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Research Article

Experimental and Numerical Study on the CCDPF's Backpressure Calibration Parameters During Clean Filter and Loading Phase

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Abstract

In this study, the performance of a CCDPF is experimentally investigated. It is found that the filtration efficiency remained high enough during active regeneration and CCDPF is able to remove the particulate matter. Also, one dimensional approach has been implemented to model the backpressure of an active regeneration of a CCDPF. Therefore, the effect of some parameters such as: Expansion/Contraction coefficient, particulate packing inside the wall, percolation constant and soot cake layer porosity on the backpressure calibration behavior is investigated during clean filter and loading phase. In fact, the aim of this study is to provide the catalysts designers with valuable data required for properly calibrating the backpressure behavior of a CCDPF. According to results, Exp/Con coefficient is the primary influencing parameter toward clean filter backpressure calibration. This parameter is reported to shifts up/down the backpressure curve at the very initial moment of the experiments. Also, percolation constant and soot cake porosity have shown to have significant effects on the slope of backpressure curve in the surface type filtration regime. However, the particulate packed density affects the slope of deep bed filtration regime during loading phase.

Keywords: DPF; HCI; Active Regeneration; NO-assisted; Soot Porosity; Soot Emissions

Abbreviations

CO_2: Carbon Dioxide; CO: Carbon Monoxide; DPF: Diesel Particulate Filter; DOC: Diesel Oxidation Catalyst; NO: Nitrogen Monoxide; O_2: Oxygen; PM: Particulate Matter; HC: Hydrocarbon

Introduction

Nowadays, one of the most important problems in mankind life is air and environmental pollutants. Environment conservation and pollutant reduction are the two most prominent issues that researchers have investigated in the recent years. One of the air pollution resources is internal combustion engines with fossil fuels. Various aftertreatment systems have been employed to reduce these emitted emissions. Diesel particulate filters (DPF) are a type of aftertreatment devices specially were designed to remove the particulate matters. Modern DPFs have been developed to meet the desirable thermal and mechanical resistant and their efficiencies is reached more than 90% [1]. The most concerns about such filters are reduction of emitted pollutant of heavy duty vehicles. Among the all exhaust emitted gases of fossil fuels like carbon monoxides CO, unburned hydrocarbons HC, Nitrogen oxides NO and NO_2, which are toxic for human health and environment, the most concerns are assigned to particulate matter. It has been estimated that thousands of people die in Europe because of particulate matter emissions [2]. For this purpose, many standards have been legislated to prevent the particulate matter and other toxic gases emissions to environment since 2000 [1].

Many researchers have studied on the number and size distribution of the Diesel engines emissions [4-6]. Other pollutants with lower concentrations are also emitted from these engines which is called non- regulated emissions [7,8]. Some other researchers have studied on the emissions of individual hydrocarbons, polycyclic aromatic hydrocarbons (PAHs) and carbonyl compounds [9-11].

However, the exhaust particulate which known generally as soot is the prominent emission of diesel engines. This particulate couldn't completely remove of the exhaust gases but it could reduce by motor modifying and improving the combustion chamber [12]. Another way to remove these particulate with more impact is applying the diesel particulate filter (DPF) as a trap to removing the soot emission [13]. Diesel particulate filter technology is applying for both light [14] and heavy duty vehicles [15,16]. The main problem of these after treatment systems is the soot accumulation in the filter substrate wall which leads to backpressure increase in the filter. Some consideration is applied to revive the filter like burning soot by oxygen, NO and hydrocarbon injection (active regeneration). Filters that equipped continues regeneration use the nitrogen oxides NO_2 in lower temperature (300°C) in comparison with oxygen reaction in the temperature range of (500-600°C) to oxidize the soot mass retained in trap [12,17,18].

The reactions which happen during regeneration could not be completely measured because of some prohibition and high costs. For this purpose, many DPF simulation model has been provided to calculate the unknown parameters like soot cake layer porosity. Weiyong., *et al*. [19,20] studied on both zero dimensional and 1-D model which both able to simulate the deep bed filtration, soot and particle storage and regeneration. They found that if the zero dimensional calibrate so well it will achieve some parameters like collected particle and pressure drop which lead to saving the cost and simulation time. They also found that using 1-D model can investigate the regeneration phenomena in more details [21,22]. During the regeneration, soot is burned and converted to CO, CO_2 and even new particulate matters. Consequently, the DPF may reduce the particulate matter but by the cost of increasing gaseous emissions especially during active regeneration. Research on the soot reaction during regeneration is important for estimation of soot burning emission.

Doozandegan., *et al*. [23] have experimentally investigated the effect of the Sulphur content in fuels on the gaseous and solid exhaust emissions in the regeneration phenomenon of a sintered metal active–passive filter. Their implemented DPF equipped with an electrical heater to burn the accumulated soot. They found that the emitted particles number during regeneration is much higher than filtration phase but, the total value of emitted particles during regeneration is less than the engine out baseline. Also, The CO emission was higher in the regeneration mode than engine baseline.

Premchand., *et al*. [24] have numerically investigated on the effect of exhaust flow and temperature on active regeneration of a diesel particulate filter. They first validated their simulation with experimental data and then predicted some pressure drop and retained mass features during passive oxidation and active regeneration. They found that, increasing of the average temperature would leads to higher PM reaction rate. They also found that with higher inlet gas mass flow rate, the PM thermal oxidation reaction rate increases.

In this study, the performance of a CCDPF is experimentally investigated and the backpressure during loading and regeneration phase has been measured. Also, its desired to know the effective parameters on the backpressure calibration curve during clean filter and loading phase. So, a one dimensional approached is used to model the effective parameters on backpressure curve. Finally, the values of these parameters for each clean filter and loading phase are numerically obtained.

Experimental apparatus

Engine and catalyst

In this section, the performance of Diesel Particulate Filter on the HSDI Diesel engine is experimentally investigated. For this purpose, the following set up has been used. A HSDI Diesel engine (1.5 L, 90 KW, Euro V) was equipped with commercial Closed-Coupled Diesel Particulate Filter (CCDPF). The main characteristics of the HSDI Diesel engine and CCDPF are reported in table 1 and table 2 respectively. Also, the picture of tested CCDPF during the experiments is shown in figure 1.

The engine was installed on a dynamometer test bench fully instrumented to measure the indicated signals and thermal characterization of the engine exhaust (before catalyst) and catalyst exhaust. The CCDPF was equipped with three thermocouples and pressure sensors which are located in different places (before DOC, after DOC and after DPF) in order to follow the temperature profile and backpressure during loading and regeneration phase.

Engine type	Diesel engine
Emissions standard	Euro V
Number of cylinders	4
Cylinder configuration	Inline
Bore	76 mm
Stroke	82.5 mm
Conrod length	134.25 mm
Cylinder displacement volume	373.3 cm^3
Total cylinders displacement volume	1497 cm^3
Compression ratio	16.5
Supercharging	Turbocharger with rotate variable geometry
Maximum torque	256 Nm at 1750 rpm
Rated power	90 Kw at 4000 rpm
Combustion order	1-3-4-2
Maximum combustion pressure	165 bar
Catalyst system	Integrated closed-coupled DOC & DPF

Table 1: Basic dimensions and features of the tested engine.

Device	DOC	Diesel Particulate Filter
Material	Rh/Pt/Pd	Silicon Carbide
Porosity	65% ± 1%	65% ± 1%
Pore Size	20 μm	20 ± 1 μm
Cell Density	400 cpsi	200 cpsi
Wall Thickness	1.524 mm	0.4064 mm
Diameter	143.81 mm	143.81 mm
Length	66 mm	152.4 mm
Cell Dimension	1.4*1.4 mm	1.4*1.4 mm
Coating	Coated	Uncoated

Table 2: Properties of applied Diesel Particulate Filter and DOC catalyst.

Figure 1: The view of tested CCDPF during experiments.

Tested fuel

The engine was fueled with a conventional diesel fuel. To test the diesel engine with obtained fuel, the fuel temperature should be tuned in somehow that the fuel temperature at the entrance of the fuel pump doesn't exceeds 38°C. The main characteristics of tested fuel is reported in table 3.

Feature	Method	Result
Cetane number	DIN EN ISO 5165	63.5
Density	DIN EN ISO 12185	816.8 kg/m^3 at 15°C
Kin. Viscosity	DIN EN ISO 3104	3.86 mm^2/s at 40°C
PAH content	DIN EN 12916	1.1%
Sulfur content	DIN EN ISO 20884	31.8 mg/kg
Water content	DIN EN ISO 12937	8 mg/kg
Carbon content	DIN EN 51 732	85.4%
Hydrogen content	DIN EN 51 732	14.3%
Oxygen content	DIN EN 51 732	<0.5%
Fatty acid methyl-ester content	DIN EN 14078	<0.1%
Total contamination	DIN EN 12662	2 mg/kg
Oxidation stability	DIN EN ISO 12205	23 gr/m^3
HFRR (lubricity)	DIN EN ISO 12156-1	480 μm at 60°C

Table 3: The main characteristics of tested fuel.

Test methodology

The standard which was considered for current experiment is New European Driving Cycle (NEDC). The experiment is done in two section: filter loading and regeneration. The engine operation condition during filter loading and regeneration phase is sketched in figure 2. The engine operation conditions at filter loading process were such as engine speed: 2033 rpm, torque: 90.6 Nm and power: 19.27 Kw, so that the engine was started initially and met these operation conditions. After reaching the engine speed to 2033 rpm, the operation conditions at loading phase remained constant (steady state condition). Then, soot with 16 gr/hr mass flow rate injected inside the filter. The test period for loading process took 4500 ± seconds and the filter was loaded at its reference accumulation target of 20 ± 2 gr of soot approximately. The filter was weighted before and after soot accumulation procedure. After filter saturation with soot particles, in order to revive the filter, the regeneration phase is started. For regeneration purpose, the exhaust gasses temperature must be enough high to supply the required soot burning temperature. In this current experiment, in order to raise the exhaust gasses temperature for beginning the regeneration phase, the engine speed is raised up to 3235 rpm and subsequently the values of torque, engine power and exhaust temperature reach to 207 Nm, 65 Kw and 584°C respectively. So, the engine operation conditions remain constant at this point and the regeneration phase is begun to remove the particles. The regeneration period took 2744 seconds and the total test time was 7233 seconds. Also, less than 1 gr soot remained inside the filter at the end of regeneration phase. The measured exhaust temperature and backpressure between and after CCDPF during loading and regeneration phase is shown in figure 3. The first peak of backpressure at 4500 seconds is correlated to filter's filling. The filter loading process is continued until the CCDPF's backpressure reaches to 22 kp linearly. Then, the soot injection is stop and the engine speed raises up to 3235 rpm to start the regeneration phase. The second peak at that moment is correlated to changing in engine's regime. With beginning of the regeneration phase, because of high exhaust volume flow, the CCDPF's backpressure increases rapidly and reaches to 47 ± 2 kp. At this time, the exhaust gas temperature reaches to 650 ± 10°C which is appropriate to remove the particles. With beginning of the soot burning, the backpressure is started to decrease until less than 1gr soot remains inside the filter and the backpressure reaches to 17 ± 2 kp. So, in this situation the experiments are completed.

Validation and simulation

In this section, a numerical simulation is used to investigate the impact of some effective parameters on backpressure during clean filter and loading phase. For this purpose, the numerical simulation should be validated first with the experimental result.

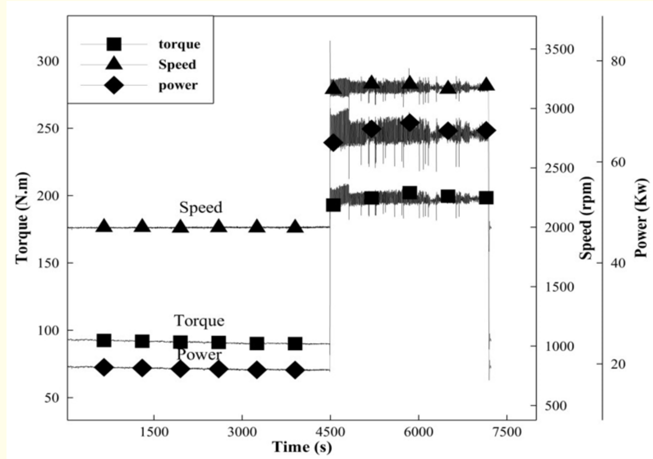

Figure 2: The engine operation condition during filter loading and regeneration phase.

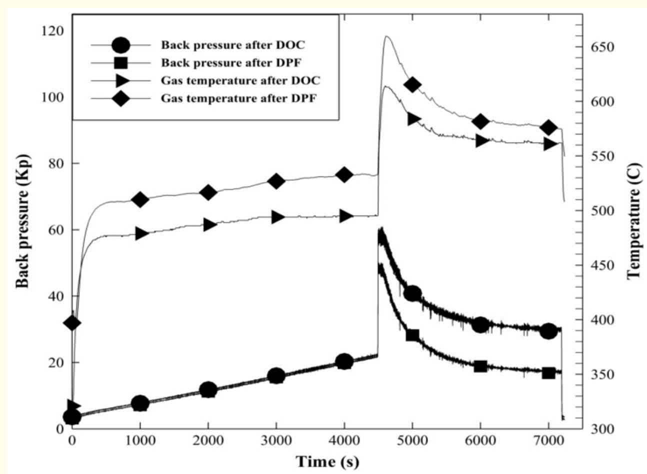

Figure 3: The experimental backpressure and exhaust temperature between and after CCDPF during loading and regeneration phase.

As it is explained in previous section, the DPF has been under loading process until the backpressure reached to 22 kp and then the regeneration phase started. Figure 4 shows the filter exhaust temperature and backpressure during loading and regeneration phase experimentally and numerically. According to figure 4, the numerical simulation has a good adaption with experimental data and the maximum digression has occurred throughout the beginning of the regeneration phase. The maximum error of the simulation is less than 20% in comparison of the experiments.

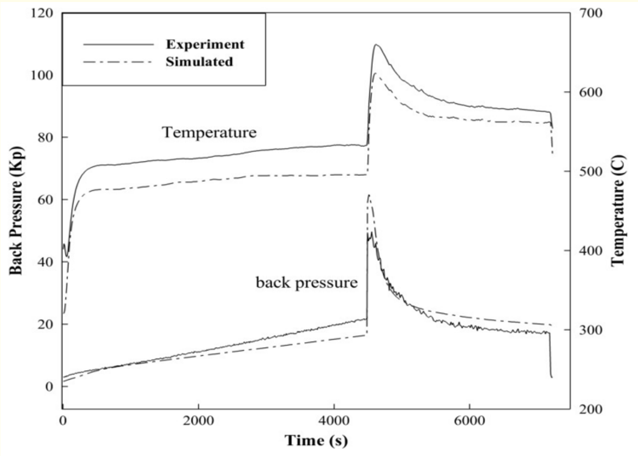

Figure 4: Validation of numerical simulation with experiments during loading and regeneration phase: exhaust temperature and backpressure.

After validation of simulation, the retained soot mass inside the substrate wall and soot cake layer are obtained in figure 5. With starting of the soot loading process, the substrate wall is became fully loaded and incoming soot stores as a soot cake layer. The maximum amount of soot loading inside the substrate wall is 0.8 gr which is happened at 1500 seconds and then remains constant until regeneration phase starts. At the end of loading process, 17.8 gr soot stored as a soot cake layer. Whit beginning of the regeneration phase, the particulate matter starts to decrease and less than 1.5 gr soot remains at the soot cake layer. Also, figure 5 shows the filtration efficiency during filter loading and regeneration. As it is obvious, with soot accumulation as a cake layer, the filtration efficiency raises up and reaches to 99.6% which indicates the good performance of CCDPF.

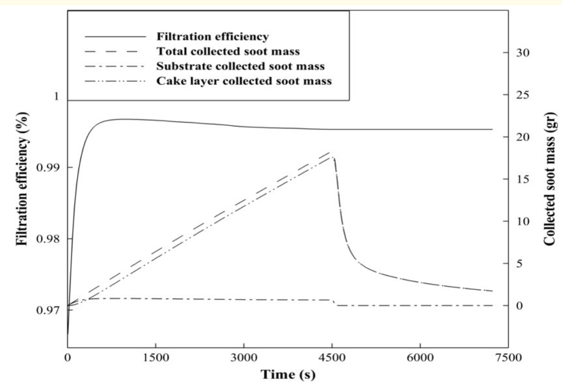

Figure 5: The evolution of soot filtration efficiency and collected soot mass inside the filter during filter loading and regeneration

To calibrate the backpressure during filter loading and regeneration phase, some parameters must be defined. These parameters are listed in table 4. Against some researchers [29-32] who have presented constant values for these parameters for each clean filter, loading and regeneration phase, it is found the different values for each phases. One of these parameters is soot cake layer porosity which varies with soot burning. This attribute has achieved 0.673 throughout the filter loading and then tuned to 0.74 during regeneration phase. This increasing is due to soot burning and decreasing of the aggregated soot mass inside the cake layer. Also, particulate packing density inside the wall is another knob to calibrate the backpressure which is decreases throughout the transition from filter loading to regeneration phase. Also, Expansion/Contraction coefficients are the parameters for calibrating of the backpressure of clean filter. These values might be constant for loading phase in order to steady inlet gas flow rate. With beginning of the regeneration phase, in order to increase the inlet gas flow rate, the Expansion/Contraction coefficients would be increased. Finding the exact value of these parameters for each loading and regeneration phase could help the users to have better perception and more accurate about backpressure calibration of the aftertreatment systems.

Achieved parameters	Loading mode	Regeneration mode
Contraction backpressure Coefficient	1.5	3
Expansion backpressure Coefficient	1.5	3
Percolation constant	0.895	0.902
Soot Cake Layer Porosity	0.673	0.74
Particulate Packing DensityInside the Wall	24 Kg/m^3	19 Kg/m^3

Table 4: Achieved parameters for calibration of backpressure during loading and regeneration phase.

Investigation of the effective parameters on backpressure

In this section, the impact of some parameters which affect the backpressure through the clean filter and loading phase is investigated. One of the parameters which affects the backpressure throughout the clean filter is Expansion/Contraction pressure drop coefficient. This parameter determines the effect of incoming gas contraction and exhaust gas expansion on the backpressure. This attribute only affects the clean filter backpressure slope and depends on the inlet gas flow rate. The trend of Expansion/

Contraction coefficient against inlet gas flow rate is shown in figure 6. When the inlet gas flow rate increases, the volume of gas would decrease at the entrance of the channel. Thus, decreasing of gas volume leads to rise the expansion/contraction coefficient up and also inlet/outlet backpressure increases. This attribute rises up linearly by increasing the gas flow rate as it is shown in figure 6. The typical value of backpressure coefficient has been reported between 0.3-3 by [32].

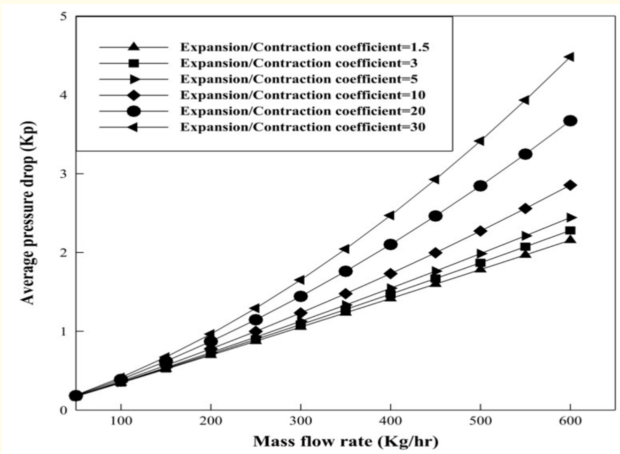

Figure 6: The effect of Expansion/Contraction coefficient on backpressure among clean filter.

There are two mechanisms for soot filtration inside the filter: deep bed filtration and surface type filtration. Also, there are some parameters that affect the deep bed filtration backpressure while some others impose negative effects on surface type backpressure. It’s too important to determine which parameters influence on which slope of the backpressure trend. Particle packing density inside the wall is an attribute that affects deep bed filtration slope on the backpressure diagram which is shown in figure 7. According to figure 7, the slope of backpressure curve in the filter substrate wall (deep bed filtration) region increases with decreasing the particulate packing density inside the wall. The effect of this parameter is taken into account in when the substrate wall is fully loaded. Since, the soot sample mass is bigger than its volume (at least bigger than 1), decreasing the particulate packing density leads to deposition of more soot particles. So, the backpressure is increased by higher number of aggregated particulates. The typical value of particulate packing density has been reported between 8-20 Kg/m^3 for backpressure calibration study [29,32].

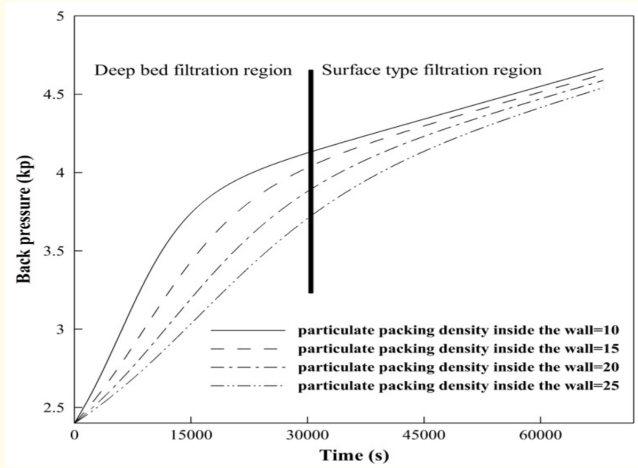

Figure 7: The effect of particulate packing density inside the wall on backpressure during soot loading phase.

Another parameter which is used to shift up/down the backpressure trend throughout the transition of deep bed filtration to surface type filtration is Percolation constant and its typical value has been reported between 0.85 to 0.95 [29,32]. Actually, this is an unknown parameter which is only applied to calibrate the backpressure throughout the loading phase indirectly. In the other word, this attribute is used to define the partition coefficient which is responsible for determining how much soot has been deposited in the substrate wall, and it varies between 0 to 1. The relation between these two parameters is described by equation 1 to 3.

$$\phi = \left[\frac{d_{c,1}^2 - d_{c,0}^2}{(\psi b)^2 - d_{c,0}^2}\right] \quad \text{------(1)}$$

Where ϕ is the partition coefficient, $d_{c,1}$ is the diameter of unite collector in the first slab of loaded filter with the unit of (m), $d_{c,0}$ is the diameter of unite collector of clean filter with the unit of (m), b is the diameter of unite cell of clean filter with the unit of (m), ψ is the Percolation constant. The parameter b and dc,0 are calculated from equation below:

$$d_{c,0} = 1.5 * \left(\frac{1-s_0}{s_0}\right) * (pore\_diameter) \quad \text{-------------(2)}$$

$$b = d_{c,0}/(1-\varepsilon_0)^{1/3} \quad \text{-----------(3)}$$

By increasing the partition coefficient, more incoming soot particles is deposited inside the filter wall and reversely the value of 0 shows all particulates has been deposited as a soot cake layer [29,32]. Thus, with increasing the percolation constant, the partition coefficient decreases subsequently. Regarding this decrement, the portion of soot particles inside the filter wall decreases and then the soot cake layer contribution increases. Therefore, aggregation of the soot particles as a soot cake layer leads to increasing the backpressure throughout the surface type filtration regime. The trend of Percolation constant and subsequently partition coefficient against time is shown in figure 8. According to figure 8, the Percolation constant has an opposite effect toward particulate packing density on backpressure during soot loading and its significant variations happened at the soot cake layer region. The result shows that the backpressure tends to increase when Percolation constant rises, and it has a strong effect at higher values. Another parameter which is used to calibrate the backpressure during loading phase is soot cake layer porosity. The trend of soot cake layer porosity against time is sketched in figure 9. According to diagram, this parameter affects the slope of surface type filtration during soot loading phase. According to the results, soot packed porosity increment is likely to decrease the backpressure throughout the soot cake layer region.

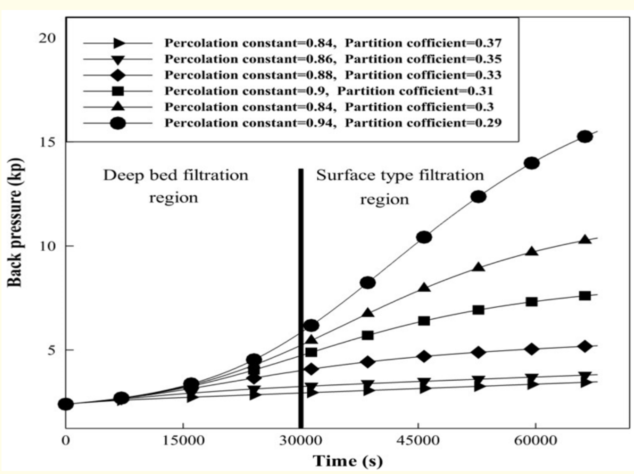

Figure 8: The effect of Percolation constant on backpressure during soot loading phase.

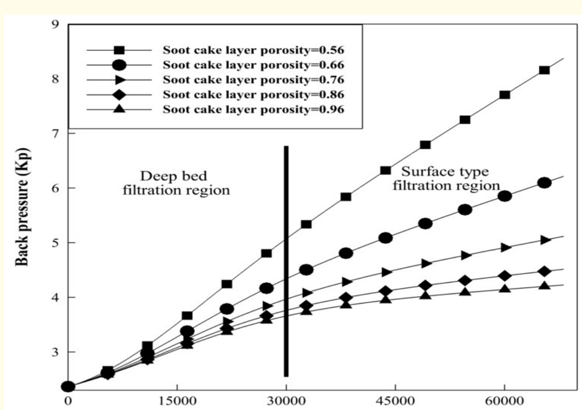

Figure 9: The effect of soot cake layer porosity on backpressure during soot loading phase.

Conclusion

In this study, the performance of a CCDPF is investigated experimentally and numerically. According to experiments, it is found that the filtration efficiency remained high enough during active regeneration and CCDPF has a good performance to remove the particulate matter. Then, one dimensional approach has been carried out to predict the behavior of some influencing parameters on backpressure trend. These parameters are usually considered constant during the backpressure simulation, while in order to accurately predict the backpressure trend, they need to be defined. Here, it is reported that the parameter "Exp/Con coefficient" is a calibration knob to shift up/down the backpressure curve at the very initial moment of the experiments. Also, percolation constant and soot cake porosity have imposed significant effects on the slope of backpressure curve in the surface type filtration regime while having had trivial effect on the deep bed filtration regime. In terms of particulate packed density, it is found that its effect on the slope of deep bed filtration regime during loading phase is considerable. Finally, it should be noted that considering the exact value of these parameters during calibration of the backpressure is mandatory to have better perception of the backpressure behavior.

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