

Micro-scale Study of DPF Permeability as a Function of PM Loading

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ABSTRACT

An investigation of the permeability evolution of a diesel particulate filter channel wall as a function of soot loading was conducted. This investigation examined the effects of varying particle characteristics and two filtration velocities (4 and 8 cm/s) on the wall permeability throughout a 1 g/L soot loading. This study was possible using the Diesel Exhaust Filtration Analysis (DEFA) system that was modified to perform temperature controlled in-situ flow tests. The DEFA system allows for isolation of the pressure drop due to the filter wall and soot cake layer greatly simplifying the permeability calculation.

Permeability evolution fundamentals and the effects of loading conditions were studied by filling 18 filters with the DEFA system. The filters were loaded using one of four operating conditions of a single-cylinder heavy-duty diesel engine. These operating conditions were comprehensively characterized giving insight into the effects of varying particle characteristics. Filter pressure drop and particle breakthrough were monitored during loading. Additionally, the loading process was 'paused' at several points to conduct in-situ flow tests resulting in a permeability evolution curve as a function of soot loading.

It was found that both filtration velocity and particle characteristics have distinct influences on the filter wall permeability during deep bed filtration as a result of varying soot packing densities and depths of penetration. High filtration velocities and large concentrations of nucleation mode particles result in a lower permeability at the loaded wall condition. Since the soot cake has a relatively small contribution to overall permeability, the conditions that determine the loaded wall permeability essentially set the filter permeability for the majority of loading.

INTRODUCTION

While much can be done with manipulating engine operating conditions to reduce particulate matter (PM) emissions, diesel particulate filters (DPFs) have been applied to exhaust systems in light-duty (LD) application for over 10 years and in heavy-duty (HD) applications for 3 years to meet PM emissions standards [1]. While DPFs are very efficient at controlling PM mass emissions, new regulations are requiring better control of particulate number (PN) emissions and more advanced regeneration strategies to minimize associated fuel penalties [1].

As such, there is a significant amount of research focused on DPF regeneration. Currently, most regeneration control methods rely on accurately estimating the soot load in the DPF typically accomplished with models and differential pressure feedback. These methods are extremely complex and are open to much uncertainty [2]. A large portion of these uncertainties arise from a lack of fundamental understanding of DPF performance parameters as a function of soot loading. Of these parameters, permeability is perhaps the least understood, especially during the initial stages of loading.

The overall pressure drop of a DPF is rather complicated and comprehension of it requires a detailed understanding of the exhaust flow hydrodynamics [3]. This is because the total pressure drop ([equation 1](#)) is the sum of a number of factors including losses through a porous wall and soot cake layer, losses to friction in the channel walls, inertial losses due to expansion/contraction, and the Forchheimer effect contribution. As seen in [equation 1](#), both the filter wall and soot cake permeability play a major role in the overall pressure drop. Complicating matters further is the fact that both of these terms are function of time that changes under varying soot loading conditions.

$$\Delta P_{total} = \frac{\mu Q}{2V_{trap}} (\alpha + w_s)^2$$

$$\left[\frac{w_s}{k_w \alpha} + \frac{1}{2k_{soot}} \ln \left(\frac{\alpha}{(\alpha - 2w)} \right) + \frac{4FL^2}{3} \left(\frac{1}{(\alpha - 2w)^4} + \frac{1}{\alpha^4} \right) \right]$$

$$+ \frac{\rho Q^2 (\alpha + w_s)^4}{V_{trap}^2 \alpha^2} \left[\frac{\beta w_s}{4} + 2\zeta \left(\frac{L}{\alpha} \right)^2 \right]$$

(1)

To accurately relate filter pressure drop to soot loading requires that clean filter wall, soot laden wall, and soot cake layer permeability all be known with a great deal of certainty. While the clean filter permeability is straightforward in obtaining, the other two values have presented much difficulty to researchers. Recent studies have achieved relatively good success in understanding variation in the soot cake layer and its permeability using extensive modeling and single-channel experiments [4, 5, 6].

However, the *pre-cake* (before soot cake formation) wall permeability is typically estimated via a combination of experimental data, simulations, and fitting empirical equations based on fundamental theories [4, 6, 7]. Many of these methods require making assumptions that don't necessarily hold true during DPF operation or aren't able to account for the constantly changing permeability throughout the entire loading process.

For this reason, researchers at the UW-Madison Engine Research Center (ERC) have developed a fundamental DPF sampling system, the DEFA system [8]. This system isolates the DPF wall greatly simplifying pressure drop and permeability calculations. In this study, the DEFA system was upgraded with an integrated temperature controlled in-situ flow bench giving it the ability to obtain full permeability evolution curves as a function of soot loading throughout the entire loading process.

EXPERIMENTAL SETUP

The experiments discussed herein utilized a single cylinder HD diesel research engine, the DEFA system with in-situ flow capabilities, and cordierite DPF samples known as wafers. The engine was run on No. 2 diesel fuel and commercial grade 15W-40 oil. The exhaust and DEFA sampling system have been designed to load the wafers with soot replicating the exact trapping mechanisms found in typical DPF on-vehicle application. A detailed description of the design of the DEFA system can be found in [8, 9, 10].

RESEARCH ENGINE

Table 1. Research Engine Specifications.

Base Engine	Single Cylinder Cummins N14
Displacement	2.3 L
Compression Ratio	14.15:1
Bore x Stroke	140 mm x 152 mm
Piston Bowl Diameter	~94 mm
Piston Geometry	Shallow Dish Mexican Hat
Swirl Ratio	1.4
Injection System	DI Common Rail
Injector	8 hole XPI

The engine used in this study is a direct injection, HD, 2.3 L single cylinder research engine based on the Cummins N14 inline 6 cylinder with specification listed in [table 1](#). A schematic of the engine and exhaust system is shown in [figure 1](#). Boost is provided via a simulated turbocharger where the intake and exhaust pressure are controlled through a bank of critical flow orifices and a series of valves, respectively. Both intake and exhaust gases are temperature controlled to simulate in-vehicle applications. Additionally, either side of the air system is equipped with surge tanks to dampen any pressure pulsation caused by the single cylinder setup.

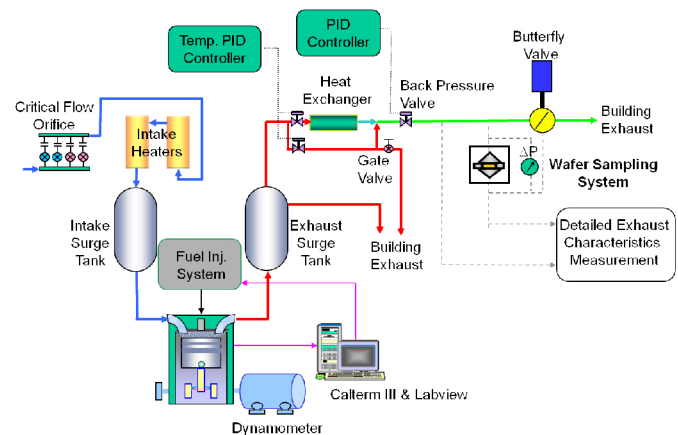


Figure 1. Schematic diagram of engine layout.

DEFA SYSTEM/IN-SITU FLOW BENCH

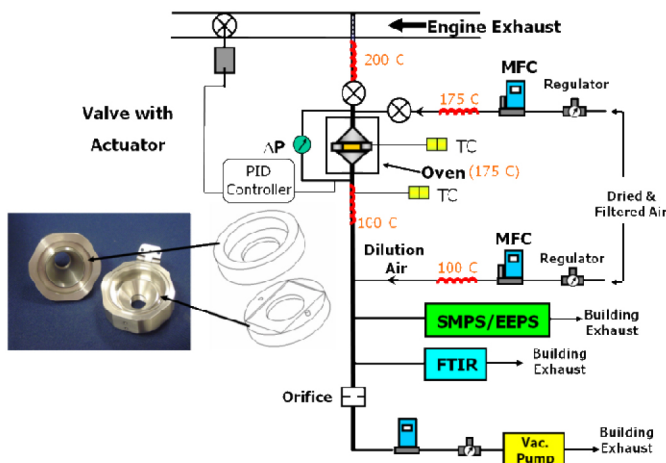


Figure 2. Schematic of the DEFA and in-situ flow system.

A schematic of the DEFA and in-situ flow system can be seen in [figure 2](#). The DEFA system was designed to load wafers with precise amounts of PM under varying loading conditions to analyze the effects of particle characteristics and filtration velocity on DPF wall pressure drop, particle breakthrough and permeability. This system eliminates all of the terms in the pressure drop calculation related to channel flow seen in [equation 2](#). The absence of these terms greatly simplifies the permeability calculation of both the loaded wall and soot cake layer represented by [equation 3](#) and [4](#) respectively. The sampling system allows for accurate control of the flow rate through the wafer with the critical flow orifice and dilution air mass flow controller (MFC). Exhaust is isothermally sampled through the perforated stainless steel tube, passed through the filter holder, diluted under controlled conditions, and finally directed to various sampling equipment. The pressure drop across the wafer is measured with a differential pressure transducer and the particle breakthrough is monitored using a TSI Engine Exhaust Particle Sizer (EEPS) spectrometer.

$$\Delta P_{loaded} = \Delta P_{loaded\ wall} + \Delta P_{soot\ cake} + \Delta P_{channel\ friction} + \Delta P_{inertial\ losses} + \Delta P_{filter\ holder} \quad (2)$$

$$k_w(t) = \frac{\mu * th_w}{\Delta P_{loaded\ wall}} * v_{filt} \quad (3)$$

$$k_{soot\ cake}(t) = \frac{\mu * th_{sc}(t)}{\Delta P_{soot\ cake}} * v_{filt} \quad (4)$$

The loading process is controlled by the wafer downstream pressure and a butterfly valve located downstream of the

sampling probe. As the pressure drop across the filter increases due to PM deposition, the PID controlled butterfly valve adjusts to increase the upstream pressure. This occurs to maintain a constant, near atmospheric pressure downstream of the filter so that the increasing upstream pressure is driving the flow. The choked flow through the orifice and constant downstream pressure maintains a constant mass flow rate through the filter. The flow rate can be adjusted by using different size critical flow orifices.

To allow for in-situ permeability testing, an additional pressure regulator, mass flow controller, full flow ball valves, and controlled heater tapes were added to create an in-situ flow bench. Compressed shop air is regulated to 15 psig and flow is controlled via an Alicat Scientific MC-5SLPM-D MFC which is operated via LabView. The flow is passed through a series of heaters to bring the air up to the DEFA operating temperature of 175° C. The necessary calculations and adjustments in flow set points are done in LabView based on system operating temperature and pressures to achieve a desired flow velocity at the wafer. Pressure drop across the filter and downstream pressure are monitored using the DEFA system transducers, an Omega PX138-005D5V and PX139-015D4V, respectively.

CORDIERITE WAFERS

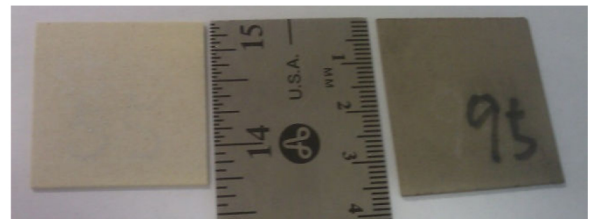


Figure 3. Washcoated and catalyzed washcoated cordierite wafers on the left and right of the ruler, respectively.

As mentioned previously, the DEFA system utilizes cordierite wafer filters. The wafers are thin, rectangular sections of DPF substrate seen in [figure 3](#). The properties for the wafers used in this study, shown in [table 2](#), are very similar to those of a full scale DPF wall. The absence of alternatively plugged channels allow for more detailed fundamental studies of the DPF wall. Additionally, the wafers are better suited for destructive testing, imaging, or mass analysis than a full scale DPF. The wafers were custom manufactured by Corning Inc. and Johnson Matthey Japan Inc. applied the washcoat and catalyst loading as they felt appropriate. Previous work done at the ERC shows that the catalyst loading has essentially no impact on clean permeability and loading history at the temperatures at which these tests were carried out [9].