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Flow velocity dependence of the pressure drop of oil mist filters

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HIGHLIGHTS

- The excess Δp of oil mist filters does not depend on the air flow rate.
- Higher air flow rates are compensated for by a reduced internal saturation.
- Long-term operation under constant conditions does not lead to a steady-state Δp.
- Continuing Δp creep was observed even after 1100 h of non-stop operation.

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ABSTRACT

The dependence of the differential pressure drop Δp and the level of internal oil saturation S on the flow velocity of the air were investigated experimentally for a typical oil mist filter composed of oleophilic glass microfiber layers. Over a wide range of filter face velocities (v = 5–70 cm/s) and liquid loading rates (R = 15–125 mg/(m^2 s)), and within the accuracy of the measurements, the "wet" pressure drop of the filter $\Delta p - \Delta p_0$ (i.e. the increase in Δp over the "dry" pressure drop Δp_0) was constant and did not show a systematic dependence on v. When decomposing the wet pressure drop into its components Δp-jump and channel-Δp, the Δp-jump was also independent of the oil loading rate. The level of internal liquid saturation S was inversely proportional to v, with an empirical fit function $S = 1/(1 + v/v^*)$. The characteristic velocity v^* was found to depend on the oil loading rate, and presumably also depends on the media structure which was not varied here. This filter behavior is consistent with the "jump-and-channel" model proposed recently by Kampa et al. (2014).

The experiments further showed that the "steady-state" pressure drop under constant filter operating conditions underwent a gradual increase with time (termed "Δp-creep") that depends on operating conditions. This Δp-creep diminishes gradually and was found to become stronger with increasing loading rate and filter face velocity. At the highest rate of increase (i.e. v = 70 cm/s, R = 125 mg/(m^2 s)), an experiment lasting for 1100 h did not suffice to attain an asymptotic level for Δp. Creep was found to be associated with a gradual increase in saturation and must therefore be classified as an(other) instability phenomenon in oil mist filters.

1. Introduction

Aerosols consisting of submicron oil droplets ("oil mist") are an undesirable by-product of widely used industrial processes such as metal cutting, engine crankcase ventilation, or the operation of oil lubricated gas compressors. One commonly practiced way to capture and remove this oil mist is by filtration with glass microfiber or other high-efficiency media. The differential pressure of such filters increases very substantially prior to steady-state operation due to loading with coalesced oil. In order to achieve and sustain steady-state operation, this oil has to be moved by the airflow to the rear of the filter, where it can drain. Maintaining this flow of coalesced liquid requires an additional Δp above and beyond the initial Δp_0.

The basic mechanisms involved in transporting the liquid and their respective contributions to the overall Δp of a filter have recently been described by Kampa et al. (2014, 2015) in the form of a Jump-and-Channel (J&C) Model. According to this model, the overall Δp of an oleophilic oil mist filter is composed of two components, an internal contribution needed to pump liquid through the media typically in distinct channel-like structures, hence denoted as "*channel-Δp*" - plus a final, rather steep "*Δp-jump*" required to overcome capillary retention forces in order to push the liquid out of the media and cause it to drain as a thin film along

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the outer surface. (We make the common assumption that the filter is installed vertically to facilitate drainage.)

According to the model, each of these two Δp components depends in a characteristic way on key filter operating parameters such as air velocity (suitably expressed in terms of filter face velocity v), liquid loading rate R, and the level of internal saturation with liquid S: The $\Delta p'_{channel}$ (strictly speaking the excess channel-Δp after subtracting Δp_0) should mainly be a function of loading rate. It should not depend on the air velocity v however, because the system reacts to changes in v by adjusting the liquid saturation level so as to maintain the constant excess channel-Δp needed to pump the liquid. The Δp-jump should be independent of both liquid loading rate and air velocity, because it is determined primarily by capillary properties of the filter media in combination with the liquid, i.e. by pore structure and surface tension. As a practical consequence, the sum of Δp-jump and excess channel-Δp of an oil mist filter in steady operation at a constant loading rate should not depend on the volumetric flow of air, a behavior that is not intuitively obvious in the realm of flow through porous media.

The objective of the current paper is to provide experimental verification and validation for these relationships, and in particular for the flow rate (in-)dependence. The experiments were performed over a broad range of filtration velocities and aerosol loading rates, with a combination of oleophilic glass microfiber medium and oil typically used in air compressors. Filter differential pressures, saturation levels and internal oil distributions were measured and compared to the model predictions.

2. Experimental materials and methods

Aerosol generation: Oil mist was generated by a Collison-type nebulizer (May, 1973) in which dry compressed air disperses a typical compressor oil (surface tension 31 mN/m, dynamic viscosity 122 mPa s) at room temperature. SMPS measurements revealed droplet sizes of a log-normal distribution with a mean diameter of about 640 nm and a geometric standard deviation of 1.9. A schematic diagram of the experimental set-up is given in Fig. 1. The rate of oil mass generation was kept constant for a given experiment by maintaining a constant Δp across the nebulizer. Further downstream this aerosol was mixed with a dry make-up flow to adjust the velocity to a desired level. Temperature and absolute pressure upstream of the filter were monitored continuously in order to compensate the effect of increasing pressure on the face velocity by the mass flow controller. The actual oil loading rate of the filter was determined from the oil drainage rate which was measured continuously on line. Aerosol penetration and oil re-entrainment were neglected in this calculation because the filters had overall efficiencies above 99.99% and entrainment was insignificant compared to the loading rate (Wurster et al., 2015).

Filter materials: The filters used is this study were built as flat "sandwiches" consisting of 10 layers each of the same oleophilic glass microfiber media (thickness about 0.5 mm, porosity 95%, mean pore size 9.1 µm) with a metal grid as downstream support. The filter samples were cut from a roll of commercial filter material manufactured by Hollingsworth & Vose. The inhomogeneity of these media was significant across the roll, as evidenced by variations in dry pressure drop of up to 30% between coupons. This was compensated to some degree by selecting sandwiches with variations of less than 10% in Δp_0. The sandwich with an effective filtration area of 8 cm × 8 cm was clamped into a metal frame and installed vertically in the filter unit.

Experimental procedures: Each experiment started with a fresh, dry sandwich that was loaded under exactly constant conditions for several hours past reaching steady-state operation. (For oil mist filters, steady state is commonly defined as operation at a constant drainage rate and pressure drop. Note however, that some filter media under certain operating conditions exhibited a kind of "Δp-creep", which will be addressed later in this paper.) At the end of a run, the sandwich was immediately taken apart to photograph each layer for the purpose of image analysis of the oil channel distribution, and/or to measure the oil content gravimetrically. The mean saturation per layer was determined from the weight increase after removing about 5 mm around the edges where the media had been clamped in the filter mount. Photographs were converted to black and white images via a predetermined threshold of gray level, and evaluated by automated image analysis for the local oil distribution, especially the size and number of oil channels. The gray level threshold was determined in such a manner that the gravimetrically measured saturation matched the area-equivalent saturation of the image analysis. (This assumes implicitly, that a given region of the filter is either fully saturated or completely dry. Consequences are discussed later.)

Data evaluation: The pressure drop components channel-Δp and Δp-jump were obtained from the temporal evolution of the overall Δp during the start-up phase of a filter by a graphical

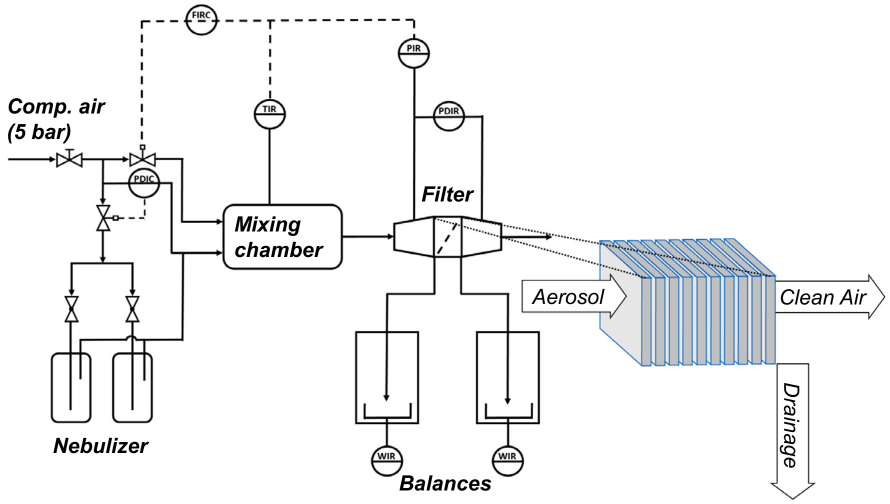

Fig. 1. Schematic diagram of the experimental set-up consisting of Δp-controlled nebulizer, a temperature and absolute pressure corrected make-up flow by a mass flow controller, a holder for mounting the sandwiches of single layers, as well as two balances to record wall flow and drainage.