely spaced geometries, we have found no evidence of internal oil drainage in the much denser coalescence media.

In summary, there is still no satisfactory *mechanistic* description relating the pressure drop (of the air!) across such an oil mist filter to the internal distribution and transport of oil, despite a number of important contributions to the subject. Furthermore, existing work deals almost exclusively with wettable filters, although both types of media are commonly used. This knowledge gap is largely due to the experimental challenges in accessing the necessary information about fluid distribution and flow inside a dense fibrous matrix while the filter is in operation. Shutting off the air flow is not an option, since the liquid tends to redistribute when the air flow is shut off (Frising et al., 2005b; Bredin and Mullins, 2012), probably due to the same capillary phenomena which are responsible for the inverse relationship between dynamic saturation and flow discussed earlier. Recent measurements with X-ray tomography (Charvet et al., 2011) were reportedly done after shutting off the flow and are thus not helpful in explaining dynamic phenomena. An MRI based method successfully imaged sufficiently large pieces of filter material in situ while being loaded with solid parti-

[1] Contal et al. do not mention the location or extent of this film, which was presumably observed after shutting off the air flow.