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Experimental observations of the transition pressure drop characteristics of fibrous filters loaded with oil-coated particles

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ABSTRACT

Oil-coated particles are often encountered in the ambient and industrial working environments. However, experimental investigations have rarely been carried out on the loading behavior of filters loaded with oil-coated particles. In this study, the effects of the overall particle size, oil volume percentage, filter material, and surface tension and viscosity of the coating oils on the filter loading characteristics were examined. It was found that the general oil-coated particle loading behavior of filters transitions from that of solid-only particles to that of oil-only particles as the liquid volume percentage in the test particles increases. The typical transition trend of oil-coated particle loading curves is believed to be due to an increase in the fluidity of deposited oil-coated particles as the liquid percentage increases. It is further observed that, when the liquid volume percentage in coated particles is less than 50%, the filter loading behavior is dominated by the effect of the liquid surface tension and the filter pressure drop is largely due to the solid core of coated particles. Both the surface tension and viscosity of coating liquid influence the filter loading behavior when the liquid percentage in coated particles is higher than 50%.

1. Introduction

One of the key parameters representing the energy consumption of filtration systems is the pressure drop. This is an important characteristic associated with filter media. However, the filter pressure is not always a constant, and it increases as more particles are filtered by the system. Generally, a designated pressure drop is used as an indicator for determining the lifetime of the filter or the maximum holding capacity. Therefore, understanding the loading behavior of filter media (the pressure drop evolution process over the filter's life span) under different conditions is vital for researchers and engineers in designing a more energy-efficient filter or a filter with a longer lifetime.

The transition loading behavior of different filter media and various influencing factors have been extensively studied in the literature for filters loaded with pure solid particles [1–7]. Essentially, for a low efficiency fibrous filter loaded with pure solid particles, the loading behavior proceeds through three different phases: depth filtration, a transition regime, and surface filtration. In these three phases, two distinct linear slopes are observed in the pressure drop evolution curves. The initial flatter slope represents the loading behavior due to particles collected by the fiber matrix in the filter media, and the final steeper slope is attributed to dust cake formation [3,8].

In contrast, fewer studies have been conducted on the filtration of pure liquid particles/mist, which contribute significantly to air pollution [1,9–12]. These pollutants include the cutting fluid mists and phytosanitary products produced by the mechanical and agricultural industries, respectively [13]. When filters are loaded with these pure liquid particles, the loading behavior becomes variable and complex. At the initial filtration stage, liquid particles are deposited mainly on the surface of the fibers and interfere marginally with the flow; the pressure drop thus increases very slowly. The pressure drop of the loaded filter accelerates due to the formation of liquid bridges, pools, and films between fibers and their intersections [14]. Therefore, it is believed that the loading behavior is closely related to the surface properties of the filter fiber (e.g., wettability) and the physico-chemical properties of the liquid (e.g., surface tension, viscosity, size distribution etc.) [9].

In reality, however, the mist particles do not always exist as pure liquid droplets only. Rather, they may take the form of solid particles coated/mixed with liquids, typically greasy oils. Examples of such greasy particles/oil-coated particles are the particles emitted from internal combustion engines or generated in vehicle crankcases, and metal working fluid (MWF) aerosols produced in grinding and milling operations. Several recent studies

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have indicated that more polycyclic aromatic hydrocarbon (PAH) species were found in vehicle crankcase emissions than in tailpipe emissions, and the crankcase emissions may contribute to in-cabin particulate matter [15–17]. There is also evidence showing that an increase in MWF aerosol exposure increases the risk of adverse respiratory health effects, and so needs to be filtered out [18–20]. On the other hand, due to their different physical properties, the pressure drop evolution curve of a filter loaded with these oil-coated particles ought to be significantly different from that of filters loaded with either pure solid or pure liquid particles. The lifetime and loading capacity of filters could also accordingly vary from the originally designed values based on pure solid/liquid particles. As such, the current pressure drop models for loading pure solid and/or liquid particles cannot be directly applied to predicting the pressure drop evolution for loading oil-coated particles. Few studies in the literature have reported experimental values for filtration using oil-coated particles, the loading behavior or the use of pre-oil filters [21,22]. Therefore, the aim of this paper is to experimentally investigate the pressure drop evolution of fibrous filters when loaded with various oil-coated particles. The specific objectives are to study the behavior of filters loaded with oil-coated particles with different oil volume percentages and to explore the effects of oil properties (surface tension and viscosity) on filter loading behavior.

2. Experimental methods

A schematic diagram of the experimental setup is shown in Fig. 1. It consists of an oil-coated particle generation system, a filter testing chamber, monitoring and sizing instruments, a pressure transducer (MKS 223BD), an Aerodynamic Particle Sizer (APS, TSI 3321) and a Scanning Mobility Particle Sizer (SMPS, TSI 3936). The co-solvent method was applied for generating oil-coated particles. A master solution of oil-coated particles was prepared by mixing two parent solutions, coating oil dissolved in 2-propanol and potassium chloride (KCl) dissolved in DI water, using a volume ratio of 1:1. The master solution was then delivered to an ultrasonic aerosol generator (Sono-tek 8700), which sprayed the solution from the top of the filter testing chamber. At the same time, clean dry air flow was introduced to carry the generated droplets downstream and to evaporate their solvents, yielding oil-coated particles for loading experiments. Located immediately downstream from the ultrasonic nozzle, four Po^{210} radioactive strips were installed in the chamber to reduce the level of electric charges in the generated droplets and to lessen undesirable particle loss.

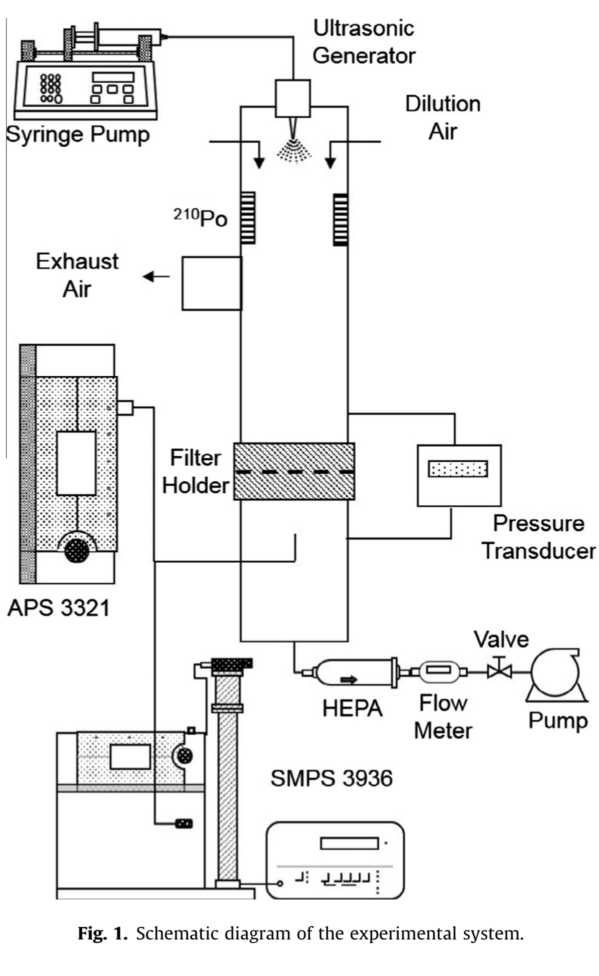

Fig. 1. Schematic diagram of the experimental system.

In this study, the size distribution of the oil-coated particles was kept almost constant, while the oil volume percentage was varied from 20% to 94%. The different oil volume percentages were achieved by changing the concentrations of the two mixed parent solutions. Mass-based GSDs (geometrical standard deviations) were carefully maintained at about 1.33, and two particle size distributions with GMDs (geometric mean diameter) of 2.5 and 5.0 μm were generated for two series of loading experiments. In each experiment, the particle loading was performed until the pressure drop in the filter reached 4 times the initial pressure drop. In addition, to verify that the generated particles were well coated with the designated amount of oil on the surface, a fluorescence microscope was used to inspect the oil-coated particles. These oil-coated particles were carefully generated using DEHS (di-2-ethylhexylsebacate) doped with a fluorescent dye. As shown in Fig. 2, the solid particles were perfectly coated with DEHS under different conditions.

Two low-efficiency filter media, a glass fiber filter and a cellulose filter, were selected. The properties of these test filter media, including base weight, porosity, and filter thickness, were characterized and are presented in Table 1. Test filter media with a diameter of 2.75" were randomly punched out from large filter medium sheets and placed in a homemade filter holder. The flowrate of the aerosol passing through the test filter media was controlled by a needle valve and monitored using a TSI flow meter (TSI 4043). The loading tests were all performed under a fixed face velocity of 11 cm/s. During the loading process, an APS and a pressure transducer were applied to measure the downstream particle size distributions and to record the dynamic pressure drop of the loaded filter, respectively. The upstream particle size distributions were confirmed by APS measurements before, in the middle and after the loading tests. To further characterize the initial stage of particle penetration, in addition to APS, a Scanning Mobility Particle Sizer (SMPS, TSI Model 3936) was also used for submicron range measurements. Experimental results indicate that the initial particle penetration curves of the two testing filter media both have a maximum at about 0.35 μm, and the corresponding values are 92% and 86% for the cellulose and glass fiber filter, respectively (Fig. 3).

Before and after each loading test, testing filter samples were weighed using a microbalance (Denver Instrument SI-215D) after conditioning the filter media in a desiccant jar for at least 24 h. The difference in weight was regarded as the total particle mass collected by the tested filter. In this study, as the densities of the core solid material and coating oils are different, the loaded particle mass per unit filter medium area (which is used in the literature) was replaced by the loaded particle volume per unit filter medium area for describing the loading behavior. As the filtration efficiency of the test filter medium was low, only part of the particles were collected by the filters. In addition, if the accumulated