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Measurement of oil entrainment rates and drop size spectra from coalescence filter media

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HIGHLIGHTS

- Drop spectra from nm to mm were recorded in real time for filters in operation.
- Oil drop spectra were bi-modal with peaks at 1–2 μm and 200–300 μm.
- Spectra and rates were similar for wettable and non-wettable media.
- Entrained drops are most likely the fragments of bursting bubbles.

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ABSTRACT

Liquid entrainment from coalescence filter media—i.e. flow induced “blow-off” of previously deposited oil—in the form of droplets is poorly understood, for one because the generated spectrum is very wide and difficult to characterize with temporal and size resolution, especially for very large drops which carry most of the mass. Such filters operate at much lower flow rates than classical demisters, often in vertical orientation, with much finer geometries, and gravity plays no direct role for entrainment. We present a novel combination of four measurement techniques used to capture the entrained oil drop spectrum from filters during operation in the size range of 0.01–2400 μm. The diameter range below 10 μm combines two established real-time methods including an electrical mobility particle spectrometer (EMPS; <1 μm) and an optical particle counter (OPC; 0.3 to 10 μm). The diameter range above 170 μm is covered by a newly developed “large drop detection system” (LDDS) based on single particle light scattering. OPC and LDDS continuously count and classify all drops originating from the entire filter coupon with a time resolution of 1 min. The EMPS was operated intermittently, following brief switches from aerosol to clear air flow. Drops in the size range between OPC and LDDS were collected and sized by an off-line method.

This measuring system was applied to two representative types of glass microfiber media operated with oil mist generated from compressor oil, in order to characterize time resolved drop formation rates and spectra in the range of nanometers to millimeters. Wettable and non-wettable filter media were found to show similar entrainment characteristics, each with multi-modal drop spectra having two pronounced peaks in the ranges of 1–2 μm and 200–300 μm, respectively. During steady-state operation both modes were generated quasi-continually, the large drops at the rate of a few drops per hour and cm^2 of filter surface, the micron size drops 10^3–10^4 times more frequently. Available indirect evidence suggests the same underlying entrainment mechanism for both types of fibrous media, namely the break-up of air bubbles formed periodically on the oil that drains on the downstream filter face. Direct detachment (blow-off) of large drops is unlikely at the prevailing operating conditions.

1. Introduction

Coalescence filters are a widely used and generally effective means to remove fine droplet aerosols from an effluent air stream, for example in engine crankcase ventilation or oil lubricated air compressors (Kampa et al., 2014). Such “oil mist” filters are often composed of multiple layers of glass microfiber and/or polymer media with relatively fine pores on the order of a

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few micrometers, which may be wettable or non-wettable to the liquid. During operation the sub-micrometer oil mist accumulates on the fibers and coalesces gradually into much larger drops (Yarin et al., 2006) which are then transported through the filter by the air flow. Once the oil reaches the back of filter, it either drains due to gravity (depending also on the orientation of the filter) or gets blown off (Mullins et al., 2005). This "blow-off" or "entrainment" of liquid by the flowing gas is highly undesirable, because newly formed drops re-contaminate the system downstream of the filter and thus counteract its effectiveness.

Among the important questions to address in conjunction with a description of entrainment from such filters are the droplet size spectra and rates (in terms of number of drops or volume of liquid) generated by blow-off during the different stages of their operation. However, such quantitative information is scarce in the scientific literature, especially for oil (Mead-Hunter et al., 2014; Mullins et al., 2014), and not helpful in identifying the underlying mechanisms.

Liquid entrainment is a well-known phenomenon in scrubbers, demisters and fractionation columns, with a large body of theoretical and practical knowledge related to the design of such separation devices (e.g. Souders and Brown, 1934; Viles, 1993). These are usually packed beds, sieves or meshes with considerable liquid mass flows and high flow velocities, wherein the movement of liquid is largely controlled by the balance between gravity and an upward air flow. However the mechanisms prevailing in such devices hardly apply to oil mist filters, which have a much finer structure and rather high efficiency, while flow velocities and oil loads are often modest by comparison. Also, high efficiency oil mist filters are more commonly operated in a vertical orientation, so that the directions of liquid drainage and air flow are perpendicular to each other.

The earliest phenomenological indications of entrainment from such *high-efficiency mist filters* are by Leith et al. (1996) who report the apparent formation of sub- and supermicron droplets due to blow-off. Raynor and Leith (2000) as well as Contal et al. (2004) later mention similar observations; however without giving any further details because these droplets contributed negligibly to the overall emitted mass. In fact, many studies on mist filter efficiency do not distinguish between the primary aerosol penetration and the generation of secondary aerosols by entrainment (e.g. Conder and Liew, 1989; El-Dessouky et al., 2000).

Aside from micron-sized entrainment droplets, one may also expect the formation of much larger drops due to blow-off or fragmentation of bursting bubbles, as suggested recently by Mullins et al. (2014). However, such very large drops tend to settle or impact rapidly rather than follow the gas stream, and are therefore not readily detected by measurements downstream of the filter (Schmidt et al., 2010).

The techniques that have been used to characterize aerosols downstream of *wire meshes* or *oil mist filters* fall into three categories: determination of the total liquid mass without time or size resolution; inertial impaction based techniques from below 1 μm to about 20 μm; and various non-contact techniques. For the following discussion it should be kept in mind though, that these techniques were not necessarily employed to characterize entrainment, but more often to measure filter efficiencies in general.

Measurements of total "liquid carryover" have been used to estimate the mass fraction of liquid due to penetration and/or entrainment, without however providing any resolution with regard to time or drop size. This has been done by electrostatic precipitation of the aerosol followed by gravimetric determination of the deposited mass (Conder and Liew, 1989; Raynor and Leith, 2000), or more recently by capturing the aerosol on a high-efficiency filter placed further downstream (Contal et al., 2004; Mead-Hunter et al., 2013; Mullins et al., 2014). Others have used more indirect techniques such as condensation and weighing in the case of water mist (Carpenter and Othmer 1955; El-Dessouky et al., 2000), or even chemical precipitation and titration in the case of sulfuric acid (Bürkholz, 1970). In all these cases, the mass fraction actually obtained depends strongly on the placement of the capturing device downstream of the filter and there is no guarantee of collecting the entire size spectrum.

Impaction techniques have also been applied early on to intercept and classify droplet aerosols. Common types of impactors are limited to aerodynamic diameters below about 20 μm but offer a limited degree of size resolution (Bürkholz, 1970; Calvert et al., 1974; Contal et al., 2004). They are limited furthermore to brief snapshots of the entrainment process, because accumulating liquid may evaporate and/or be blown off the impaction stages. Chilton (1952) and Calvert et al. (1974) circumvented such difficulties by using water-sensitive paper on which impacting water drops of up to 10 mm in diameter left behind craters from which the size of the original drops could be inferred via a calibration. May (1950) describes a similar technique for non-water soluble drops (e.g. oils) based on magnesium oxide coated glass slides as impaction medium.

Non-contact techniques such as electrical mobility spectrometry (Frising et al., 2005; Charvet et al., 2008; Mead-Hunter et al., 2013) or optical particle counters (Leith et al., 1996; Boundy et al., 2000; Peters et al., 2001; Mullins et al., 2014) are readily available today, and have been used extensively to obtain droplet size spectra and concentrations below 20 μm. However, with the exception of Mead-Hunter et al. (2013) these techniques were never employed to study entrainment, but primarily to measure aerosol penetration through filters in the micron and submicron range, with large drops mostly outside the field of view. Brunazzi and Paglianti (1998) actually used laser diffraction to characterize entrainment. This technique covers a much wider size range from about 1 μm up to several millimeters, but it is not a single-drop technique and requires significant concentrations within a limited detection volume to obtain reliable data (Ma et al., 2000). Unfortunately large drop entrainment is a rare event that occurs at the rate of perhaps one drop per minute originating from anywhere on a large area of filter surface. This has to do with the way oil drains intermittently across the downstream face of a filter (Liew and Conder, 1985; Kampa et al., 2014) and requires the ability to monitor a large region of the filter surface. A third difficulty, affecting especially the detection of large drops, arises from the fact that the operating behavior—and therefore presumably also the entrainment behavior—of coalescence filters changes gradually over very long periods of time (Conder and Liew, 1989; Contal et al., 2004; Charvet et al., 2010; Kampa et al., 2015). For example, it typically takes several hours for a filter to reach steady state, during which oil accumulates and thereby increases the interstitial air velocity, which presumably also affects entrainment. Suitable measurement techniques must therefore be capable of covering a large field of view at very low data rates over a very long period of time and across a very wide spectrum of sizes—a combination of requirements that eliminates virtually all established techniques. Extending real-time measurement techniques into the millimeter size range is nevertheless a worthwhile endeavor for a better understanding of entrainment mechanisms, as well as for practical reasons because large drops transport most of the entrained mass.

This paper describes a measurement system combining four separate, overlapping techniques to cover the droplet size range from about 0.01 μm to 2.5 mm, three of which collect entrainment data in real time. One of them is an optical technique developed specifically for the size range $>150\,\mu m$, that continually counts and sizes entrained drops coming from a representative filter area of 5 cm × 5 cm. To illustrate the performance of this system, we apply it to microfiber filter media with compressor oil as a working fluid.