

Development of the Diesel Exhaust Filtration Analysis System (DEFA)

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ABSTRACT

The development of the Diesel Exhaust Filtration Analysis system (DEFA), which utilizes a rectangular wafer of the same substrate material as used in a full-scale Diesel Particulate Filter (DPF), is presented in this paper. Washcoat variations of the wafer substrate (bare, washcoat, and catalyzed washcoat) were available for testing. With this setup, the complications of flow and temperature distribution that arise in the full-scale DPF can be significantly minimized while critical parameters that affect the filtration performance can be fully controlled.

Cold flow experiments were performed to test the system's reliability, and determine the permeability of each wafer type. A Computational Fluid Dynamics (CFD) package was utilized to ensure the flow uniformity inside the filter holder during the cold flow test. The system was then exposed to several engine exhaust flow rates drawn by a sampling probe in the exhaust line to test the consistency of emissions measurements with other standardized techniques. Particulate Matter (PM) size distribution measurements from this new sampling system were found nearly identical to the measurements found with a commercial dilution system. Finally, the system was tested in a PM filtration condition. The DEFA proved to have the capability for performing PM filtration experiments at various filtration velocities.

INTRODUCTION

With the tightening of diesel engine emission regulations, the implementation of aftertreatment devices such as DPF will become necessary. Many extensive experimental and computational works have been conducted in the past twenty years on studies of full-scale and mini-DPFs (small wall-flow monoliths or wafer disks) to gain a more fundamental understanding of its filtration and regeneration performance [1, 2, 3, 4, 5, 6, 7]. However, full-scale DPF studies have some limitations. For example, simultaneous variations in the

stages of filtration at different locations within the DPF (clean, wall-loading, and cake-layer formation) and thermal gradients during regeneration across the DPF are difficult to account for [8]. Research with mini-DPFs have mostly focused on extracting kinetic parameters for modeling the regeneration process [9], gaining more understanding of reaction phenomena in regeneration process [10, 11], or determining collected soot microstructural properties [12, 13]. A stand-alone device was also developed to perform various tests (cold flow test, filling and regeneration experiments) simultaneously for mini-DPFs [14]. Its results were used to directly compare with full-scale DPFs to evaluate substrate materials and the DPF's chemical and physical properties under realistic exhaust conditions. However, development of a carefully designed system that can perform PM measurements downstream of a mini-filter, while allowing multiple undiluted exhaust filtration velocities to be selected is still needed. This system would allow studies of PM filtration dependency on the diffusion, interception, and impaction mechanisms while maintaining PM characteristics (particle size distribution, mass and number concentration, and chemical composition) of the real engine exhaust. In this present study, such an alternative sampling system, which can controllably expose a wafer filter to various engine exhaust flow rates and PM characteristics, has been developed. In addition, the system allows the use of PM measuring equipment (such as real-time PM mass concentration and PM size distribution instruments) downstream of the wafer filter. The ultimate goal for the development of this setup is to create a deeper fundamental understanding of the interaction between the detailed characteristics of diesel engine exhaust and DPF filtration and regeneration performance. This study also opens a new research avenue to look at the PM composition caught in the pores of the filter substrate with more details.

The structure of the paper is as follows. First, details of the design and setup of the DEFA system including its functionality are fully discussed. Then, details of both cold flow and real engine exhaust tests are

investigated. The results were compared to those from the commercial dilution system used in the laboratory. Finally, a preliminary result of the test on DEFA holding a wafer filter is presented.

EXPERIMENTAL METHOD

DEFA SETUP

A schematic of the DEFA that was developed in this study is shown in Figure 1. The exhaust is isothermally sampled through a perforated stainless steel sampling probe and collected on the rectangular wafer encapsulated in a custom stainless steel filter holder. The wafer and filter holder assembly are enclosed in an oven. The temperature inside the oven can be varied and maintained at temperature up to 400°C. The pressure drop across the filter holder is monitored and recorded by a differential pressure sensor and a digital pressure read-out. As the pressure drop increases with more PM depositing on the wafer, the main engine exhaust back pressure will be adjusted accordingly by means of a PID-controlled butterfly valve to maintain constant mass flow rate throughout the system.

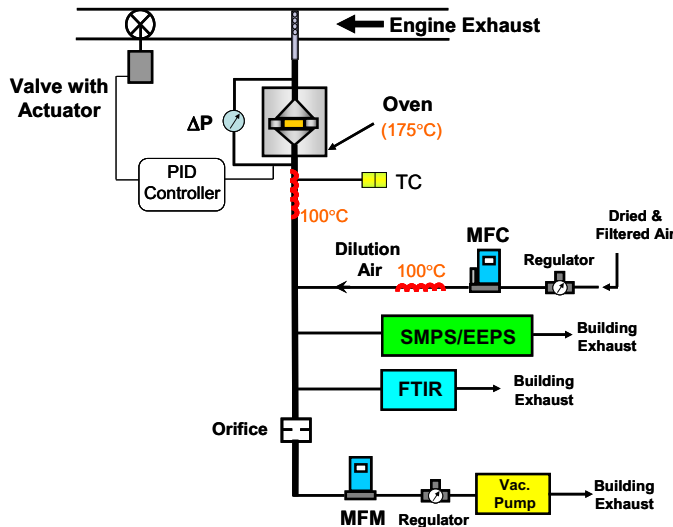


Figure 1. Schematic of the DEFA

The filter holder was adapted from a commercial Rupprecht & Patashnick (R&P) filter holder (Figure 2 [left]) and fitted with the custom-designed adapter (Figure 2 [right]). The wafer was placed in a rectangular recess in the adapter as shown in Figure 2 [right] and sealed with high temperature silicon gaskets. The filtration area is circular with a diameter of 1 inch.

Downstream of the oven, flow temperature is allowed to cool to 100°C and is maintained at this temperature until it is diluted with laboratory air heated to 100°C. The amount of dilution air used is precisely controlled with a mass-flow controller. The accuracy of mass-flow controller is ±1% of full flow rate. An orifice is used downstream of the dilution point to ensure constant flow rate during sampling. Various orifice sizes can be used to adjust the system exhaust sampling flow rates. The

sampling system is connected to several different PM measurement devices as shown in Figure 1.

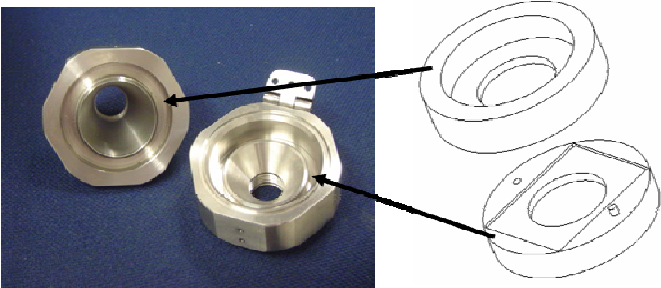


Figure 2. R&P filter holder (left) and wafer adapter (right)

Figure 3 shows a Cordierite wafer sample supplied by Corning, Inc. for this research study. The washcoat and catalyzed washcoat were prepared by Johnson Matthey, Inc. The wafer specifications are shown in Table 1. As this paper was written, information on washcoat and Pt loading was not available.



Figure 3. A Cordierite wafer sample

Table 1. Wafer specifications

Wafer Designation	X	Y	Z
Material	Cordierite		
Size (mm x mm)	39 x 31.5		
Thickness (mm)	0.8636		
Substrate Porosity, ϵ	0.48	0.49	0.41
Mean pore dia., d50 (μm)	14	15	24
Washcoat	Yes	Yes	No
Catalyst Loading	Yes	No	No

Wafer X and Y are from the same batch. They have the same substrate properties except that Wafer X is catalyzed washcoated while Wafer Y is only washcoated. Wafer Z comes from a different batch and does not have any washcoat on it.

A pore size distribution from porosimetry measurement using the Micromeritics Autopore IV 9520 Mercury Porosimeter of Wafer X is shown in Figure 4. This data was provided by Corning, Inc.

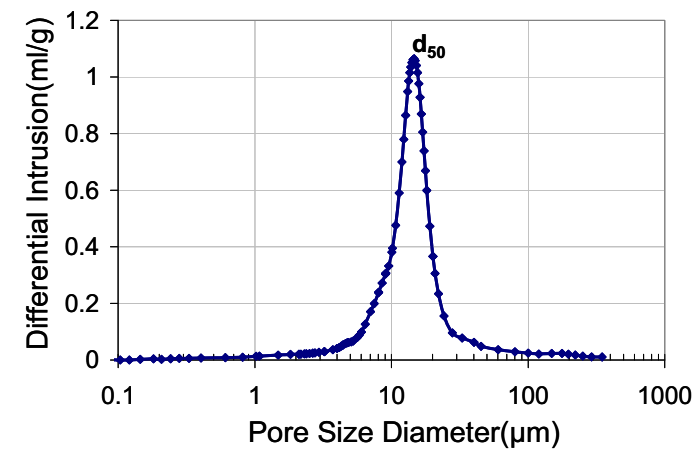


Figure 4. Pore size distribution of Wafer X

ENGINE SETUP

A single-cylinder diesel research engine adapted from an in-line six cylinder Cummins N14-series engine was used in this study. More details of the engine setup and the exhaust system can be found in [15]. Recently the fuel injection system has been upgraded to a common rail system. The common rail high pressure pump was engine driven. The operating injection pressure can be set up to 1800 bars with 5 injections per cycle capability. An overview of the engine specifications is shown in Table 2.

Table 2. Overview of engine specifications

Single Cylinder Cummins N 14	
Cycle	4-Stroke
Displacement (cm ³)	2300
Bore/Stroke (mm x mm)	139.7 x 152.4
Compression Ratio	16:1
Injection System	Direct Injection

For the current study, ultra-low sulfur diesel fuel (sulfur content 7.5 ppm) from BP-Amoco was used.

Engine Operating Conditions

In this study, two engine operating conditions based on CARB 8 modes were chosen to test the DEFA performance, namely Mode 3 and 6. Details of these two engine modes are shown in Table 3.

Table 3. Engine operating conditions

Engine Mode	Mode 3	Mode 6
Speed (rpm)	1800	1200
Load (%)	33	75
Torque/2 (N.m)	45	101
Exhaust Temp. at Surge Tank (°C)	426	634
Exhaust Temp. at the Inlet of Sampling System (°C)	260*	260*

*Exhaust was cooled by a heat exchanger located downstream of the exhaust surge tank.

EMISSION MEASUREMENT

For the raw exhaust analysis, an R&P Model 6100 two-stage mini dilution tunnel (MDT) was used as the dilution sampling system. This system has been used in many research projects conducted at ERC in the past [8, 15, 16]. The exhaust is rapidly and isothermally diluted to best measure PM conditions as they exist in the exhaust line. Thermodynamic states of the particles entering the tunnel are accurately controlled to minimize system measurement artifacts. The dilution is carried out in two stages to gradually cool the sample temperature before being routed to the emission measurement equipment. Engine-out emissions were characterized by using the equipment listed in Table 4.

Table 4. Equipment used in this study for measuring exhaust emission

Equipment	Description
SMPS	Measuring the size distribution and number-based total concentration of PM in the range of 7-210 nm with 90 sec time resolution
EEPS	Measuring the real-time size distribution and numbered-based total concentration of PM in the range of 5.6-560 nm with 1 sec time resolution
47 mm Filters	Collecting PM on filters at controlled flow rate and temperature, and analyzing for total gravimetric particulate mass (Teflon filter)
FTIR	Measuring gas phase emissions to monitor the engine-out emissions and DEFA system dilution ratio