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Validation of a new phenomenological “jump-and-channel” model for the wet pressure drop of oil mist filters

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HIGHLIGHTS

- Total Δp is determined by oil transport across interfaces and through channels.
- Interfaces require Δp jumps determined by media properties not operating conditions.
- Conversely, channel Δp is determined by oil transport rate and oil viscosity.
- Local saturation is determined by the local Δp required to pump the oil.
- The model applies to wettable and non-wettable glass fiber media.

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ABSTRACT

The “wet pressure drop” of oil mist filters (i.e. the increase in differential pressure of the air flow due to loading of the filter with liquid) is presented as a function of two mechanisms by which coalesced oil is transported through the filter. These mechanisms operate in separate regions of the filter and make separate (and separately measurable) contributions to the overall wet pressure drop. This new concept, which was first formulated qualitatively in a phenomenological model by Kampa et al. (2014), leads to semi-quantitative predictions regarding the dependence of pressure drop Δp and saturation S on filter operating conditions, filter properties and liquid properties. These predictions are first formulated and then validated for a range of wettable and non-wettable filter media in combination with 4 mineral oils of different viscosity. The key findings, summarized below, are consistent with the model and apply to both wettable and non-wettable media.

Oil transport across media interfaces (i.e. transitions between regions of different porosity and/or wettability) was associated with a relatively sharp increase in pressure drop Δp and oil saturation S over a very thin layer of the filter (a “Δp jump”). The magnitude of this Δp jump was determined by the media properties. It correlated well with the respective static break-through pressures for oil or air, but did not depend on the oil viscosity and loading rate of the filter (at constant air velocity). Oil transport through channel regions of the filter (i.e. the regions connecting interfaces) was associated with a linear increase in Δp with channel length and liquid throughput. The corresponding saturation level S was relatively flat throughout the channel region and lower than at an interface. (Both quantities are media dependent, of course.) An increase in oil viscosity μ (at constant oil throughput) led to different responses depending on filter wettability.

1. Introduction

Aerosols consisting of sub-micrometer oil droplets (“mist”) are an undesirable contaminant of effluent air from engine crankcases, oil lubricated compressors and other industrial processes (Brink et al., 1966; Leith et al., 1996; Boundy et al., 2000). A very common way of eliminating oil mist is by fibrous filters (Fairs, 1958; Mohrmann, 1970). During the operation of such filters, aerosol accumulates continuously on the fibers where it coalesces into larger drops which begin to redistribute in the fibrous matrix under the influence of friction forces induced by the gas flow (Walsh et al. 1996; Contal et al., 2004; Kampa et al., 2014), and for relatively open-pore media also due to gravity. The accumulation of liquid is associated with a very significant increase in filter pressure drop Δp [1] – usually a multiple of the dry pressure drop

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[1] Note that in this paper “pressure drop” always refers to the flow of air.

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(Fairs, 1958; Charvet et al., 2008) – which manufacturers try to minimize by appropriate measures. Such optimization strategies require a physical model linking the "wet" pressure drop to filter design and operation.

The increase in Δp is obviously due to an increase in liquid saturation S of the filter matrix, although very sensitive to its exact spatial distribution. As a first approximation, the saturation profile within a filter has been treated as uniform (Liew and Conder, 1985; Raynor and Leith, 2000), or as linear in the direction of flow (Andan et al., 2008). Contal et al. (2004) noticed that their filters exhibited a more complex internal saturation profile in the direction of air flow, which shifted with time as oil accumulated and spread inside the media. The resulting Δp increase as a function of loading time (up to steady state) was therefore simulated on the basis of the momentary local filter efficiency, which provides the incremental deposition of oil for each filter layer, which can in turn be converted to an incremental contribution to Δp using semi-empirical expressions taken from filtration theory (Frising et al., 2005). This refined approach was able to reproduce actual Δp-data in a more realistic way. However it required assumptions at the microscopic level of how oil acctually accumulates on fibers, how it coalesces into larger structures, and how these structures then affect the local deposition efficiency and pressure drop.

Measuring internal liquid distributions in oil mist filters is complicated by the fact that capillarity tends to redistribute the liquid once the air flow is shut off, resulting in artifacts. MRI imaging on filters is typically too slow, except in steady state (Agranovski et al., 2001). Furthermore, oil mist filters can be composed of both wetting ("oleophilic") and non-wetting ("oleophobic") media with rather different behaviors, or even mixtures of both types of fibers (Kulkarni et al., 2012). Kampa et al. (2014) developed special techniques to investigate the distribution and transport of oil in multi-layer stacks of glass fiber media. These techniques permitted to observe in greater detail, how characteristic oil patterns develop in wettable and non-wettable media, and to associate these patterns with specific oil transport mechanisms in the filter. Based on these observations a new semi-quantitative model relating pressure drop to oil transport was formulated, which applies in principle to both wettable and non-wettable fibrous filter media. Aside from lending physical meaning to the pressure drop curve, this model operates with mesoscale quantities more readily accessible to measurement.

The current paper validates this model with quantitative experiments. Following a summary of its principal features, we derive predictions from the model with regard to the dependence of Δp on key physical parameters related to filter operation (air velocity v, aerosol mass concentration c, and oil loading rate $c \cdot v$), filter characteristics (average pore size, wettability, order and number of wettable and non-wettable layers), and oil properties (viscosity μ and surface tension σ). We then proceed step by step to verify these predictions experimentally with a range of glassfiber media and oils.

2. Summary of the "jump-and-channel" model for Δp and its verifiable predictions

The model as first formulated qualitatively by Kampa et al. (2014) groups the features of oil distribution observed in both wettable and non-wettable filter media by two principal transport mechanisms, which operate in separate regions of the filter, operate independently of each other, and each make a distinct contribution to the wet pressure drop. (The wet pressure drop is defined as the pressure differential above and beyond the Δp needed to move air through the dry filter.) These transport mechanisms apply to both wettable and non-wettable media. One mechanism provides for liquid transport across media interfaces, while the other transports it inside media, as explained below:

Differential pressure is required to drive liquid across media interfaces, such as the front face of a non-wettable medium or the rear face of a wettable medium[2]. This Δp increase is due to the formation of a thin liquid film across that interface, which causes the pressure to rise steeply over a very short distance and therefore suddenly (relative to the loading time required to attain steady state) — hence the term *Δp jump*. One can think of it as the means to overcome the capillary pressure which retains liquid in a wettable matrix or prevents it from entering a non-wettable matrix, keeping in mind however that we are actually dealing with a dynamic process, namely the energy to pump a dispersed flow of liquid, rather than a hydrostatic phenomenon (such as in dewatering of filter cakes or the bubble point pressure).

Once liquid has entered the filter, it is transported toward the rear in multiple parallel channels spanning almost the entire thickness of the filter — hence the term *channel Δp* for the associated pressure drop required for "pumping". Such channel-like tortuous paths were first observed by Agranovski et al. (2001) by imaging filters with MRI. The channel Δp increases linearly with channel length, much like a Darcy flow through uniform porous media. A caveat applies here as well, in that these "channels" should not be envisioned as continuous liquid filled tubes, but more like a succession of coalesced oil drops moving along the same preferred pathways.

Fig. 1 shows a key result of the model with four representative cases of pressure increase vs. time: for a filter consisting entirely of wettable layers, where the channel Δp precedes the Δp jump; a non-wettable medium, where the order is reversed; a set of wettable layers followed by non-wettable layers, where the interface is internal; and the reverse combination, where liquid can transit without any internal barrier and where the jumps are on the outside. In summary, the model suggests that the total wet pressure drop of an oil mist filter can be obtained by adding up the "modular" contributions of the individual layers, which depend on where a layer is situated in the overall sandwich.

Despite their obvious limitations, the analogies to capillary pressure and fluid flow through channels are useful because they are useful in deriving verifiable semi-quantitative predictions for the system response to a change in key parameters: for example, the Δp jump should depend primarily on 'capillary' properties such as interfacial tension σ or wettability. On the other hand the channel Δp should be a function of the viscosity μ as well as the amount of liquid to be pumped through the filter per unit time (in other words the liquid loading rate $c \cdot v$). The media structure should affect both Δp components in the same sense, with finer pores implying a steeper jump as well as more energy to maintain the channel flow.

A third, very important but less obvious prediction by our model concerns the *relationship between pressure drop and liquid saturation level S* in the various regions of the filter. While the common view of fluid flow through porous media suggests that Δp is a consequence of S – in other words the more pore volume is lost to accumulated liquid, the higher Δp will become, with some complex relationship between the dependent and the independent variables – we propose the reverse. The saturation S at a given point in the filter rises to exactly the level required to build up the additional Δp necessary to transport the fluid. This view

[2] Aside from external interfaces to air, a filter can also have internal interfaces such as the transition between wettable and non-wettable filter layers in contact with each other. Although this is a dynamic concept, capillarity provides a useful analogy for the functioning of an "interface".