TABLE 19.4
Properties and Performance Parameters of Diesel Filters with Two Different Cell Configurations and Constant Total Filtration Area

Property and performance parameter	100/17 cell	200/12 cell
L (cm)	0.254	0.180
t (cm)	0.043	0.030
N (cells/in^2)	100	200
OFA	0.345	0.345
MIF	0.035	0.035
D_h (cm)	0.211	0.150
SFA (cm^2/cm^3)	6.54	9.25
BPI (cm^{-1})	1.0	1.17
TFA (cm^2)	X	X
l (cm)	1	0.5851

From Gulati, S., in *Structured Catalysts and Reactors*, Cybulski, A. and Moulijn, J.A., Eds., Marcel Dekker, New York, 1996, pp. 15–58 and 501–542. Courtesy of Marcel Dekker, New York.

It shows that despite the compact volume of the 200/12 filter it will experience 17% higher back pressure than the 100/17 filter. Such a back-pressure penalty, as is shown later, may well exceed 17% as the soot membrane begins to build up on the surfaces of open channel walls. In addition the pressure drop through porous walls can also be significant. It is clear from Table 19.4 that filter design often calls for trade-offs in performance parameters that, in turn, require prioritization of durability and performance requirements on the part of filter designer.

19.4.4 Filter Size and Contour

Both mechanical and thermal durability requirements favor a circular contour for the filter since it lends itself to robust packaging and at the same time experiences less severe temperature gradients during regeneration. Furthermore, circular filters are easier to manufacture and control tolerances, making them more cost effective than noncircular contours. Indeed, the latter have also been manufactured for special applications where space constraint is the dominating factor.

Filter size is generally dictated by engine capacity and is normally equal to engine volume. This "rule of thumb" for designing the filter size has worked well in both mobile and stationary applications in that it helps control soot collection and regeneration without impairing filter durability and imposing high back-pressure penalty. We illustrate these benefits with a realistic example.

Consider a 10-liter, 170 kW diesel engine for a medium- to heavy-duty truck for urban areas. We design the total filter volume to be 10 liters with a microstructure commensurate with 90% filtration efficiency. Based on prior experience we limit the soot loading to 10 g/liter of filter volume to ensure safe regeneration at intervals of two hours. Then

$$\text{Total soot collected} = \frac{10 \times 10}{2} = 50\,\text{g/h}$$

$$\text{Rate of soot emitted by engine} = \frac{50}{0.9} = 55.5\,\text{g/h}$$

which in standard units works out to 0.18 g/kWh. This is a good representation of soot output of new modern-day diesel engines. Let us note that the filter will help reduce the soot emissions from 0.18 to 0.018 g/kWh due to its 90% collection efficiency.

In the next section we develop the pressure drop model and estimate the back pressure due to the above loading.

19.4.5 Pressure Drop Model

The pressure drop model is based on the following assumptions [72]:

1. Incompressible gas
2. Laminar flow
3. Constant density and viscosity at a given temperature
4. Cylindrical pores in filter walls
5. No cross-flow between pores

Referring to Figure 19.14, the total pressure drop across the filter is made up of five components:

$$\Delta p_{\text{total}} = \Delta p_{\text{en}} + \Delta p_{\text{ch}} + \Delta p_{\text{w}} + \Delta p_{\text{s}} + \Delta p_{\text{ex}} \tag{19.15}$$

The entrance and exit losses, Δp_{en} and Δp_{ex}, are relatively small compared with other losses. Hence they will be neglected. The remaining three losses can be estimated from the generic equation for a circular pipe:

$$\Delta p = \frac{32\mu v l}{g d^2} \tag{19.16}$$

where μ = gas viscosity (kg/m/sec), v = gas velocity through pipe (m/sec), l = effective pipe length (m), d = effective pipe diameter (m), and g = gravitational acceleration (m/sec/sec).

We will apply the above equation to estimate each component of pressure drop through a 10-liter filter (26.67 cm diameter × 17.78 cm long) with 100/17 cell configuration. To this end, we assume engine size = 10 liters, engine speed = 1500 rpm, gas temperature = 325°C. Then

$$Q = \text{flow rate} = 7500\,\text{l/min at } 325°\text{C}$$

For the checkerboard plug pattern (we assume a diameter of 10 in (25.4 cm) for the checkerboard region due to fully plugged peripheral region, 0.25 in (0.635 cm) wide)

$$A_{\text{open}} = 175\,\text{cm}^2$$
$$v_{\text{ch}} = \frac{Q}{A_{\text{open}}} = 14.4\,\text{mm/s}$$
$$d_{\text{ch}} = (L - t) = 0.207\,\text{cm}$$

Substituting the above quantities in Equation (19.16) gives

$$\Delta p_{\text{ch}} = \frac{32\mu\, v_{\text{ch}}\, l}{g\, d_{\text{ch}}^2} = 5\,\text{mbar} \tag{19.17}$$

The effective length of pores in the filter wall depends on their tortuosity and mean pore diameter, which for the filter will be taken as 12.5 μm. The effective pore length is

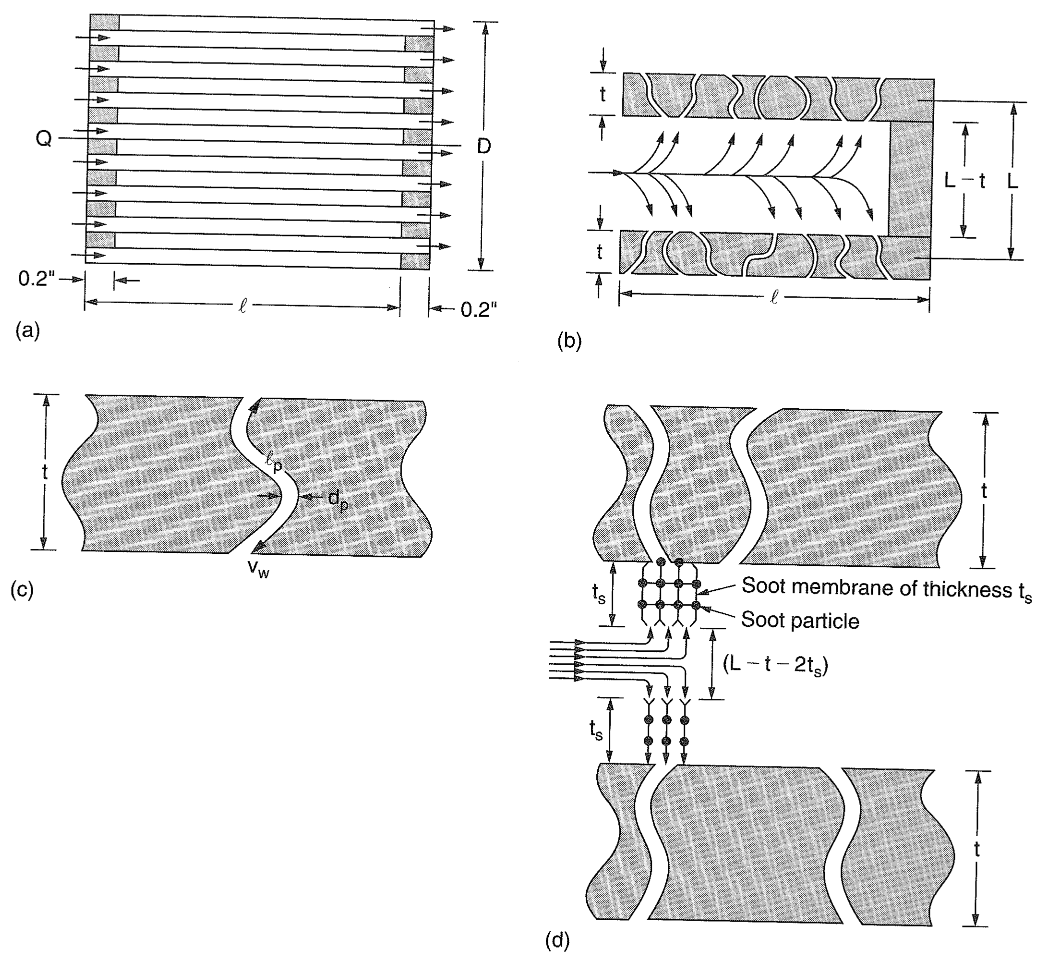

FIGURE 19.14 Flow model for pressure drop calculations: (a) entry and exit losses; (b) pressure drop through clean channel; (c) pressure drop through cell wall; (d) pressure drop through sooted channel.

approximately $3t$, with t being wall thickness [72]. The gas velocity through the pores is readily obtained by the continuity equation:

$$v_{ch}(L - t)^2 = v_w \times 4P(L - t)l \qquad (19.18)$$

where P denotes fractional porosity of filter walls which will be taken as 0.5. Substituting $L = 0.254\,\text{cm}$, $t = 0.043\,\text{cm}$, $P = 0.5$, and $l = 6.6$ in in Equation (19.18), we obtain

$$v_w = 0.0063; \qquad v_{ch} = 8.93\,\text{cm/sec}$$

Substituting $l_p = 3t = 0.128\,\text{cm}$, $d_p = 12.5\,\mu\text{m}$, and $v_w = 8.93\,\text{cm/sec}$ in Equation (19.16) we obtain

$$\Delta p_w = 7\,\text{mbar}$$

Thus, pressure drop through the wall is 38% higher than that through the channel. The above estimate of Δp_w is based on clean and open pores. As these pores accumulate

soot, their mean diameter will decrease, the flow velocity will increase and Δp_w will go up. To re-estimate Δp_w, we can still use Equation (19.16) once we know the amount of soot trapped in the pores.

The pressure drop through the soot membrane is negligible due to both its open structure and small thickness. However, as the membrane thickness increases with continuous deposition of soot, the hydraulic diameter of a sooted channel decreases and the gas velocity increases thereby contributing to Δp_{ch}. To estimate the incremental pressure drop due to soot membrane we must first study the kinetics of soot deposition.

Recall that the maximum allowable soot accumulation for safe regeneration is typically 10 g per liter of filter volume. For a filter volume of 10 liters, the total soot collected prior to regeneration is 100 g over a two-hour filtration cycle. With a filtration efficiency of 90%, the soot output of a 170 kW engine is given by

$$\text{Soot output} = 0.326\,\text{g/kW/h}$$

$$\text{Soot accumulation rate} = \frac{50}{60} = 0.833\,\text{g/min}$$

$$\text{Active filter volume} = 8500\,\text{cm}^3$$

$$\text{Total filteration area} = \text{SFA} \times V_f = 5500\,\text{cm}^2$$

The soot density has been reported in the literature and is approximately $0.056\,\text{g/cm}^3$ [60]. Using this value we can estimate the rate at which soot volume, hence the soot membrane thickness, builds up.

$$\text{Rate of soot volume collected per filter} = 14.9\,\text{cm}^3/\text{min}$$

$$\text{Rate of increase in soot membrane thickness} = 0.00028\,\text{cm/min}$$

$$\text{Total thickness of soot membrane after 2 h} = 0.033\,\text{cm}$$

$$d_{ch} = 0.145\,\text{cm}$$

$$A_{open} = 830\,\text{cm}^2$$

$$v_{ch} = \frac{Q}{A_{open}} = 28.9\text{m/sec}$$

Substituting into Equation (19.16), we obtain

$$\Delta p_s = 21\,\text{mbar}$$

Thus, the pressure drop through a sooted channel (with 10 g/l of soot loading) is three times as large as that through the wall and over four times as large as that through the clean channel.

The above computations were also carried out for a 10.5 in diameter × 5 in long filter with 200/12 cell configuration (and identical total filtration area as the 10.5 in diameter × 7 in long filter with 100/17 cell configuration). Table 19.5 compares the individual pressure drop components for the two filters. It is clear from this table that the largest contribution comes from flow through the sooted channel. Furthermore, the small hydraulic diameter of 200/12 cell results in nearly three times higher pressure drop than that for the 100/17 cell which explains the popularity of the 100/17 cell configuration for filter applications.

TABLE 19.5
Comparison of Pressure Drop for Two Filters with Identical Total Filtration Area but Different Cell Configurations (in mbar)

	10.5 in diameter × 7 in length filter (100/17 cell)	10.5 in diameter × 5 in length filter (200/12 cell)
Δp_{ch}	5	7
Δp_{w}	7	10
Δp_{s}	22	74
Δp_{total}	34	91

From Gulati, S., in *Structured Catalysts and Reactors*, Cybulski, A. and Moulijn, J.A., Eds., Marcel Dekker, New York, 1996, pp. 15–58 and 501–542. Courtesy of Marcel Dekker, New York.

The foregoing pressure drop model is only an approximation, which helps quantify the effect of flow rate, open frontal area, and hydraulic diameter. It also provides the relative contributions of open and sooted pores in the wall as well as those of open and sooted channels to the total pressure drop. A more refined model is needed which must correlate well with the experimental data.

19.5 PHYSICAL PROPERTIES AND DURABILITY

Physical properties of ceramic diesel filters, which can be controlled independently of geometric properties, have a major impact on their performance and durability. These include microstructure (porosity, pore size distribution, and microcracking), coefficient of thermal expansion (CTE), strength (crush strength, isostatic strength, and modulus of rupture), structural modulus (also called E-modulus), fatigue behavior (represented by dynamic fatigue constant), thermal conductivity, specific heat, and density. These properties depend on both the ceramic composition and the manufacturing process, which can be controlled to yield optimum values for a given application.

The microstructure of diesel filters not only affects physical properties like CTE, strength, and structural modulus, but it also has a strong bearing on filter/catalyst interaction which, in turn, affects the performance and durability of the catalytic filter. The coefficients of thermal expansion, strength, fatigue, and structural modulus of a diesel filter, which also depend on cell orientation and temperature, have a direct impact on its mechanical and thermal durability [73–77]. Finally, since all of the physical properties are affected by washcoat formulation, washcoat loading, and washcoat processing, they must be evaluated before and after the application of the washcoat to assess filter durability.

19.5.1 Physical Properties

The initial filter compositions were designed to offer a number of microstructures to meet different filtration efficiency and back pressure targets set by engine manufacturers [58]. However, they were not optimized with respect to thermal durability, which became a critical requirement to survive regeneration stresses. A more advanced filter composition, EX-80, with superior performance was developed in 1992. This material is a stable cordierite composition with low CTE and has demonstrated improved long-term durability over a wide range of operating conditions. Moreover, it offers high filtration efficiency and low pressure drop. The low CTE reduces thermal stresses thereby permitting numerous regeneration cycles

TABLE 19.6
Physical Properties of Four Different Diesel Particulate Filters

Property	EX-80 (100/17)	EX-80 (200/18)	RC (200/19)	SiC (200/18)
Intrinsic material properties				
Melting point (°C)	~1470	~1470	~1470	~2400
Density (g/cm^3)	2.51	2.51	2.51	3.24
Specific heat at 500°C (J/g/°C)	1.11	1.11	1.11	1.12
DPF material properties				
CTE (22 to 800°C) (10^{-7}/°C)	3.3	7.0	6.0	45.0
Wall porosity (%)	48	50	45	43
Mean pore size (μm)	13	12	13	9
Permeability (10^{-12} m^2)	0.61	0.61	1.12	1.24
Axial E-modulus (GPa)	4.34	4.69	9.10	33.31
Axial MOR (MPa)	2.83	2.83	4.67	18.62
Thermal conductivity (W/m/°C)	<2	<2	<2	~20
Thermal shock index (°C)	1970	860	855	130
Weight density (g/cm^3)	0.46	0.46	0.70	0.85
Heat capacity per unit volume of filter at 500°C (J/cm^3/°C)	0.54	0.51	0.82	0.95
Soot filtration area (1/in)	16.6	23.5	21.5	21.1

From Cutler, W. and Merkel, G., International Fuels and Lubricants Meeting and Exposition, Baltimore, MD, October 2000, SAE 2000-01-2844. Courtesy of SAE.

without impairing the filter's durability. This composition is now one of the industry standards for diesel exhaust after-treatment [61].

Table 19.6 compares the nominal physical properties of EX-80 filter compositions with two different cell structures as well as those of RC 200/17 and SiC 200/18 filters; the latter two are more advanced filters that are discussed in a separate section. The strength and E-modulus data are those measured at room temperature. The axial coefficient of thermal expansion is the average value over the 25 to 800°C temperature range. It is clear from Table 19.6 that the EX-80 filter offers an optimum combination of properties, namely small mean pore size, high strength, low modulus of elasticity (MOE), and low CTE, which together ensure superior performance compared with that of the other filter compositions.

19.5.2 Thermal Durability

Thermal durability refers to a filter's ability to withstand both axial and radial temperature gradients during regeneration. These gradients depend on soot distribution, soot loading, O_2 availability, and flow rate, and give rise to thermal stresses, which must be kept below the fatigue threshold of filter material to prevent cracking. A detailed analysis of thermal stresses requires the temperature distribution, which is readily measured with the aid of 0.5 mm diameter, Type K chromel–alumel thermocouples during the regeneration cycle [69–71]. To assess the relative thermal durability of different filter candidates we compute the thermal shock parameter using physical properties data and the following equation:

$$\mathrm{TSP} = \frac{(\mathrm{MOR}/\mathrm{MOE})@T_p}{\alpha_c(T_c - 25) - \alpha_p(T_p - 25)} \tag{19.19}$$