

FIGURE 19.9 Proposed oxidation mechanism for the platinum/cerium fuel additive in combination with a platinum-catalyzed particulate trap. NO is oxidized to NO₂ over supported platinum. Subsequently, the formed NO₂ oxidizes the soot, forming NO. In parallel, a platinum/cerium-catalyzed oxidation with O₂ occurs.

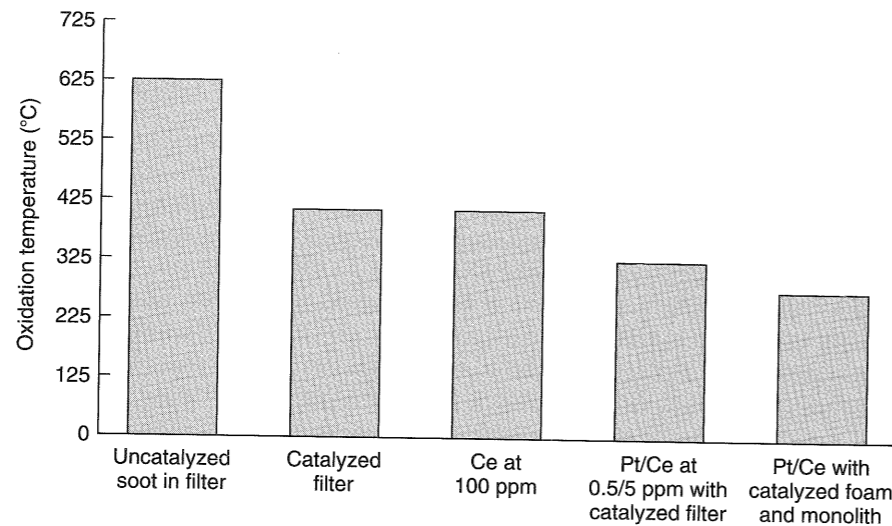


FIGURE 19.10 Comparison of the oxidation temperature of cerium and platinum/cerium-catalyzed diesel soot. (After Jelles, S.J., Krul, R., Makkee, M., and Moulijn, J.A., *Catal. Today*, 53, 623–630, 1999 and Valentine, J.M., Peter-Hoblyn, J.D., and Acress, G.K., SAE 2000 Spring Fuel and Lubricants Meeting and Exposition, Paris, June 2000, 2000-01-1934.)

such as PM loading, trap volume, trap materials, trap pore size, additive concentration, oxygen concentration, engine type, and engine load.

19.3.2 INDIRECT CONTACT CATALYSTS FOR DIESEL SOOT OXIDATION

Some catalysts can oxidize soot without having intimate physical contact. They catalyze the formation of a mobile compound (NO₂, O_{ads}, etc.) that is more reactive than O₂. In the absence of physical contact, the formation of those mobile species is the main advantageous property of this type of catalyst. For indirect contact catalysts, two main reaction mechanisms are known: NO_x-aided gas-phase mechanism and spill-over mechanism.

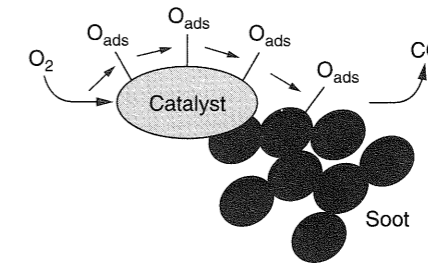


FIGURE 19.11 Spill-over mechanism in metal oxide-catalyzed soot oxidation.

Cooper and Thoss [54] patented a way of using gas-phase NO₂ as an activated mobile species for soot oxidation (NO_x-aided gas-phase mechanism) in combination with a filter device. The reaction of NO₂ with carbon material was published as early as 1956 [55]. They proposed that NO₂ accelerates soot combustion:



Some catalysts can dissociate oxygen and transfer it to the soot particle, where it reacts as if it were in a noncatalytic reaction. This mechanism is known as the spill-over mechanism (Figure 19.11).

There are some examples that show that contact is not a prerequisite in this type of reaction. For instance, Baumgarten and Schuck [56] showed that the rate of catalytic coke oxidation can be accelerated while there is no direct contact between the catalyst and the coke, which they explained by oxygen spill-over. Baker and Chludzinski [57] showed that Cr₂O₃ could accelerate edge recession of graphite while being motionless. Mul et al. [30] showed with a labeled oxygen study that spill-over and redox oxidation can occur simultaneously. They discussed that the dominating mechanism will depend on the degree of physical contact between the catalyst and soot.

19.4 DESIGN/SIZING OF DIESEL PARTICULATE FILTER

The filter concept shown in Figure 19.12 involves having the alternate cell openings on one end of the unit plugged in checkerboard fashion. The opposite end or face is plugged

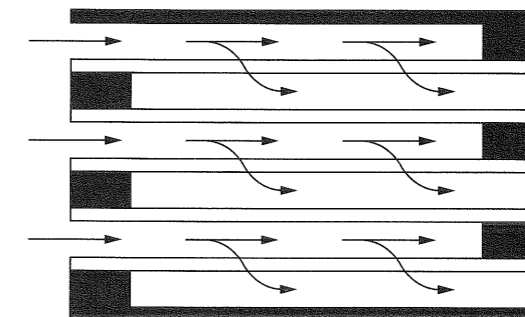


FIGURE 19.12 Wall-flow filter concept with alternate plugged cells.

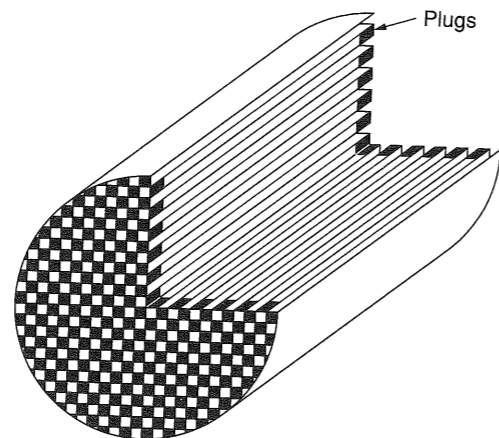


FIGURE 19.13 Schematic of diesel filter with checkerboard plug pattern.

in a similar manner, but one cell displaced, allowing no direct path through the unit from one end to the other as indicated in Figure 19.13. The exhaust gas entering the upstream end is therefore forced through the porous wall separating the channels and exits through the opposite end by way of an adjacent channel. In this way, the walls of the honeycomb are the filter medium [58,59].

They can be made sufficiently porous to allow exhaust gas to pass through without excessive pressure drop. This wall-flow concept offers a large amount of filter surface area in a reasonably compact volume together with high filtration efficiency. Periodically, the soot that is collected is oxidized to CO_2 — a process known as regeneration — which renders the filter clean. The fact that the filter is constructed of special ceramic materials results in its ability to withstand high temperatures while being chemically inert. One of these materials is a porous cordierite ceramic with magnesia/alumina/silica composition ($2\text{MgO}\cdot 2\text{Al}_2\text{O}_3\cdot 5\text{SiO}_2$). A key property of this composition is a very low coefficient of thermal expansion. The material used to plug the cell openings in the faces is similar in nature to the body in composition and thermal characteristics. It is a high temperature foaming cement which during firing seals to the cell walls and is impervious to gas flow. More advanced materials capable of withstanding even higher temperature are discussed later. The walls contain a series of interconnected pores of a volume and size sufficient to enable the exhaust gas to flow completely through but restrain most of the particles.

The performance characteristics of wall-flow filter can be varied and managed. Its collection efficiency can be controlled to a large degree by the properties of the walls that form the channels. These include total pore volume, pore size distribution, and the thickness of the wall itself. The flow through the wall can be made more restrictive by adjusting the porosity of the wall. A smaller pore volume creates a highly efficient filter but at the same time restricts the flow and produces high back pressure. Conversely, with porosity adjusted in the opposite direction, low back pressure is achieved, but at the expense of reduction in collection efficiency.

19.4.1 PERFORMANCE REQUIREMENTS

The four basic requirements that the DPF should meet are [60]:

1. Adequate filtration efficiency to satisfy particulate emissions legislation.
2. Low pressure drop to minimize fuel penalty and conserve engine power.

3. High thermal shock resistance to ensure filter integrity during regeneration.
4. High surface area per unit volume for compact packaging.

Although a high filtration efficiency would make the filter more effective, it must not be accomplished at the expense of high back pressure or low thermal integrity. Indeed, the microstructure and plugging pattern of a ceramic filter can be tailored to obtain filtration efficiencies ranging from 50 to 95% per engine manufacturers' specification. Furthermore, recent advances in ceramic composition have led to filters with high filtration efficiency, acceptable back pressure, and excellent thermal integrity [61–65]. As the PM is trapped in the filter walls, it begins to build up on the surface of open cells forming a soot layer which also acts as a filter. With increasing thickness of soot layer the hydraulic diameter of the channel decreases resulting in higher back pressure. Obviously, the initial and final channel size must be controlled via filter design and soot accumulation level to limit the back pressure to an acceptable value. Again, this can be accomplished by designing the microstructure, the cell geometry, the plugging pattern, and the size of ceramic filter, which in turn are dictated by engine size, flow rate, and engine-out emissions.

The dominant component of trapped particulates is soot carbon which is formed during combustion of a fuel-rich mixture in the absence of adequate oxygen. Although some of the soot may be oxidized to CO_2 during the latter part of power stroke, a major portion does not get oxidized due to slow process [66]. The other major component of PM consists of heavy unburned hydrocarbons. Since the chemical energy of soot carbon and heavy hydrocarbons is high, once they are ignited during regeneration they release a great deal of heat which, if not dissipated continuously, can result in high temperature gradients within the filter [67]. Thermal stresses associated with such gradients must be kept below the fatigue threshold value of the filter material to ensure thermal integrity over its lifetime [67,68]. This is best accomplished by using a ceramic composition with ultralow thermal expansion and modestly high fatigue threshold value [61]. Other approaches to improving thermal integrity include the use of fuel additives and/or catalysts to effect regeneration at lower temperatures [69]. Alternatively, more frequent regenerations can also reduce the temperature gradients and enhance thermal integrity but at the expense of fuel penalty if a burner is used for regeneration.

The honeycomb configuration of ceramic filters offers high surface area per unit volume, thereby permitting a compact filter size [70]. The absolute filtration surface area depends on cell size, filter volume, and plugging pattern, all of which are design parameters whose optimization, as will be shown shortly, calls for trade-offs in pressure drop, filtration efficiency, mechanical durability, thermal integrity, and space availability.

19.4.2 COMPOSITION AND MICROSTRUCTURE

The filter composition that has performed successfully over the past two decades is cordierite ceramic with the chemical formula of $2\text{MgO}\cdot 2\text{Al}_2\text{O}_3\cdot 5\text{SiO}_2$. Its unique advantages include low thermal expansion, ideal for thermal shock resistance, and tailorable microstructure to meet filtration and pressure drop requirements. The extrusion technology for producing automotive catalyst supports also helps manufacture diesel filters. Consequently, the unit cell design can be achieved via die design while the porosity and microstructure are best controlled by composition and process modifications.

The most common cell density employed for diesel filters is 100 cells/in² with 0.017 in (0.043 cm) thick cell wall. This choice offers the best compromise in terms of filtration area and back pressure. While 200 cells/in² structure offers 41% larger filtration area and has been used for diesel filters, it results in higher pressure drop. Similarly, thicker cell walls (0.025 in or 0.064 cm thick) offer 50% higher strength but they too result in higher pressure drop.

Another parameter that affects pressure drop is mean pore size, which can range from 12 to 35 μm . Although the pressure drop decreases with increasing pore size, so does filtration efficiency. Hence, a compromise is necessary in tailoring the pore size, wall thickness, and cell density. The wall porosity also affects pressure drop and mechanical strength. Both pressure drop and mechanical strength decrease as the wall porosity increases, thus calling for a compromise in selecting the wall porosity. Most filter compositions and manufacturing processes are designed to yield a wall porosity of 45 to 50%. Filters with low mean pore size are designed to offer high filtration efficiency ($>90\%$), those with intermediate mean pore size are designed for medium filtration efficiency (80 to 90%), and those with large mean pore size are designed for low filtration efficiency (60 to 75%).

19.4.3 CELL CONFIGURATION AND PLUGGING PATTERN

Figure 19.13 shows the wall-flow filter with square cell configuration and checkerboard plugging pattern. The open frontal area (OFA) and specific filtration area (SFA) for such a filter are defined in terms of cell spacing L and wall thickness t :

$$\text{OFA} = 0.5 \left(\frac{L-t}{L} \right)^2 \quad (19.4)$$

$$\text{SFA} = \frac{2(L-t)}{L^2} \quad (19.5)$$

Since the cell density N for square cell structure is given by

$$N = \frac{1}{L^2} \quad (19.6)$$

it follows from Equation (19.5) that the specific filtration area is directly proportional to the cell density. As the cell density increases, the hydraulic diameter defined by

$$D_h = L - t \quad (19.7)$$

decreases. Hence a portion of the total pressure drop due to gas flow through the open channels of the filter, which depends inversely on the square of hydraulic diameter, increases. Thus, care must be exercised in selecting the appropriate cell density [70]. Other factors that play a key role in designing the filter are its mechanical integrity and filtration capacity. The former is defined by the mechanical integrity factor MIF, which, for a given wall porosity, depends on cell geometry via

$$\text{MIF} = \frac{t^2}{L(L-t)} \quad (19.8)$$

The filtration capacity is the total amount of soot that can be collected prior to safe regeneration. It is directly related to total filtration area TFA defined by the product of specific filtration area and filter volume:

$$\text{TFA} = \frac{2(L-t)}{L^2} V_f \quad (19.9)$$

where the filter volume V_f is given by

$$V_f = \frac{\pi}{4} d^2 l \quad (19.10)$$

in which d and l denote filter diameter and length, respectively.

As noted earlier, most filter compositions enjoy 50% wall porosity to limit the pressure drop to acceptable levels. The mean pore size, which also has a bearing on pressure drop due to gas flow through the wall, is primarily dictated by filtration efficiency requirement. As emissions legislation becomes more stringent, filtration efficiencies $\geq 90\%$ become desirable calling for mean pore diameter of 12 to 14 μm . With microstructure fixed in this manner, the two common cell configurations for diesel filters that have been manufactured are 100/17 and 200/12. It may be verified that they have identical open frontal area and mechanical integrity factor. However, the specific filtration area of 200/12 is 41.5% greater than that of 100/17 configurations implying lower (for constant total filtration area) filter volume for the former, which may be desirable to meet space constraints. However, the hydraulic diameter of 200/12 is 30% smaller than that of 100/17 configurations implying higher pressure drop for the former, which may not be acceptable. Furthermore, the 200/12 configurations may also experience fouling due to ash buildup following several regenerations. The model for total pressure drop is discussed in a later section; however, for a comparison of two different cell configurations we need to write the expression for pressure drop, under fully developed laminar flow conditions, due to gas flow through open channels, Δp_{ch} , namely

$$\Delta p_{\text{ch}} = \frac{C v_{\text{ch}} l}{D_h^2} \quad (19.11)$$

where C is a constant and v_{ch} denotes gas velocity through the channel, which is given by

$$v_{\text{ch}} = \frac{Q}{A_{\text{open}}} \quad (19.12)$$

Here Q is the flow rate through the filter and A_{open} is the open cross-sectional area given by

$$A_{\text{open}} = \frac{\pi}{4} d^2 \times \text{OFA} \quad (19.13)$$

In view of identical open frontal area, filters with 100/17 and 200/12 cell configurations will have identical open cross-sectional area and gas velocity through their respective channels under constant flow rate conditions. Thus, the pressure drop Δp_{ch} will now be proportional to l/D_h^2 according to Equation (19.11). We define this ratio as "back pressure index" or BPI:

$$\text{BPI} = \frac{l}{D_h^2} \quad (19.14)$$

Since the specific filtration area of 200/12 configuration is 41.5% greater, the filter length with such a configuration can be 58.5% smaller than that of the filter with 100/17 cell configuration for identical total filtration area. In this manner, Equation (19.14) helps estimate the back pressure penalty (the pressure drop due to channel flow is a significant fraction of total pressure drop through the filter) due to smaller hydraulic diameter of 200/12 cell configuration. The results of this exercise are summarized in Table 19.4, which compares the properties and performance parameters of filters with two different cell configurations.