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TEMPORAL EVOLUTION OF THE SATURATION PROFILE OF AN OIL-MIST FILTER

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ABSTRACT

Oil-mists are generated by many industrial processes, including engine crankcase ventilation and generation of compressed air by oil lubricated compressors. It is necessary to remove these mists to avoid problems further downstream or to meet health and safety regulations. The most common method for removing such particles from an air stream is the use of fibrous filters. These filters usually operate with a given quantity of retained liquid, termed the filter saturation, which is usually not uniformly distributed in the flow direction. The temporal evolution of this saturation profile in the flow direction was determined for multi-layered oleophobic and oleophilic filters. The local oil distribution, highlighted by a series of images, indicates the formation of oil channels. This work has improved the understanding of the evolution of the pressure drop in such filters.

KEYWORDS

Mist Filtration, Coalescence Filter, Liquid Saturation, Transport in Porous Medium

1. Introduction

Oil-mists, i.e. liquid aerosols with a typical droplet size of a few hundred nm are generated by many industrial processes, including engine crankcase ventilation and generation of compressed air by oil lubricated compressors. It is necessary to remove these mists to avoid problems further downstream or to meet health and safety regulations. The most common method for removing these mist droplets from an air stream is the use of fibrous filters. Mist droplets are deposited on the fibres due to diffusion, interception or inertial impaction (Brown, 1993). With more and more droplets being captured by a fibre, they coalesce into larger drops (Yarin et al., 2006). Then these large drops are transported to the rear of the filter, where they drain. Finally a steady state is reached, in which oil accumulation and drainage rates balance out (Contal et al., 2004). Filters operate in such a steady state for almost their entire life. Nevertheless, the evolution of the filter parameters before the steady-state is reached gives important insights into the oil transport within the medium.

The saturation is a measure of the global oil distribution. For multi-layer filters typically used in industry, the saturation of each layer and thus the saturation profile of the entire filter in the flow direction was determined. The local oil distribution, and hence the nature of the oil in the filter is highlighted by photographic pictures. This information leads to an understanding of the oil transport in an oil-mist filter, which will, in addition, be used to extend the common explanation (Contal et al., 2004, Frising et al., 2005) of the evolution of the pressure drop.

2. Evolution of the saturation profile

To measure the saturation profile, filters consisting of ten layers of standard glass fibre media (fibre diameter ≲ 1 µm, packing density 5%, thickness 0.5 mm) were loaded with oil mist (loading rate 0.2 kg h^{-1} m^{-2}, average droplet size 0.3 µm). The aerosol was generated by an atomizer and passed through the filter, which was mounted in a flat sheet filter chamber, with a face velocity of 0.3 m s^{-1}. The evolution of the saturation profile of an oleophobic filter (Fig. 1 left) was measured by determining the saturation profile of a filter, which was loaded with oil mist for a specific time. To measure the saturation profile, the saturation of each individual layer was determined gravimetrically after the flow was stopped and the filter sandwich was disassembled.

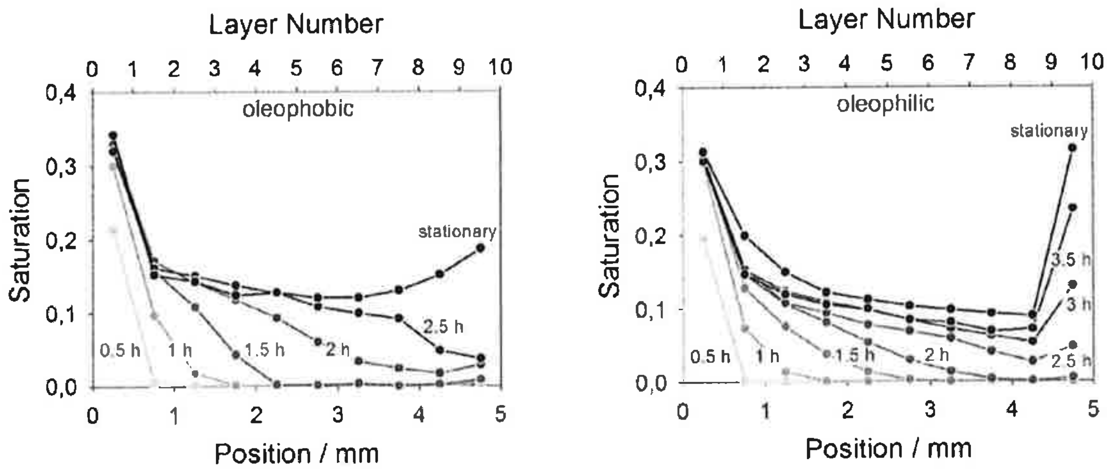

Figure 1: Evolution of the saturation profile of an oleophobic filter (left) and an oleophilic micro glass fibre filter (right) loaded with 0.2 kg h^{-1} m^{-2} at 0.3 m s^{-1}.

During the first half hour mainly the first layer is saturated, since most of the oil droplets are deposited there, remain there and coalesce into larger drops. Therefore the saturation in the first layer is relatively high. After one hour some oil is already transported to the second layer. With increasing duration of filter operation the oil is transported through the filter in the flow direction, while the former layers have already reached their maximum saturation. The upstream front of the saturation profile forms a wedge, which moves towards the rear. The slope of the saturation profile becomes flatter as it approached the downstream side of the filter. This might have two reasons. Firstly, some amount of the oil is retained in the previous layers. In addition, the gas expands towards the rear of the filter, since the pressure drops over the filter. This results in a larger gas velocity, which incurs a larger drag force on the oil and hence the oil is pushed to the rear more quickly. The larger saturation towards the end results from the fact that the oil cannot flow out freely at the rear of the last layer. Therefore the oil accumulates in front of the grid, which supports the multilayer filter.

The evolution of the saturation profile is very similar for oleophobic and oleophilic filters (Fig. 1 right). Due to the better wettability, the wedge moving towards the rear is much flatter for oleophilic than for oleophobic filters. The high saturation datum of the last layer results on one hand from the oil accumulation in front of the grid and on the other hand from imbibing the film after the last layer when the airflow was shut off. This film covers the rear face of the last layer and the oil arriving at the rear is drained within it (Fig. 2 right). Despite imbibition of the film after the experiment, the liquid moves but does not redistribute between different layers. However at filtration velocities an order of magnitude lower and concentrations an order of magnitude higher, where the flow forces are less dominant than the capillary forces, a redistribution of the liquid was found in oleophilic filters (Contal et al., 2004).

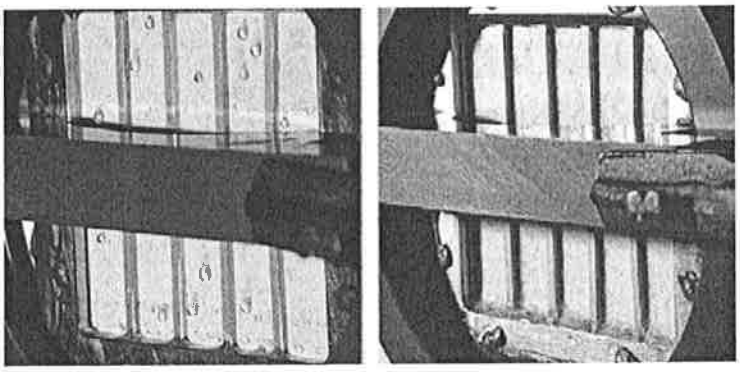

Figure 2: Rear drainage as individual drops for oleophobic media (left) and as oil film for oleophillic as media (right) at a special open grid, face velocity 3 cm s^{-1} each. The filter rear face measures 8 cm x 8 cm.

A similar steady-state saturation profile was observed for the filtration of water droplets in oil (Bitten and Fochtman, 1971). Depending on the efficiency of the medium, the peak in the first layer can be much lower, spanning several layers or almost be missing (Richardson et al., 1952, Contal et al., 2004). For reasons of simplicity, here the words “first layer” are chosen, whereas, to be pedantic, “after most of the oil was deposited”, or “after the initial saturation peak” would be scientifically more appropriate.

3. Macroscopic and microscopic oil distribution

While the overall saturation of the filter is only a measure of the global oil distribution over the depth of the filter, the local oil distribution within one layer can be highlighted with photographic pictures. For an oleophobic medium, which was loaded for 2 hours, the oil in the first layer is distributed very homogeneously (Fig. 3). There the oil is deposited and coalesces into large drops, which are transported into “oil channels”.

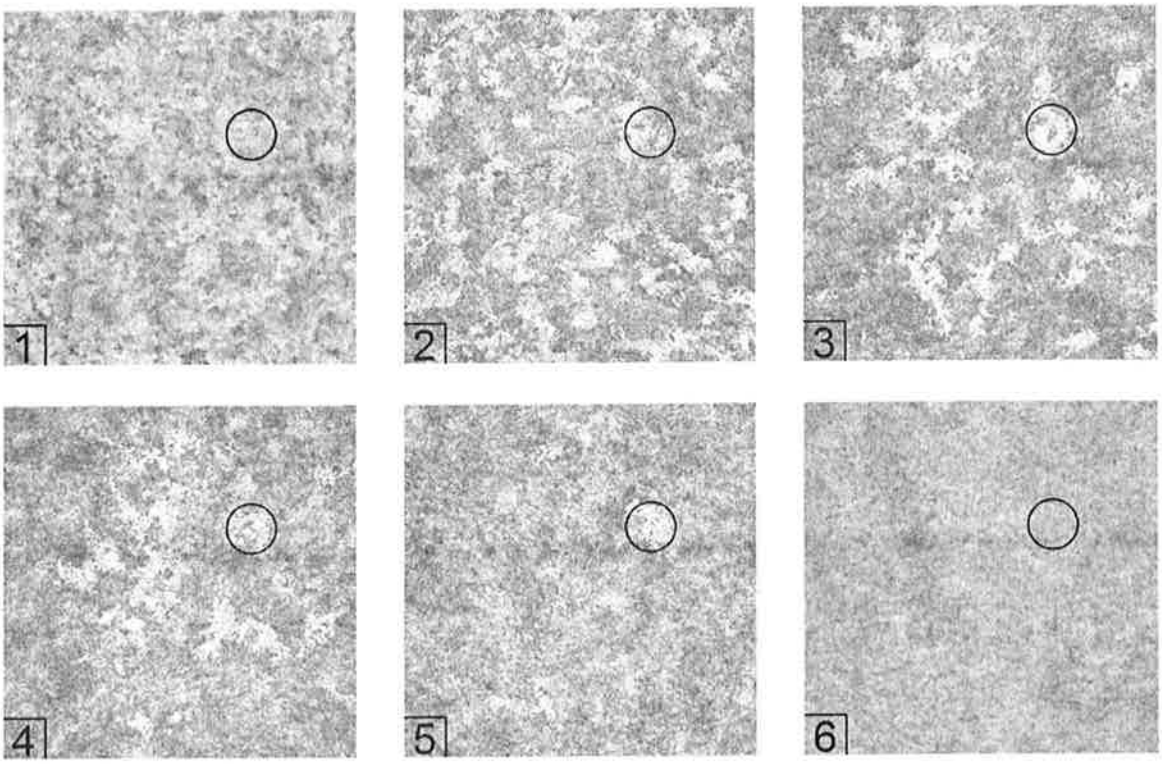

Figure 3: The macroscopic oil distribution of layers 1-6 (layer number in the lower left corner of each picture) for a 2-hour experiment with an oleophobic filter. The circle shows the cross section of an oil channel.

Oil channels are fully saturated regions which extend up to the last layer (such an oil channel is indicated with a circle for the 2 hour experiment in Fig. 3). These channels are separated from the void space (Fig. 5), where the gas stream passes through. An approach similar to the oil channels was introduced as a model in the coalescence literature (Spielman and Goren 1970), but in our case channels may join and split and usually span several fibres. In these oil channels the oil is transported to the rear. That means, coalesced drops only exist in the first layer (Raynor and Leith, 2000) (Fig. 4), but not in all subsequent layers (Fig. 5).

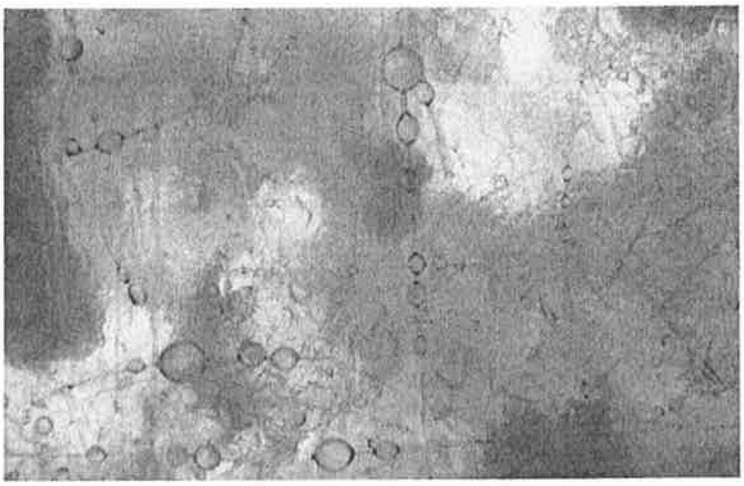

Figure 4: Coalesced oil drops in front, fully saturated regions of oil channels in the background of an oleophobic layer.

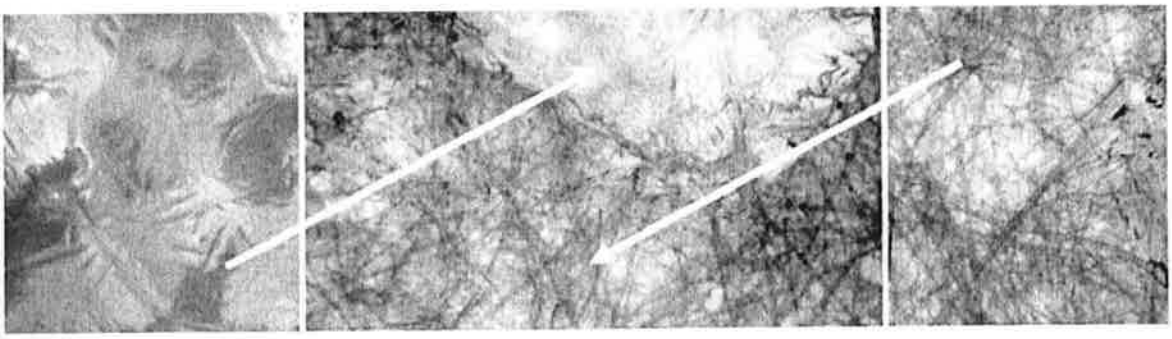

Figure 5: Clear separation between oil channels (left) and void space (right) for an oleophobic medium.

The formation of the oil channels can be explained as follows. Even if the fibres are more or less equally distributed in a medium, there are whole regions, which have a lower permeability than other regions. This might result from a locally larger amount of small fibres or that these regions are blocked by the binder material. In the beginning of the filtration, the flow first passes through regions of high permeability. Hence the droplets are deposited there first. Then these droplets join into drops, which are transported with the air flow into the regions of high permeability and form oil channels. As a result, the high permeability regions are then blocked with oil and unavailable for the gas stream to pass through. Therefore the air flow then goes through regions of low permeability.

The oil channels usually form in the second layer of a multilayer filter and remain present until the end of the filter. If such channels formed in the first layer, the flow would pass through the unsaturated regions and the aerosol would be deposited there. Accordingly these regions would be saturated. Therefore the oil is distributed almost homogeneously in the first layer, whereas in the subsequent layers there are larger "patches" of oil which correspond to cross sections of the oil channels (Fig. 3). In oleophobic media the oil channels have a bigger size than in oleophilic media due to the higher surface energy. Due to the non-wettability, they are confined more rigidly in oleophobic media, hence the limit between the void space and the channels is sharper in oleophobic than in oleophilic media.

4. Evolution of pressure drop

The different nature of oil as well as their evolution is reflected in the pressure drop signal and is, to some extent, interpreted in literature (Contal et al., 2004, Charvet et al, 2009).

For oleophobic media (Fig. 6), the pressure drop increases rapidly, since the deposited droplets (from the collected aerosol) remain as clamshell droplets on the fibre (Mullins et al., 2005). Since the pressure drop signal in the first layer is governed by droplet deposition and coalescence, the initial increase in pressure drop is similar for a one and a ten layer filter. This is also expected for causality reasons, in other words, the oil in the first layer does not know, whether it later on might pass through additional layers or not (inset of Fig. 6). The further evolution of the pressure drop is governed by the region of oil channels. In this region the oil distribution does not change significantly, once the oil has reached a specific layer. Due to the increasing length of the oil channels while loading the filter, the pressure drop increases linearly. The flow forces push the oil channels into the holes of the grid, from which the oil drops drain or blow-off (Fig. 2 left).

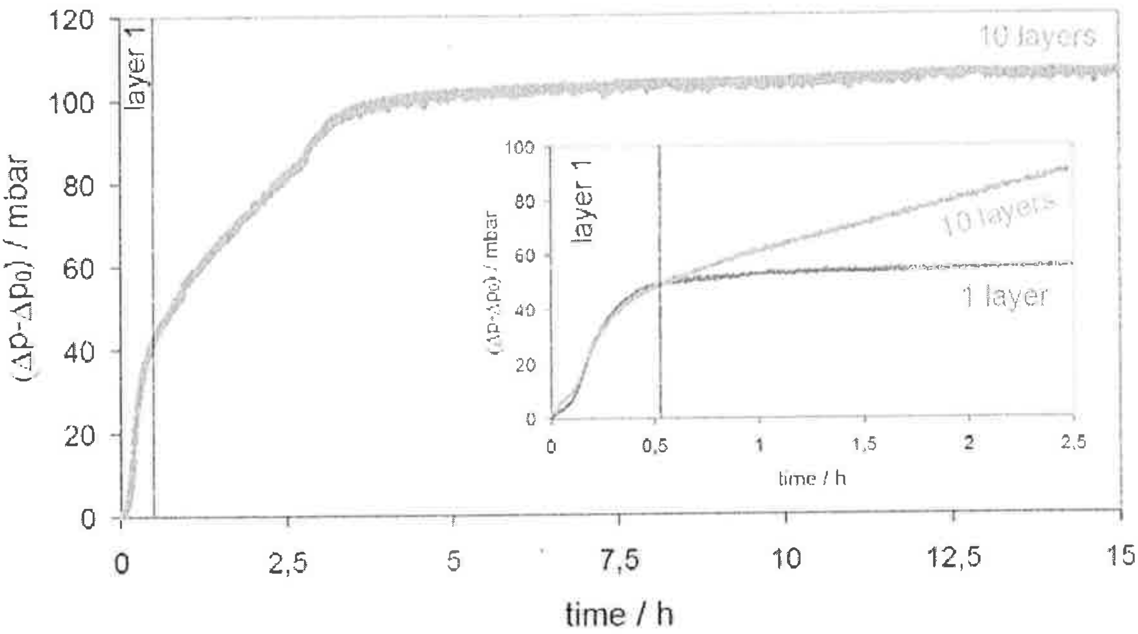

Figure 6: Evolution of the pressure drop Δp relative to the initial pressure drop Δp_0 of an oleophobic filter (0.2 kg h^{-1} m^{-2} at 0.3 m s^{-1}). The first layer is governed by the droplet deposition and coalescence and hence the pressure drop increase is similar for a one and a ten layer filter (inset). In layers 2-10 the pressure drop increases linearly due to the oil channels.

For oleophilic media (Fig. 7), the pressure drop increases slightly in the beginning since the initially deposited droplets immediately spread on the fibre and form a thin film (Mullins and Kasper, 2006), which has low flow resistance. This very different increase in pressure drop for both, oleophobic and oleophilic of media clearly indicates that the common assumption, the pressure drop increase is related only to an increase in packing density (Carvet et al., 2009) cannot be true. For oleophilic media, a kink in the pressure drop signal when the first layer has been saturated, could be related to some re-distribution of the oil (Walsh et al.,1996) and indicates that the oil starts to form channels. Within the region of the oil channels, the pressure drop increases linearly, as for oleophobic media. As soon as the oil channels reach the rear face, they spread and form a film at the rear face, in which the oil is drained (Fig. 2 right). Additionally, the oil is imbibed by the filter regions directly in front of the solid area of the perforated metal plate supporting the filter through capillary forces. Hereby fibre intersections are closed (Contal et al., 2004), and hence liquid bridges are formed (Liew and Conder, 1985). This causes a rapid increase in the pressure drop. For filters consisting of a single layer this increase takes place at a shorter time than for a filter consisting of several layers (Fig. 7). The reasons is, that in a single-layer filter the oil channels reach the grid almost instantly, whereas in a multilayer-filter, there are larger time intervals between the frontiers of different channels (see also Fig. 3).

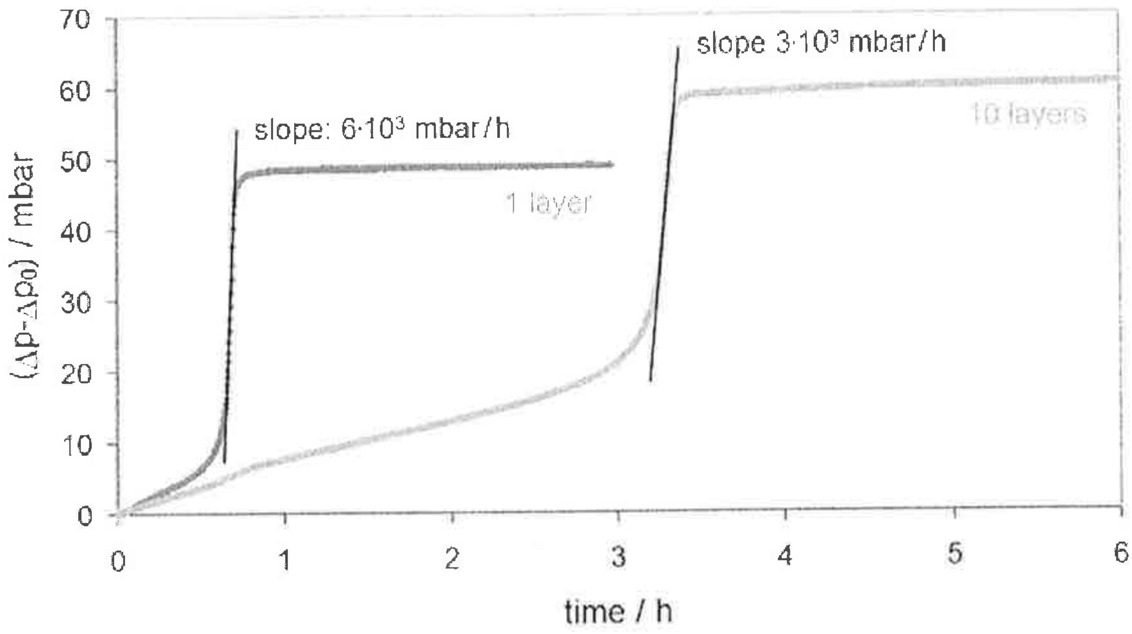

Figure 7: Evolution of the pressure drop Δp relative to the initial pressure drop Δp_0 of an oleophilic filter (0.2 kg h^{-1} m^{-2} at 0.3 m s^{-1}). The first layer is governed by the droplet deposition and coalescence. Then the kink indicates the beginning of the channel region. In layers 2-9 the pressure drop increases linearly due to the oil channels. In front of the grid the oil flows in the cross flow direction which results in a steep increase in pressure drop. For a single layer filter this increase is much steeper, since all channels arrive backwards at almost the same time.

5. Conclusions

The temporal evolution of the saturation profile in the flow direction was determined for oleophobic and oleophilic multi-layered filters. Due to increased wettability, the oil spreads more easily in the flow direction for oleophilic media. In addition to coalesced drops, the saturation of the first layer is composed of individual droplets for oleophobic media and by a film for oleophilic media. This difference is reflected in the pressure drop signal, which increases more rapidly for oleophobic media than for oleophilic media, since the film has less flow resistance than the droplets on the fibre. In the subsequent layers the oil transport takes place in oil channels, which range until the end of the filter. Hence a linear increase in the pressure drop signal was observed. In front of the grid supporting the filter layers, the oil flows into the cross flow direction to form a film for oleophilic filters, which results in a steep increase in pressure drop. Since the oil cannot flow sideways in oleo-phobic media (due to non-wettability), there is no such increase in the pressure drop.

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