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Bubbling vs. blow-off – On the relevant mechanism(s) of drop entrainment from oil mist filter media

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ABSTRACT

A comparative investigation was conducted on wettable and non-wettable glass-fiber filters to clarify the mechanism(s) leading to flow induced entrainment of oil and to determine the influence of oil concentration and filtration velocity on the rate of secondary droplet production. Entrainment rates from a wettable and a non-wettable glass-fiber filter were measured over prolonged periods of time and with high time resolution by two optical techniques covering the drop size regions of about 0.5–10 μm and 150–2000 μm. The rates were compared with oil drainage patterns recorded over time, and with estimates of the forces required to detach drops by blow-off as compared to drop run-off (drainage) or to form air bubbles in a drainage film.

It was found that initially oleophobic (i.e. non-wettable) media underwent a one-time transition in apparent wettability during normal operation, due to a change in drainage behavior from individual drops to a film-like flow pattern of oil. The transition was associated with a temporary increase (“burst”) in entrainment rate. After that, both types of media had steady-state entrainment rates that were comparable within a factor of two and depended mostly on the loading rate of the filter (which in turn determines the drainage rate), but showed little or no at all on filtration velocity. In conclusion, blow-off was ruled out as a mechanism contributing significantly to oil entrainment under the prevailing operating conditions, regardless of media wettability. Secondary droplets are due to fragments from bursting air bubbles, which are formed within the liquid film on the downstream face of the media. The entrainment burst of an initially non-wettable medium is also due to bubbles formed on draining oil drops.

1. Introduction

Oil-lubricated gas compressors and other machinery generate a fine, mostly submicron droplet aerosol (“oil mist”), which is typically captured and removed by microfiber filter media. Such filters are designed to coalesce and drain the accumulating oil continually in order to maintain a steady mode of operation at constant Δp throughout their useful life. The exact functioning and improvement of such filters is a topic of ongoing research [2–4] summarized in a recent review paper [5].

Detailed insight into the liquid transport mechanisms taking place inside such filter media [6,7] reveals that coalesced oil is not able to drain internally by gravity because the microfiber matrix is too dense, but rather from the downstream filter face where it is transported to by the airflow. The drainage pattern on the (vertically installed) filter face appear to depend on its wettability, with a film-like drainage flow on wettable media vs. drainage of individual drops on non-wettable media. In addition to drainage, the air flowing through the filter may cause some of the oil to become re-entrained (“blown off”) in the form of a secondary aerosol. Such entrainment is highly undesirable because it diminishes a filter’s effectiveness and re-contaminates the downstream system. The underlying mechanisms of secondary aerosol formation are currently not understood however, beyond the reasonable working assumption that they should be linked to the drainage pattern [1,4].

The presence of secondary droplets in the micron and submicron aerosol spectrum behind fiber filters has been observed before, without however providing much detail regarding their dependence on operating parameters or mechanisms of formation [2,8,9]. Glass fiber media actually generate a very broad secondary oil droplet spectrum ranging from below 0.1 micrometer up to several millimeters [1], which exhibits two principal modes, a narrow but rather abundant “fine droplet” mode in the range of 1–10 μm, and a “large droplet” mode with a broader maximum situated between roughly 100 and 500 μm. These modes are rather similar in position and relative magnitude for wettable (“oleophilic”) and

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non-wettable ("oleophobic") media, and could be due to either drop blow-off or bursting air bubbles. It was not possible to distinguish between these mechanisms on the basis of available data.

Liquid entrainment is a well known phenomenon in wet scrubbers, fractionating columns and packed beds, which has been studied extensively both from the angles of engineering design (e.g. [10,11]) and the microphysics of liquid filament break-up, the latter indebted heavily also to spray processes. Industrial demisters are far coarser structurally than oil mist filter media. They are typically operated in horizontal orientation with air and liquid (almost exclusively water or water-like substances) flowing countercurrent at much higher liquid loads and flow velocities than in oil mist filters. The gas velocity is considered a critical parameter for drop blow-off in such devices and usually modeled via a critical Weber number, which can be used to estimate the forces required to detach large drops retained on a fiber by surface tension [12,13]. Aside from engineering studies, there is abundant scientific literature on the microphysics of liquid film break-up with related descriptive models [14–16]. What we learn from there is that predominantly small droplets (<10 μm) are sheared off and entrained into the gas flow when a liquid film is relatively thick and the gas velocities are high [17], whereas larger drops (>100 μm) are generated in case of thin liquid films and/or low gas velocities [18]. Incidentally, dripping leads to a similarly bimodal drop spectrum as liquid blow-off or disintegrating liquid jets [13,19], with typically a few smaller satellite (or "daughter") drops for each large parent drop [20,21], because they are all based on the same basic mechanisms.

Liquid blow-off is not the only conceivable mechanism to generate secondary oil aerosols from fibrous filter media. Bursting air bubbles are known since the work of Garner [22] to produce a multi-modal fragment spectrum that fits quite well to the observations of Wurster et al. [1]. In the case of water or an aqueous salt solution, micron sized film drops are generated during rupture of the bubble cap, while much larger jet drops can be ejected under certain conditions when the bubble cavity collapses (e.g. [22–25]). These phenomena are well documented for the most elementary of geometries, i.e. on a free liquid surface. The influence of a "substructure" such as the porous filter matrix or a grid beneath the liquid surface on the size of the bubbles or their subsequent break-up is not known however.

Another factor to consider specifically for oil mist filters is media wettability, which is known to affect the drainage pattern as mentioned above [6,7], and should therefore be relevant if not the deciding factor for the prevailing entrainment mechanism. Oil drainage in the form of an extended film would suggest fragmentation of bubbles to contribute to the secondary drop spectrum, whereas the presence of millimeter-sized drops clinging to the downstream filter face would point to blow-off. The dominant mechanism should affect the concentration of the small-droplet mode (because bubble caps break up into many more film drops than the rupturing filament of from a large drop, at least for water), but also the formation rate of large drops which depends strongly on air velocity. Surprisingly however, a recent study of secondary oil droplet spectra generated by glass fiber filters did not show a pronounced influence of media wettability, even though liquid blow-off was unlikely at the filter face velocities typically prevailing in oil mist filters [1].

In summary, the literature offers a wealth of information about fragment drop spectra generated in various proportions by specific liquid break-up mechanisms. However these spectra – including those generated by oil mist filters – are qualitatively too similar to serve as a reliable guide in distinguishing between entrainment mechanisms such as bubble bursting or liquid blow-off. Moreover, we lack sufficient data for the types of media and conditions of interest to our application, in order to make a clear distinction, even though the issue is quite important for subsequent abatement strategies.

In this paper we present experimental data on drop entrainment rates as a function of filter face velocity and filter loading rate with oil aerosol. They were obtained for representative glass microfiber filter media of similar fiber geometry, one wettable and one non-wettable. Entrainment rates as a function of time were measured on line for both the large droplet and the small droplet modes of the entrainment spectrum using standard compressor oil. In order to interpret these data, they are correlated with additional, quantitative and qualitative measurements of oil movement on the downstream face of the filters while in operation, and with estimates of the forces required to detach individual drops or to form air bubbles. This leads us to conclusive answers concerning the prevailing entrainment mechanism.

2. Experimental set-up, materials and methods

The formation of secondary oil aerosol by entrainment was studied on vertically oriented flat sheets of filter material. Starting always with fresh and dry media, these filters were loaded with submicron oil aerosol at a predetermined, very constant rate until the differential pressure Δp no longer increased and oil began to drain from their downstream face. Since the onset of entrainment coincides roughly with the beginning of oil drainage [1], filter operation was continued well beyond this point in time, typically for another 5 h. The pressure drop Δp across the filter, the gravity driven drainage flow, as well as the size spectrum and concentration of secondary aerosol formation were recorded continuously during each experiment. More experimental detail regarding aerosol, filter media, and optical measurement techniques is given in the following subsections. See also Kampa et al. [6] for a more elaborate description of the basic set-up and procedures.

Certain experiments were performed with fluorescent oil in order to visualize its momentary distribution on the surface of the filter, and to correlate this distribution with entrainment rates. While regular compressor oil is almost colorless and thus not readily visible against the whitish background of the filter media, adding about 0.1% oil-soluble fluorescent dye (Umbelliferon, Carl Roth) was sufficient to make it fluoresce without altering the fluid properties significantly. When illuminating the filter with UV light around 470 nm, oil distribution and drainage patterns could thus be visualized and photographed in-situ while the filter was in operation. Note that this technique was used exclusively for initially oleophobic filter surfaces, because oleophilic media are covered from the very beginning by a thin drainage film [6].

Separately, estimates were made of the forces required to form an air bubble in an oil film, or to physically detach an oil drop hanging on the face of a filter either by the action of gravity or friction due the air flow. The respective estimates are based on simple experiments with different oils, which are described together with the results.

2.1. Aerosol generation and filter loading conditions

Oil mist was generated from mineral oil (typically used in compressors (density 0.9 g/cm^3, viscosity 0.1 Pa s, surface tension 0.03 N/m; all properties at room temperature) by nebulization with compressed air in a Collison type device [26]. The size distribution of the primary oil mist was equally stable and roughly lognormal in shape with a mean drop diameter around 0.3 μm and a geometric standard deviation of 1.7. This was determined by electrical mobility spectrometry, a well established technique to characterize submicron aerosols.