

Experimental and Modeling Study of Ash Impact on DPF Backpressure and Regeneration Behaviors

Yi Liu, Changsheng Su, James Clerc, and Arvind Harinath
Cummins Emission Solutions

Leigh Rogoski
Cummins Inc

ABSTRACT

One field-retained DPF loaded with a high amount of ash is examined using experimental and modeling approaches. The ash-related design factors are collected by coupling the inspection results from terahertz spectroscopy with a calibrated DPF model. The obtained ash packing density, ash layer permeability and ash distribution profile are then used in the simulation to assess the ash impact on DPF backpressure and regeneration behaviors. The following features have been observed during the simulation:

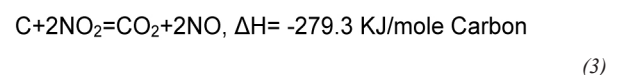
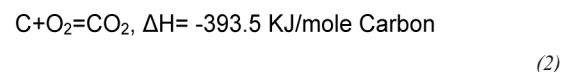
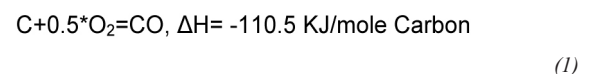
1. The ash packing density, ash layer permeability and ash distribution profile should be collected at the same time to ensure the accurate prediction of ash impact on DPF backpressure. Missing one ash property could mislead the measurement of the other two parameters and thus affects the DPF backpressure estimation.
2. The ash buildup would gradually increase the frequency for the backpressure-based active soot regeneration. However, the accumulated ash reduces the energy density during the regeneration event as well as adsorbing exotherm, lowering the thermal cracking risk.

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INTRODUCTION

Diesel particulate filters (DPF) have been widely used in the modern diesel emission control system to remove the hazardous particulate matters (PM) in the exhaust. Typical DPF are ceramic monoliths with alternative plugs at each end of adjacent channels. The exhaust in the inlet channel is forced to flow through the porous wall of DPF and exit from the adjacent outlet channels, leaving the PM inside DPF [1, 2]. The accumulation of PM inside DPF gradually fills up the channel and increases the flow resistance for the filtration process. Since the majority of PM is combustible soot particles, there are two major strategies for DPF PM regeneration. The first one is oxygen-assisted soot regeneration [3, 4]. When DPF inlet temperature is higher than 450 °C, residual oxygen in the exhaust could react with soot to produce CO and CO₂ as reactions (1) and (2) show. This highly exothermic soot combustion process could lower the accumulated PM amount in a short period of time and generate a significant temperature rise. To achieve a DPF inlet temperature higher than 450 °C typically requires heat addition to the exhaust. Hence, this method is named as active regeneration. Another method for PM reduction is NO₂-based soot regeneration [5, 6]. In this regeneration mode, DPF temperature should be lower than 400 °C to enable the NO₂ presence and avoid NO₂ thermodynamic decomposition. NO₂, serving as the oxidizing agent, could react with soot to form NO via reaction (3). Since soot is simultaneously reduced by NO_x under a

lower temperature, this soot removal process is less exothermic than active regeneration. This method can often occur at typical exhaust temperatures without the addition of heat. Hence, this method is named as passive regeneration. The typical PM control in the vehicle is a combination of these two methods using DPF backpressure as the indicator [7, 8]. For example, the passive regeneration is dominating during the normal backpressure range. When DPF backpressure is higher than a threshold value, the active regeneration is triggered to combust soot in a short duration and lower backpressure back to the normal range.



Although the soot regeneration could remove the majority of PM, some incombustible particles, named as ash, still remain in the DPF. DPF ash usually consists of inorganic components, such as Ca, Mg, P, Zn, Fe and Cr, originating from the additives in lubricant oil and diesel fuel as well as the wear debris from engine and aftertreatment components.

components [9, 10, 11]. Since these compounds cannot be removed during the soot regeneration, the gradual ash buildup will increase the backpressure across DPF and eventually a service interval is required to clean the ash inside DPF. For instance, EPA has required a 150,000 mile minimum filter maintenance interval for 2007 model year heavy duty vehicles [12]. Other adverse effects of ash include inducing the DPF corrosion at high temperature [13] and increasing the frequency of active regeneration events [14]. Hence, a thorough understanding of ash properties and their impact on DPF performance is critical to ensure the design compliance to regulatory requirements at the end of useful life.

Previous research shows various parameters, including duty cycle, soot-to-ash ratio and exhaust conditions, affect the ash distribution inside the DPF. Ishizawa et al reported that ash mainly accumulated in the end of DPF inlet channel as large agglomerates in active regeneration system, while passive regeneration system produced small cluster ash particles along the DPF channel [15]. Harris et al observed the re-suspension of ash during the periodic active soot regeneration and a high soot-to-ash ratio led to a plug-type ash distribution [16]. A. Dittler described the soot-induced ash transport mechanism based on the ash exposure to flow, ash particle structure re-entrainment and axial ash transport. Soot-to-ash ratio, flow velocity, particle size and particle agglomerate structure were found to be the key parameters controlling the ash distribution [17]. Sappok et al studied the regeneration-induced and flow-induced ash deposition process using the in-situ optical investigation and modelling tools. They also observed that the soot-to-ash ratio was critical to the ash transportation [14].

Besides the ash distribution profiles, differences in ash properties, such as ash packing density, ash layer permeability and ash particle porosity, are reported in the literature. Ash packing density is defined as the average density of accumulated ash, and is lower than theoretical ash density due to the void fraction in ash particles. Ash layer permeability describes the permeability of ash layer deposited along DPF channel. Youngquist et al conducted the accelerated ash loading test of DPFs with various substrates and observed different ash compositions, morphologies and distributions with the substrate materials [18]. Sappok et al reported that the lubricant formula and exhaust conditions affected the soot and ash properties, such as packing density and porosity [7, 10]. For example, CJ-4 lubrication oil led to a higher ash packing density than Ca or Zn rich formulas. Morcos et al conducted the characterization of ashes from active and passive regeneration system. The passive ash had significant morphological and phase change differences relative to the active ash during the heat treatment, though they had similar particle sizes and compositions [19]. Based on previous studies [7, 10, 17, 18, 19, 21, 31], ash packing density ranges between 100 to 1000 kg/m³ and ash layer permeability between 5e-12 to 1.7e-14 m², both of which have an order of magnitude difference.

Variations in the observed ash properties and ash profiles cause the different views of ash impact on DPF performance. Gaiser et al reported that loading ash in the end of channels generated a higher backpressure than loading ash on the wall for soot-loaded DPF [20]. In contrast, a study by Hitachi showed that small cluster ash particles on wall caused a higher backpressure increase than large agglomerated ash

accumulated in the end of DPF [15]. In Reference [7], DPF with ash on wall from passive regenerated DPF was observed to have a higher backpressure increase than DPF with ash on the end from active regenerated DPF at an ash loading higher than 10 g/l.

Although various understandings on DPF ash have been reported among the literature, few studies have considered all the ash-related design factors during their analysis. In this paper, we developed a process to collect the ash-related information from a field-return DPF using the combination of the experimental inspection and modelling study. While other nondestructive techniques have been reported for DPF soot and ash measurement [22, 23, 24], it is the first study to utilize terahertz imaging and spectroscopy for ash investigation. The obtained ash properties were then used to assess the ash impact of DPF backpressure and regeneration behaviors.

ASH INSPECTION TECHNIQUES

The ash-loaded DPF used in this study was collected from a 2010 model year mid-range truck using Cummins ISB engine and aftertreatment system. This truck had an accumulated mileage more than 90,000 miles under a line-haul type duty cycle. No fault code was reported during the regular operation and maintenance. The dimension of this DPF is 9 inch in diameter and 11 inch in length. DPF has been decanned and baked in air between 400 to 600 °C for 20 hours to remove the soot and moisture before inspection.

A non-destructive 3D computed tomography (CT) imaging method (Advantest TAS 7000) was used to provide a quantitative distribution of ash across a filter. This CT technique uses the terahertz (THz) wave spectral information to provide a quantitative mapping visualization of ash distribution because of its good sensitivity to low atomic weight atoms. Before each analysis, the substrate was placed in an oven at 150 °C for three hours to remove any moisture that may influence weight measurement and THz wave transmission through the sample. A reference sample containing no ash was analyzed as the baseline. The sample filter retrieved from the field test was analyzed by CT, and the characterization of ash distribution can be visualized by subtracting the baseline signal.

A borescope (Milliscope P08) coupled with a light source (Zibra ZC-LED50) were used to determine the depth of ash plug in DPF inlet channels. Light through the probe tip can be controlled by adjusting the aperture of the light source. This involved placing the filter with the inlet face up and move the probe slowly toward the inlet plug. Representative channels from the center, midsection and rim of each quadrant were inspected to understand the amount and distribution of ash.

A Hitachi S-3700 Scanning Electronic Microscope (SEM) equipped with Energy Dispersive X-Ray Spectroscopy (EDX) was used to study the morphology of ash particle and elemental distribution of ash loaded filter. The EDX technique is limited to elements above atomic number 4. One needs to be careful while analyzing the EDX spectra, as some atoms could have overlapping peaks at a particular energy level. Sometimes, peaks arise due to secondary fluorescence of the sample holder or from the microscope components. The sample

was collected from the ash plug at the end of DPF channel. Figure 1 shows the ash compositions from SEM-EDX. The major components are Ca, Mg, P and Zn, in line with the literature [2, 7, 9, 10, 11].

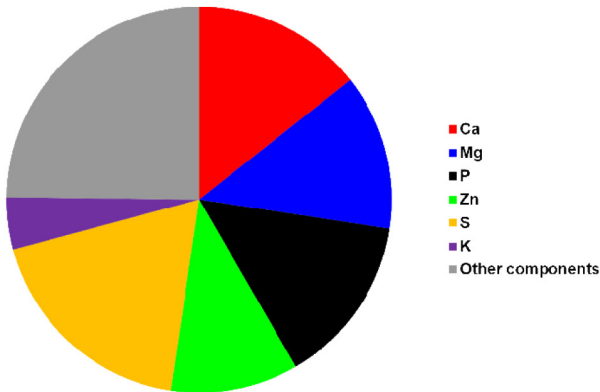


Figure 1. Ash composition from SEM-EDX inspection.

Backpressure of clean and ash-loaded DPF during the flow sweep were measured using a laboratory flow stand. Restrictions before and after DPF were collected to calculate the backpressure across the DPF in a volumetric flow rate range from 0.1 to 0.5 actual cubic meter per second (acms).

DPF MODEL SETUP AND VALIDATION

The one-dimensional DPF mathematical model has been built based on previous work of Bissett [4], Luss [25], Konstandopoulos [26, 27], Opris [28], Johnson [29] and Wang [21]. The basic equations for mass, momentum and energy balances of exhaust gas as well as the applied boundary conditions are summarized in Table 1.

Table 1. Mathematical descript of DPF model.

Mass conservation:	$\frac{d(\rho_i v_i)}{dz} = (-1)^i \frac{4}{d_i} \rho_w v_w$
Momentum conservation:	$\frac{dP_i}{dz} + \frac{d(\rho_i v_i^2)}{dz} = -\frac{f \mu v_i}{d_i^2}$
Energy conservation:	$Cp_g \frac{d(\rho_1 v_1 T_1)}{dz} = \frac{4}{d} h_1 (T_s - T_1)$ $Cp_g \frac{d(\rho_2 v_2 T_2)}{dz} = \frac{4}{d} (h_2 + Cp_g \rho_w v_w) (T_s - T_2)$ $\frac{\partial(\rho Cp_w T_s)}{\partial t} = \lambda_t \frac{\partial}{\partial z} \left(w_t \frac{\partial T_s}{\partial z} \right) + \lambda_t w_t \frac{\partial^2 T_s}{\partial z^2} + h_1 (T_1 - T_s) + h_2 (T_2 - T_s) + Cp_g \rho_w v_w (T_1 - T_s) + (\Delta H) R_{int}$
Darcy's law:	$P_1 - P_2 = \left(\frac{\mu w_p}{k_p} + \frac{\mu w_s}{k_s} + \frac{\mu w_a}{k_a} \right) v_w$
Soot layer thickness:	$\rho_s \frac{dw_s}{dt} = (-M_c R_{int})$
Boundary conditions:	$T_1(0, t) = T_{inlet}(t), \quad T_2(0, t) = T_s(0, t), v_1(0, t) = v_{inlet}(t), v_2(0, t) = 0, \frac{dT_s}{dz}(0, t) = 0$ $v_1(L, t) = 0, P_2(L, t) = P_{atm}, \frac{dT_s}{dz}(L, t) = 0$

In this model, we apply the following assumptions:

1. DPF has been well insulated and thus an adiabatic reactor;
2. Active regeneration kinetics is considered in this study and they are based on the previous report from Yezerets [30];
3. Flow distribution is uniform among the channels;
4. Initial soot and ash layer distribution is uniform along the channel wall;
5. Filtration velocity and solid temperature across soot layer, ash layer and substrate at a given axial and radial position are equal due to the strong heat and momentum convection;
6. Gas and solid temperature are the same within the DPF wall;
7. The mass transport properties of exhaust gas are estimated according to correlations in the Reference [27, 31];
8. The momentum and heat transport properties of gas and substrate are calibrated using the internal test procedures.

The listed differential equations and boundary conditions have been used to construct the in-house DPF model. This enables the simulation of DPF backpressure and temperature behaviors under both steady-state and transient conditions.

To gain the confidence in the resulting DPF model, its backpressure prediction was validated against the test results from flow sweep. Figure 2 shows the backpressure of a 9"×11" DPF as a function of volumetric flow rate under different soot loadings. DPF backpressures are normalized based on the most severe condition with 5 g/l soot at 0.5 m³/s volumetric flow rate. The blue and red lines represent the directly measured DPF backpressures under 0 g/l and 5 g/l soot loadings, separately, while the blue and red dots denote the DPF backpressures from simulation. Since the dots and lines match well with each other, the DPF model is validated for backpressure analysis.

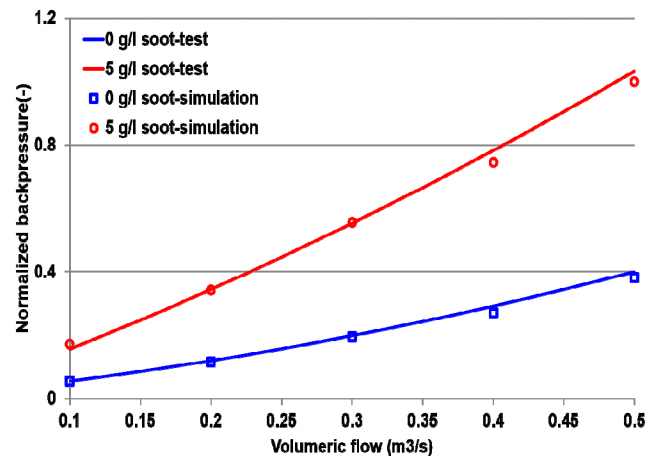


Figure 2. Normalized backpressure over clean and soot loaded DPFs under different flow rates.

In addition to the backpressure prediction, the DPF model can capture the thermal behavior in the active soot regeneration event. Figure 3 compares the temperature evolution profiles from test and simulation during the active soot combustion in a 9"×11" DPF loaded with 5 g/l soot under an average space velocity of 35,000 1/h. The black line represents the inlet temperature, which is the input to both test and