

Investigation into Ash Loading and Its Relationship to DPF Regeneration Method

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ABSTRACT

A diesel particulate filter (DPF) controls and maintains a constant pressure drop across the filter by repeating the regeneration process for PM (Particulate Matter). However, the regeneration results in ash accumulation on the DPF. Although this ash accumulation is very slow, it eventually causes increased pressure drop which affects the product life of the DPF.

Metal elements in the lubricant additives in the engine oil are the source of the ash. Since ash is an oxidized substance, the amount of ash produced depends on such factors as the amount of oil consumed in the engine and the kinds of lubricant additives contained in engine oil. According to the reference literature [1-3], ash accumulates on a DPF differently depending on use of either a passive regeneration system or an active regeneration system. With the passive regeneration system, ash accumulates uniformly on the filter wall while ash accumulates near the outlet of the filter with the active regeneration system. Even though the amount of ash collected on the filter is same regardless of the regeneration method, the difference in the way ash accumulates on the filter between the two regeneration systems affects the characteristics of pressure drop across the filter. Therefore, the regeneration method is another parameter that affects filter performance, and the selection of a regeneration strategy is important to extend the useful life of the DPF.

According to observations of ash accumulating on a DPF through both bench and engine tests of the regeneration process and accumulated ash removed

from the DPFs of fleets, the authors found that ash is different in its particle size depending on temperature of PM combustion during regeneration. The particle size was smaller at lower combustion temperatures and larger at higher combustion temperatures as in the cases of the passive and active regeneration systems, respectively. As a result of these observations, a hypothesis was developed to explain the effect that the regeneration system had on how ash would accumulate on a DPF.

The authors investigated the effect that ash accumulating on a DPF had on pressure drop across the filter and PM filtering performance. DPFs were sampled from a high-mileage fleet and evaluated for both pressure drop and PM filtering performance. Subsequently, the DPFs were cut to observe how ash had accumulated on the filter. Various patterns of ash collection on a DPF were artificially created using fly ash, and their effects on both pressure drop and PM filtering performance were evaluated. The results of these investigations revealed how ash collected on the filter would affect the pressure drop and PM filtering performance.

According to the results of various tests and evaluations, the authors describe the mechanism of ash loading on the DPF and propose a DPF regeneration system that produces an ideal accumulation pattern of ash on the filter to keep PM filtering performance at the optimal level for useful life.

INTRODUCTION

According to general understanding among Japan's engine researchers, each component used for a commercial vehicle powered by a diesel engine is designed to last approximately 1.5 million kilometers. This also applies to components in an aftertreatment device. In a DPF, the filter needs to be either cleaned or replaced with a new one during the useful life of the vehicle because of the problem of ash build-up on the DPF.

Ash is a substance that remains on a DPF after regeneration is performed to remove PM collected on the filter. Figure 1 shows ash accumulated on the filter. A list of metal and chemical elements determined in the ash is also included in the figure. The results of chemical analysis indicate that the ash consists primarily of oxides of metallic substances found in engine oil such as phosphorous (P), sulfur (S), calcium (Ca), and zinc (Zn).

There is spherical and clustery ash mixed with ash in fine particles, as shown in the images obtained with transmission electron microscopy (TEM) in Figure 2, and this ash also contains oxides of P, S, or Zn regardless of shape. Although low-ash engine oil has been used for diesel engines equipped with DPFs to reduce ash, it is impossible to eliminate entirely the production of ash.

As ash accumulates on a DPF, the filtration area decreases, as shown in Figure 3. Not only is ash observed near the outlet of the filter, but also on the filter where particulate collects. Some filtration areas were completely covered with ash, and other areas were covered with ash and particulate in layers. Thus, the increase in the pressure drop is accelerated as ash accumulates on the filter, and this increases risk of

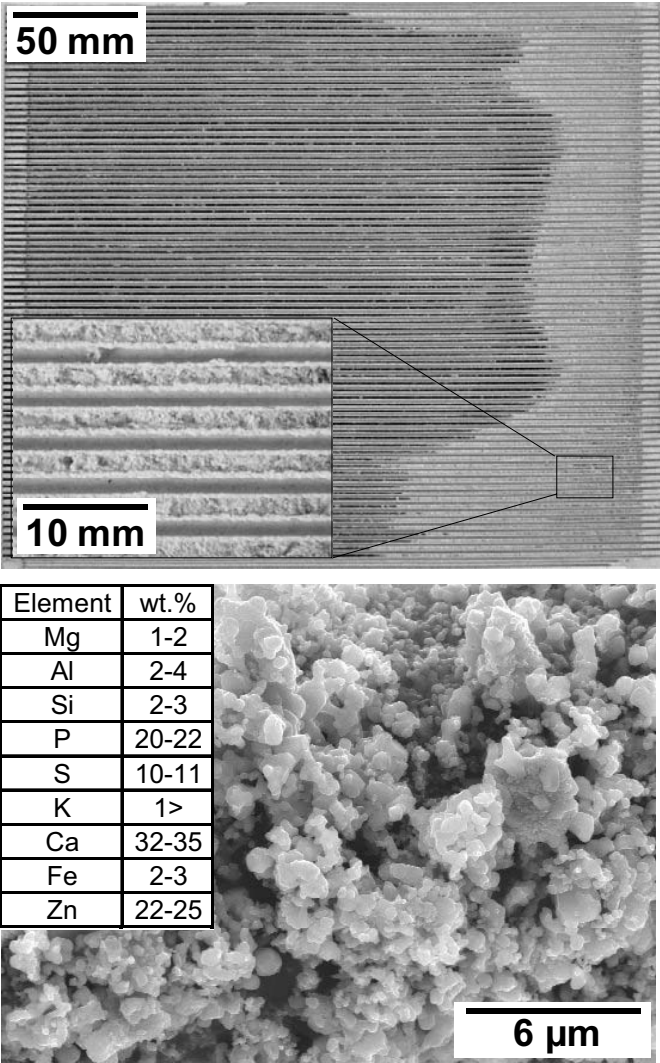


Figure 1 Accumulated Ash on a DPF Sampled from a High-Mileage Fleet and the Ash Constituents

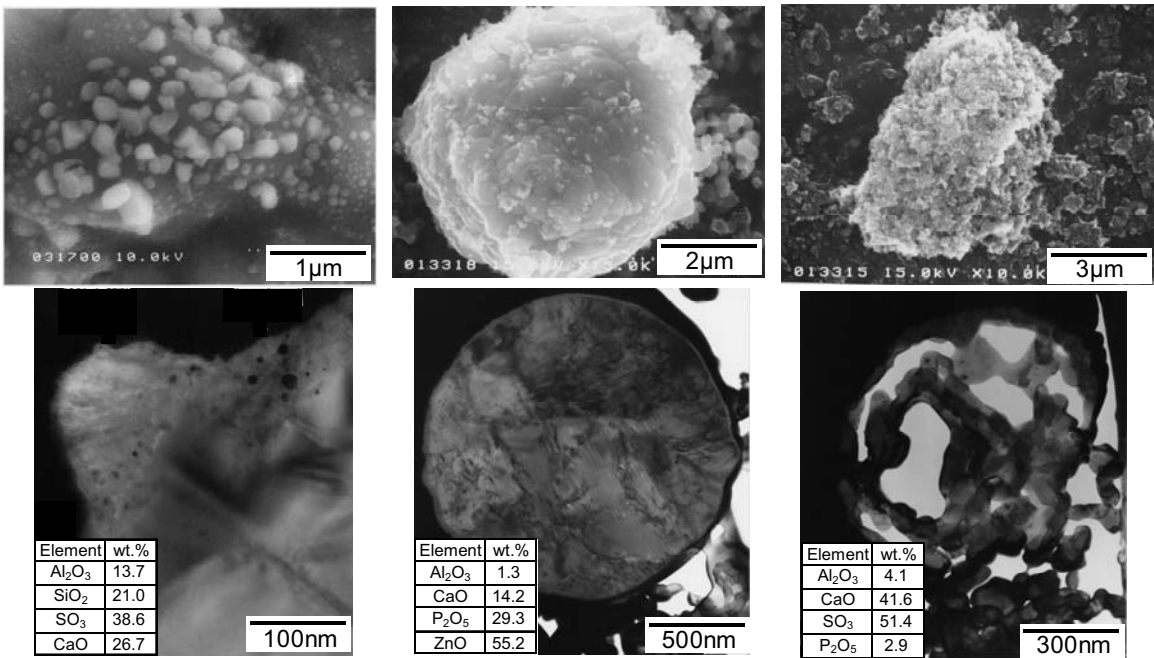


Figure 2 Ash Analyzed with TEM and Its Constituents

generating uncontrollable combustion during regeneration of the DPF. Even with no particulate loaded on the filter, the accumulation of ash on the DPF causes the pressure drop to increase.

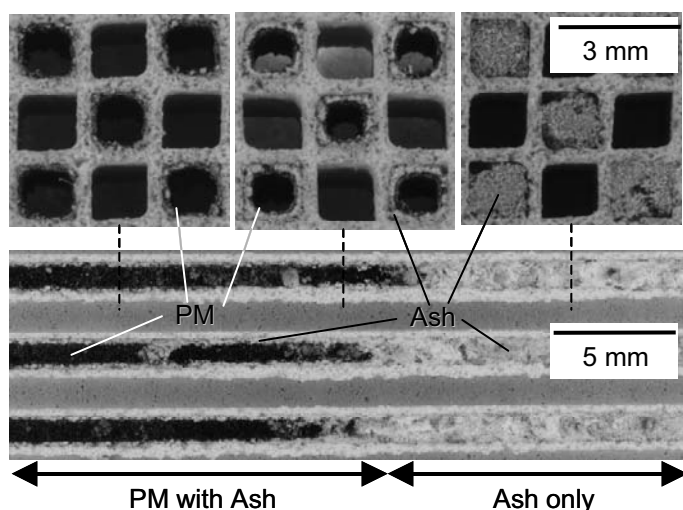


Figure 3 Ash and PM Loaded on DPF

It is generally understood that ash accumulates on a DPF differently depending on the method of DPF regeneration [1-3]. On a DPF passively regenerated at relatively low temperatures of 400-500 deg. C, ash uniformly accumulates on the filter wall from its inlet to the outlet. However, on the actively regenerated DPF at higher temperatures of more than 600 deg. C, ash mostly accumulates near the outlet of the filter. Since various factors such as exhaust gas flow rate, concentration of oxygen in exhaust gas, and the amount of particulate all affect the way ash accumulates on the filter during regeneration, it may not be appropriate to distinguish the formation of ash on the filter simply based on the regeneration method. Nonetheless, the two significant factors are the state of ash loading and the regenerating conditions.

Not only the amount of ash accumulated on the filter, but also the difference in ash loading influences the deterioration of DPF performance. According to the reference literature [1-2], the pressure drop across the filter is greater when ash loading is spread uniformly on DPF than when ash is mostly collected near the outlet of the filter. Also, increase in the pressure drop due to particulate loading on DPF becomes greater when ash accumulates near the outlet of the filter [3-4].

Thus, it is important to control the aftertreatment system with both feedback information and the prediction of DPF performance considering deterioration due to the accumulation of ash on the filter, although prediction is difficult. The amount of ash collected on the filter correlates with consumption of the engine oil from which the ash originates. However, there are some unknowns including, for example, the fraction of metals in the oil consumed in the engine, the amount of ash produced in the engine that actually accumulates on the filter with

other particulate matter, and the fraction of metals exhausted with the consumed oil that becomes ash on the filter and remains on the filter. These amounts of metal elements are affected by such factors as the DPF's filtration efficiency and vehicle operating conditions. According to the results found in reference literature [4-7], the amount of ash collected on the filter varies widely in the range of 3 to 50 percent of the metal elements in the engine oil. Thus, the relationship between the accumulation of ash and the deterioration of DPF performance is still unclear.

As DPF developers, we at Hitachi participated in a joint DPR development program with Hino Motors in July 2000. DPR stands for Diesel Particulate active Reduction system. As the name indicates, the system is an active regeneration method for PM combustion [2]. During this development with Hino, we analyzed a variety of regeneration conditions. We were also able to learn from on-road filters in use in the market after the development phase.

This paper presents results from both analyses and tests conducted on DPFs sampled from a fleet and DPFs tested at the laboratory to determine the effects that ash load on a DPF had on its performance. The results were produced during the course of the joint development program for DPR [2] that Hitachi Metal and Hino Motors have performed since July 2000.

ASH LOADING DEPENDING ON REGENERATION METHOD

During the initial development stage, the passive regeneration process was chosen for the DPR to regenerate a DPF. Later, the method was changed to the active regeneration process because the increase in pressure drop across the filter was significant due to the accumulation of ash on the filter. Figure 4 shows photographs of cross sections of DPFs with the passive regeneration system and the active regeneration system.

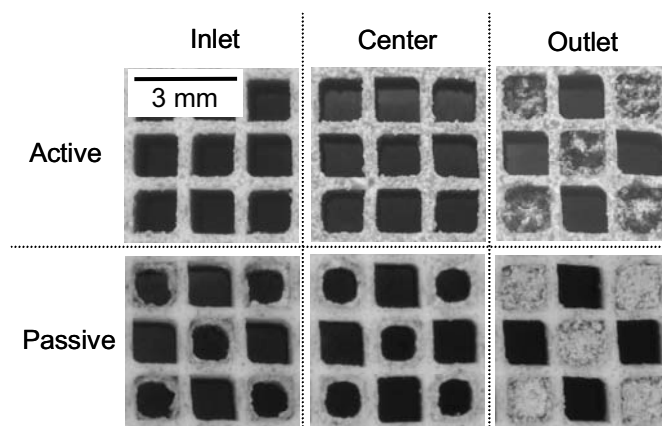


Figure 4 Ash Accumulated in the Flow Passages of DPFs with a Passive Regeneration System and an Active Regeneration System

As described in the previous section, ash accumulates uniformly from inlet to outlet of the DPF with the passive regeneration system. With the active regeneration system, clustered ash was observed on the outlet side of the DPF. Figure 5 shows photographs of ash observed on the filter regenerated both with the passive regeneration system and with the active regeneration system. Ash observed on the filter with the passive regeneration system appears to be relatively less than that observed on the filter with the active regeneration system. Ash that clogged the flow passages of the filter was suspected to increase the pressure drop across the filter.

Detailed observations of the ash confirmed that the particle size became greater when the active regeneration system was used to regenerate DPF, although no difference in the constituents of ash was determined between the two results. Figure 6 shows the particles of ash observed with a scanning electron microscope (SEM).

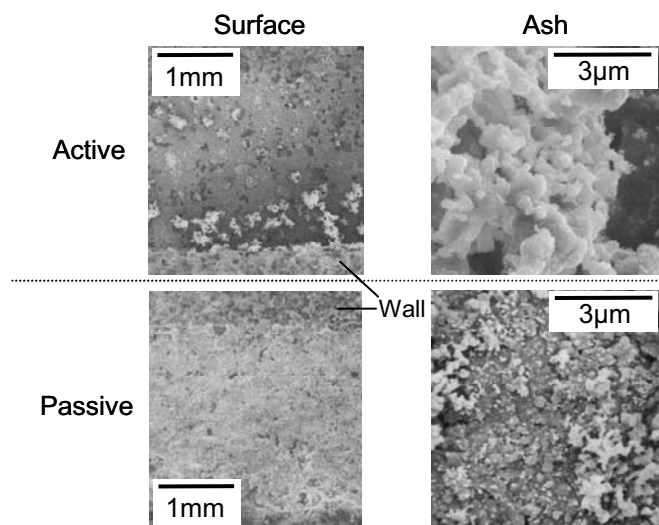


Figure 5 The Effect of DPF Regeneration Method on Ash

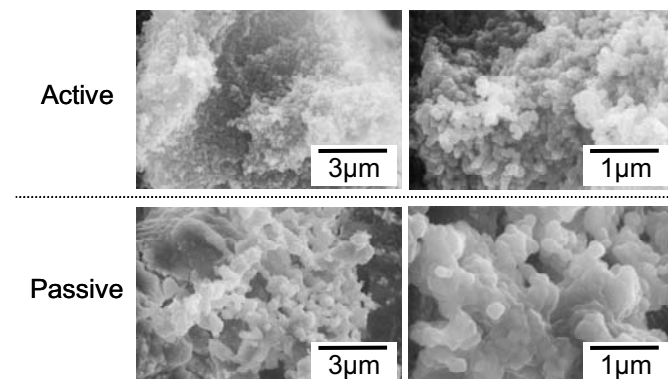


Figure 6 Particle Size of Ash observed with SEM

Compared to the active regeneration system, the passive regeneration system burns a relatively smaller amount of particulate at lower temperatures of about 450

deg. C. Thus, the relatively low-temperature combustion of PM is believed to have reduced the particle size of the ash. The authors then observed ash collected on a filter that was regenerated at various temperatures. The DPF was tested on an engine test bench to collect particulate for the specific amount of about 9 grams per liter (g/L). A specimen of this DPF was regenerated at temperatures elevated from 400 to 600 deg. C by 50-deg. C increments. Figure 7 shows the effect of regeneration temperature on ash observed on the DPF specimen. As the regeneration temperature was increased, particle size of the ash increased.

Experiments continued for observation of change in the particle size at elevated temperatures. Another specimen was obtained from the DPF with PM loading of 9 g/L that was previously used for evaluation of temperature effects. The specimen was heated at 430 deg. C for 16 hours to burn particulate, and formation of ash was determined. Subsequently, the temperature was increased to 630 deg. C for two hours. While the ash was being observed, the particles began to agglomerate at the higher temperatures and the size became greater as shown in Figure 8. According to this experiment, not only does the particle size of ash depend on the PM combustion temperature, but, once produced, ash changes its particle size depending on the thermal environment. Since PM combustion temperature of the passive regeneration system is relatively low, the particle size of the resulting ash is smaller. On the other hand, even when the particle size of ash on the DPF with active regeneration system is small, the particle size can be larger if the active regeneration is repeated, raising the temperature and causing the particles to agglomerate.

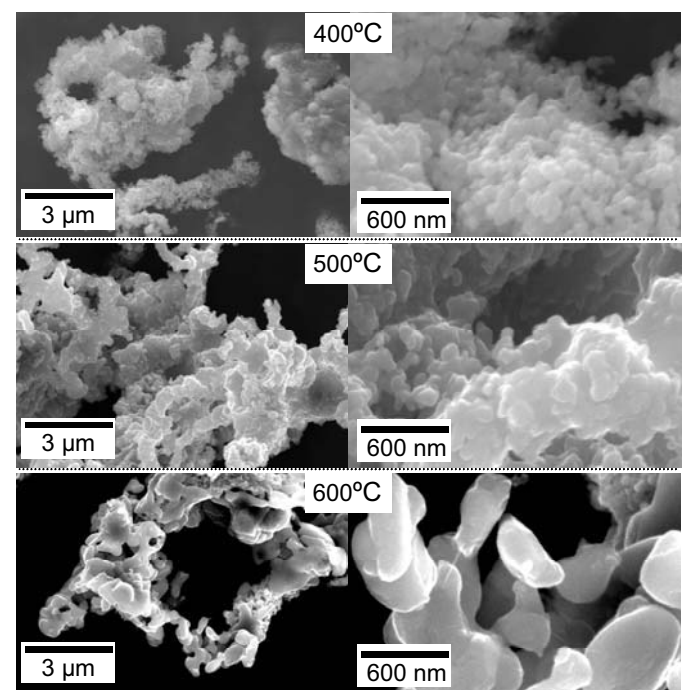


Figure 7 The Effect of Regeneration Temperature on Particle Size of Ash