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Study on the filtration behavior of a metal fiber filter as a function of filter pore size and fiber diameter

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ABSTRACT

The filtration characteristics of a metal fiber filter on dry soot particles have been investigated empirically as a function of the filter pore size and fiber diameter. Six types of metal fiber filters, having various pore sizes and fiber diameters, were examined experimentally, with a focus on the pressure drop, deposited mass, and filtration efficiency. Filtration efficiency was calculated based on the particle number concentration and expressed as a function of the electrical mobility diameter and time. Dry soot particles were generated by a soot generator (mode diameter: 100 nm; total number concentration: $3.48 \times 10^{10}/cm^3$). The deposition temperature, total flow rate, and deposition time were set to 250 °C (equivalent to a particle approach velocity of 1.7 m/s), 29.2 sLPM, and 1 h, respectively.

Our results showed that the pressure drop, mass, and particle number concentration-based filtration efficiency exhibited the same tendencies. Specifically, the filter pore size influenced the initial and final filtration efficiencies, while the fiber diameter had a significant effect on the rate of increase of the filtration efficiency.

1. Introduction

Growing concern over vehicle emissions has prompted increasingly strict international regulations, with a focus on the reduction of particulate matter (PM). Especially for Diesel vehicles, of which the strengths of high power, low fuel consumption, and lower CO_2 emission were not fully exhibited due to drawbacks of higher exhaust emission problems, reduction of PM became basic essentials to be applied in the automotive industry.

PM is composed mainly of soot particles, the carbonaceous agglomerate of primary particles generated by the pyrolysis of hydrocarbon fuels (Desantes et al., 2005), usually accompanied by ash, sulfates, and water. The generation of PM is governed by the sulfur content and cetane number of the fuel (Sarvi et al., 2008) and combustion factors, which include the fuel injection pressure, injection start, combustion chamber design, and nozzle spray patterns (Agarwal et al., 2013).

Soot particles are a major concern in terms of their harmful effects on human health and the environment. In addition to the deposition of these particles in the lungs and their potential carcinogenic effect (Mokhri et al. 2012), a recent research

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Nomenclature

General abbreviations

C_{in}	soot particle number concentration measured by a scanning mobility particle sizer (SMPS) at the front of the filter
C_{out}	soot particle number concentration measured by SMPS at the filter outlet
$\sum C_{in}$	sum of the soot particle number concentration measured by SMPS at the front of the filter
$\sum C_{out}$	sum of the soot particle number concentration measured by SMPS at the filter outlet
CPC	condensed particle counter
DMA	differential mobility analyzer
DPF	diesel particulate filter
sLPM	standard liter per minute
MLP	multilayer pad
MXP	mixed pad
NEDC	new European driving cycle
PM	particulate matter
SMPS	scanning mobility particle sizer
SP	sliver pad
TWP	thin web pad
wt%	weight percent

Chemical abbreviations

Al	aluminum
CO	carbon monoxide
CO2	carbon dioxide
C3H8	propane
Cr	chromium
Fe	ferrum
HC	hydrocarbon
N2	nitrogen
NOx	nitrogen oxides
SiC	silicon carbide

report shows that the soot particles can penetrate human cells directly (Ushakov et al., 2013). Soot particles also accumulate in the water and soil (Schreck et al., 2011) and cause a reduction in atmospheric visibility (Rahman et al., 2013).

A more than 90% reduction in soot particle emission can be achieved by a filtration process using a diesel particulate filter (DPF) (Yamamoto and Nakamura 2011). Most DPFs are composed of SiC and cordierite materials; soot particles flow through the DPF filter channels and become deposited on the porous channel walls (Tsuneyoshi and Yamamoto, 2013). Emission reduction is usually categorized into particle number- or mass-based reduction. Because recent international regulations have introduced particle number-based restrictions (Bensaid et al., 2009), and particle mass-based reduction is generally accompanied by an increase in the number concentration of ultrafine particles (< 100 nm) (Beatrice et al., 2012), particle diameter and number concentration-based reduction has been predominantly accepted. The filtration efficiency of currently used DPFs is 99.5% in terms of the number concentration and 99.3% for mass-based measurements, as evaluated during the New European Driving Cycle (NEDC) (Tente et al., 2011; Bergmann et al., 2009).

A metal fiber filter is another type of DPF substrate, consisting of metal filaments formed into a three-dimensional (3-D) structure. These filters have a high porosity (> 85%) and a high permeability, accompanied by a low pressure drop. The metal fiber DPFs also exhibit outstanding characteristics, such as a high mechanical strength, high durability, thermal shock resistance capability, and flexibility in terms of their shape and dimensions (Park et al., 2014).

Numerous studies have investigated the filtration characteristics of fiber filters. Klouda et al. (2011) performed experiments on the collection efficiency of metal fiber filters for a high air velocity (10 m/s). Huang et al. (2007) studied the fiber filter penetration of 4.5 nm to 10 μm-size aerosol particles. Ardkapan et al. (2014) examined the filtration efficiency of an electrostatic fiber filter as a function of ultrafine particle exposure and composition.

However, empirical filtration characteristics of metal fiber filter for the purpose of DPF application are not yet to be defined. Empirical results should contain actual filtration phenomenon that is critical to the application fields; pressure drop, deposited mass, and filtration efficiency. Also, since the fiber filters can be produced for the specific filtration purpose (higher filtration efficiency, lower pressure drop,…etc.) with the combination of fiber diameter and pore size, empirical filtration characteristics as a function of fiber diameter and pore size should be defined for the application of metal fiber filter DPF.

In this study, the filtration behavior of metal fiber filters, having various pore sizes and fiber diameters, was examined experimentally in terms of the pressure drop, mass, and soot-particle number concentration. Previous study was conducted and published in the same methodology of current study, on the filtration behavior of metal foam filter (Seok et al., 2014). Because the pore size and fiber diameter are critical parameters in the filtration process, this study aimed to verify specific correlations between these parameters and the filtering capabilities of metal fiber filters.

2. Experiment

2.1. Filter samples

Table 1 lists the filter samples and their specifications for the experiments performed in this study. The filters were manufactured by FiberTech (Korea), with properties (fiber diameter, unit weight, mean pore size, porosity, and thickness) appropriate for the specific filtration purpose. The filters were made from Fe, Cr, and Al, with model names corresponding to