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# MODELLING OF REGENERATION AND FILTRATION MECHANISM IN DIESEL PARTICULATE FILTER FOR DEVELOPMENT OF COMPOSITE REGENERATION EMISSION CONTROL SYSTEM

Pre-treatment techniques employed for exhaust emission control of compression ignition engines were found to reduce the emission levels by small percentage only, failing to meet the required emission regulations. Post-treatment technique including diesel particulate filtration, diesel oxidation catalysis and selective catalytic reduction is found to be an effective solution. While the fuel-based regeneration of diesel particulate filter leads to uncontrolled combustion affecting the durability of the filter. Development of an effective regeneration system is one of the major technical challenges faced by automotive industry for meeting emission norms. A composite regeneration system with the application of microwave energy is proposed in this paper. As an initial phase, a three-dimensional model of the system is developed and its flow analysis is carried out by considering the case of single channel flow. Simulation of the regeneration process is also done by developing a Simulink model. The results of simulation showed that an engine running continuously for a period of 24 hours would require three regenerations.

## 1. Introduction

Diesel engines are well known for their higher thermal efficiency and performance compared to gasoline engines [1]. However, the exhaust emissions from these engines are found to be dangerous in nature contributing a noteworthy part in ecological contamination [2]. Diesel engines are considered as second driving anthropogenic source of soot particles. Soot particles released by diesel engines are toxic and carcinogenic in nature causing a major threat to environment and human life. The exhaust emissions from diesel engine incorporates carbon mon-

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oxide, hydrocarbons, nitrates and particulate matter [3]. These emanations can be lessened by two procedures specifically pre-treatment and post-treatment. Pre-treatment techniques include modifications in the engine and other techniques like cylinder alterations, fuel injection strategies, injection timing retard [4] and use of biofuels like vegetable oil [5], rice bran oil [6], Jatropha oil [7] etc. Investigation on nitrate emissions from diesel engine after the application of copper oxide and water based Nano-fluid as coolant showed that nitrate emissions of about 881ppm was released from the engine at high load conditions [8]. Reduction efficiency of particle oxidation catalyst was calculated for different values of start of injection and fuel injection pressure in [9] where the results showed that the application of pre-treatment techniques alone cannot reduce the emission to acceptable levels.

Post-treatment technique involves treatment of gases discharged from the engine by the utilization of frameworks for Diesel Oxidation Catalysis (DOC), Diesel Particulate Filtration (DPF) and Selective Catalytic Reduction (SCR). Oxidation of carbon monoxide, nitrides and hydrocarbons takes place inside the diesel oxidation catalyst filter [10]. Diesel oxidation catalysis system consists of a monolith substrate with a coating of alumina wash coat where the catalyst is impregnated. Commonly used catalysts in DOC are precious metals like platinum, palladium and rhodium. DOC systems with non-noble metals doped to precious metal catalysts was developed by [11], to compensate for the expensive nature of these catalysts. The particulate matter is trapped by depth filtration in diesel particulate filter. Trapped soot particles get accumulated on the pores and results in a rise of backpressure inside the filter [12]. Accumulated soot particles have to be regenerated frequently by suitable methods prior to the transition from depth filtration to cake filtration [13]. Fuel-based regeneration system is used traditionally for meeting this purpose, but it is found to affect the durability of the filter owing to uncontrolled combustion inside the filter substrate [14]. Major technical challenge is to develop an innovative alternate regeneration system for effective operation of diesel particulate filter [15]. Various alternate regeneration techniques with application of electric heaters [16], corona discharge [17] and pulsed discharge [18] could not make any appreciable improvement in the durability of the filter substrate. Application of microwave energy is considered to be a suitable alternative solution [19]. A composite regeneration system with microwave-based active regeneration and fuel additive based passive regeneration has been proposed.

## 2. Modelling and analysis

As an initial phase of the project, a three dimensional model of the proposed emission control system has been developed in this paper using PTC CREO software and single channel flow analysis of DPF substrate has been carried out in ANSYS FLUENT 16.0 software. A mathematical model for regeneration has also been developed in MATLAB/SIMULINK for the case of an engine with 1.5 litre volume and running at 1500 rpm.

### 2.1. Modelling of filter

Model of the emission control system with filters has to be developed for carrying out the exhaust gas flow analysis. PTC CREO software has been used for the modelling of the filters. Initially, three dimensional model of the DOC and DPF filter is developed as shown in Fig. 1 and the geometry is taken from the existing filter substrate. Specifications of the designed models are given in Table 1. The dimensions of the channels are calculated based on cell density and the area of the designed models is compared with that of the existing standard filter substrates. The results of comparison showed that area is 98% same as that of the standard filter substrate.

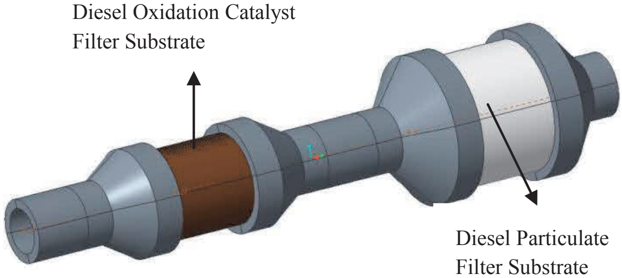



Fig. 1. Designed emission control system with DOC and DPF

Table 1.

Specifications of the designed models

| Parameter | DOC | DPF |
|---|---|---|
| Diameter (mm) | 100 | 144 |
| Length (mm) | 152.4 | 152.4 |
| Cell density (cpsi) | 300 | 200 |
| Area ($mm^2$) | 7853.98 | 16286.02 |
| Number of cells | 3652.11 | 5048.68 |
| Area of a cell ($mm^2$) | 2.15 | 3.23 |
| Thickness (mm) | 0.4 | 1 |
| Width of a cell (mm) | 1.067 | 0.796 |
| Area of designed model ($mm^2$) | 3776 | 13213 |
| Area of standard filter substrate ($mm^2$) | 3700 | 13087 |

The channels of the filters are accurately designed to match the standard filter substrates. In reference [20], the filters were designed by considering it as generic porous medium inside the substrate to represent the channels. DOC filter substrate has simple straight channels of rectangular cross section as shown in Fig. 2 and it will be having a coating of alumina wash coat for impregnation of catalyst.

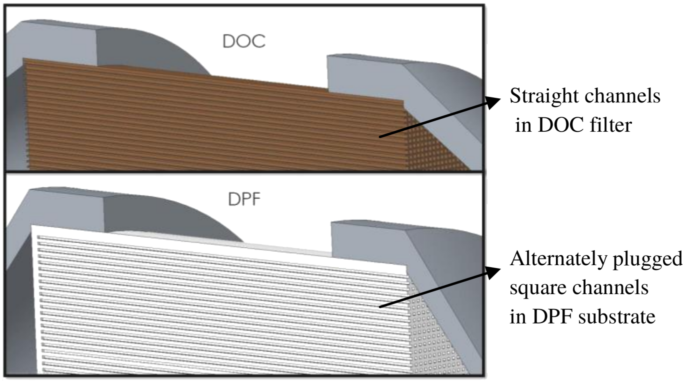



Fig. 2. Sectional view of DOC and DPF filter substrate

DPF filter substrate has alternately plugged channels of rectangular cross section, where the open channels at inlet side will be closed at its outlet side forcing the gases to flow through the porous wall. Particulate matter gets trapped in the porous wall by depth filtration. Cut view of DPF filter substrate is shown in Fig. 3. Soot particles will start accumulating in the porous wall of the DPF filter substrate by depth filtration and the pores will get occluded blocking the flow of exhaust gases. Accumulated soot particles act as a medium for filtering the soot particles by cake filtration process for certain duration only. Pressure drop across the DPF filter substrate will increase eventually as the amount of accumulated soot particle increases.

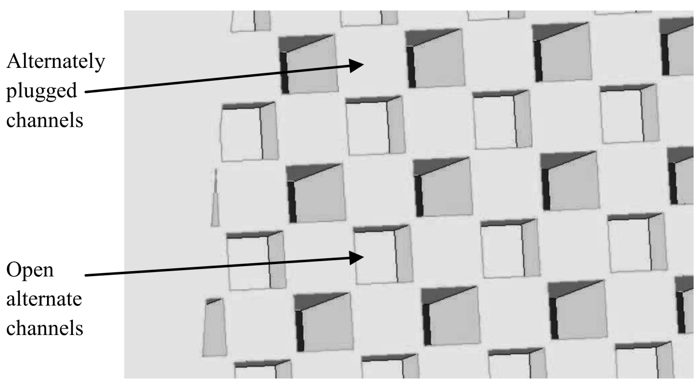



Fig. 3. Alternately plugged channels of DPF

## 2.2. CFD analysis on single channel flow

Computational Fluid Dynamics (CFD) analysis is an effective tool for deciding the execution qualities of composed models prior to production of prototype [21]. Simulations in this work were carried out in ANSYS software by making a virtual condition of genuine application by giving numerical equations with limit conditions. Models developed in SOLIDWORKS software were imported to ANSYS WORKBENCH as an IGS file. The model imported to ANSYS has to be inverted for analysis purpose.

### 2.3. Regeneration control simulation

Regeneration involves oxidation of accumulated soot particles at the transition stage from depth filtration to cake filtration. Regeneration process may be active or passive. Active regeneration involves use of external heat source to burn the accumulated soot particles. Passive regeneration is a continuous regeneration process which occurs with the help of exhaust gas temperature or by use of fuel additives or catalysts. However, active regeneration has higher regeneration efficiency than passive regeneration.

Traditional fuel-based active regeneration involves injection of fuel to the accumulated filter channels for burning the soot particles. But it affects the durability of the DPF since it leads to uncontrolled combustion and also causes lubricant oil dilution [14]. Various other regeneration techniques like application of electrostatic precipitation system [22], electric heaters [13] and pulsed electric charge [18] failed to improve the durability of DPF substrate after several regeneration cycles. Microwave radiations are considered as best alternative for regeneration since microwaves can burn the soot particles by selective absorption owing to its dielectric properties [23]. Composite regeneration is the combination of active and passive regeneration where the fuel additives and external heat source, preferably microwave radiations, will be applied simultaneously for better efficiency [24]. Ceramic filter substrate has to be employed for effective regeneration of the accumulated soot particles since ceramic materials have better dielectric properties [25] and also chances of corrosion will be reduced [26].

The regeneration system must be independent since the device will be outside the car system. A mathematical model is developed in MATLAB/SIMULINK for regeneration control and pressure drop analysis. The model simulates for the case of an engine with 1.5 l volume and speed of 1500 rpm running for a period of 24 hours.

## 3. Results and discussion

### 3.1. Single channel flow analysis

Pressure drop is the major parameter determining flow across the system and major drop of pressure occurs in the DPF substrate. To study in detail the pressure drop across DPF, simulations were carried out in single pair of adjacent DPF channels. The properties of exhaust gases and the other parameters considered in initial and boundary conditions are extracted from [20], where flow analysis of the exhaust system in light commercial vehicles were carried out. Simulation parameters are detailed in Table 2.

Table 2.

Simulation parameters

| Parameter | Value |
|---|---|
| Turbulence Model | K – epsilon |
| Fluid | Exhaust gas |
| Fluid density | 0.5508 kg/m$^3$ |
| Fluid viscosity | 0.00003814 Pa·s |
| Viscous coefficient | 3.236 e$^7$ m$^2$ |
| Pressure jump coefficient | 20.015 m$^{-1}$ |

Mass flow rate of exhaust gas for different temperatures were calculated and the simulations were carried out for each case. Since only single channel flow is considered in this case, flow rate in each cell is calculated assuming that there is uniform flow. Variation in the density of the exhaust gas with temperature is plotted in Fig. 4.

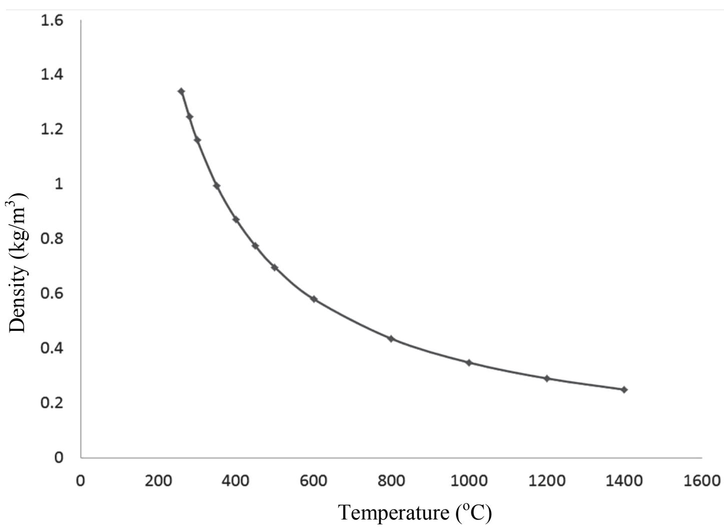



Fig. 4. Variation in density of exhaust gas with temperature

Exhaust gas mass flow rate has been calculated by considering an engine with 1.5 l of combustion chamber volume and speed of 1500 rpm. Single pair of filter channel intakes only a small amount of the whole flow. The ratio of the cell area to the area of the whole filter is calculated to determine the amount of flow that is going inside the channel by assuming that the flow is uniformly distributed. The calculated values of exhaust flow rate and cell flow rate at different temperatures is mapped in graph as shown in Fig. 5.

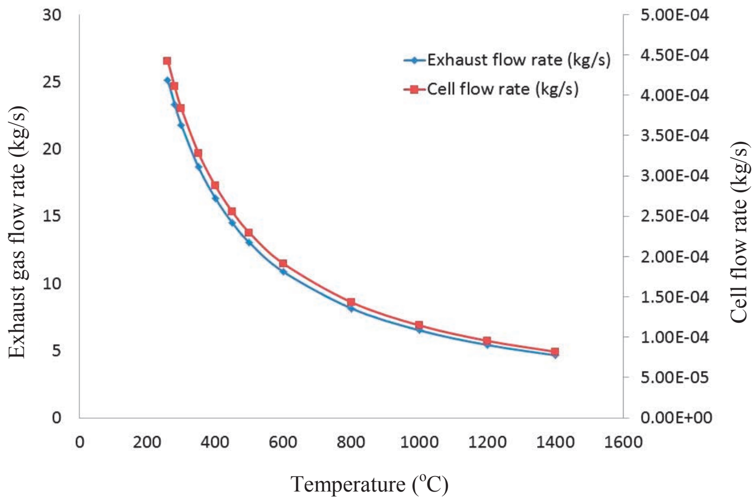



Fig. 5. Variation in exhaust flow rate with temperature

Simulations were carried out without considering porous medium initially to highlight the phenomenon non-linked to porous cause. The pressure drop due to shape and geometry can be determined from these results. Various factors contributing to the total pressure drop ($\Delta P_{Total}$) across the DPF is detailed in Eq. (1). There, $\Delta P_{cont}$ is the local pressure drop due to contraction in the outlet loft side of the filter, $\Delta P_{\exp}$ is the local pressure drop due to expansion in the inlet loft side of the filter, $\Delta P_{in\_channel}$ is the pressure drop along the inlet channel, $\Delta P_{out\_channel}$ is the pressure drop along the outlet channel, $\Delta P_{wall}$ is the pressure drop along the filter wall, $\Delta P_{ash}$ is the pressure drop due to ash layer in the inlet channel and $\Delta P_{soot}$ is the pressure drop due to presence of soot layer in the inlet channel of DPF.

$$\Delta P_{Total} = \Delta P_{cont} + \Delta P_{\exp} + \Delta P_{in\_channel} + \Delta P_{out\_channel} + \Delta P_{wall} + \Delta P_{ash} + \Delta P_{soot} \,. \tag{1}$$

Porous medium is applied on the white stripe as shown in Fig. 6. The porous medium clearly induces a velocity drop when exhaust gas flows through it. Velocity drop is about 25% as compared to that of the flow without porous medium. There is no leakage and mass flow rate is constant, which is evident from Figs. 7a and 7b where the contours of velocity at inlet and outlet side are plotted.

For pressure drop analysis, simulations were carried out for different mass flow rates and the results were plotted in a graph as shown in Fig. 8. From the results it was found that the pressure at inlet and outlet has direct proportionality with the mass flow rate. Pressure drop is found to increase with the mass flow rate of the fluid which proves the Darcy's law for flow through the porous medium as shown

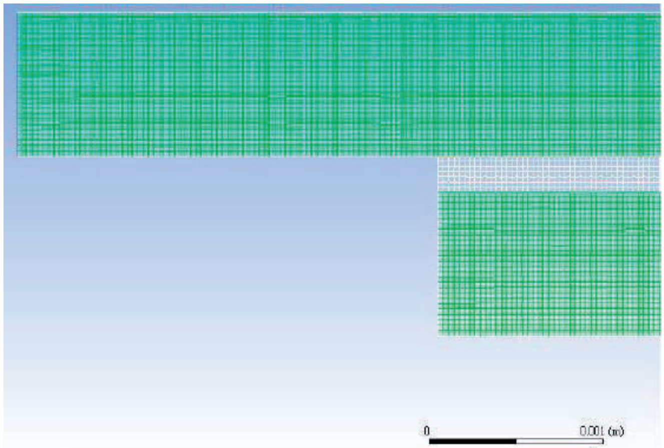
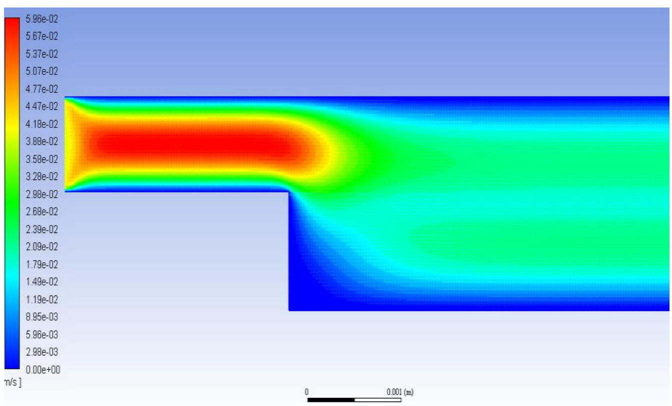
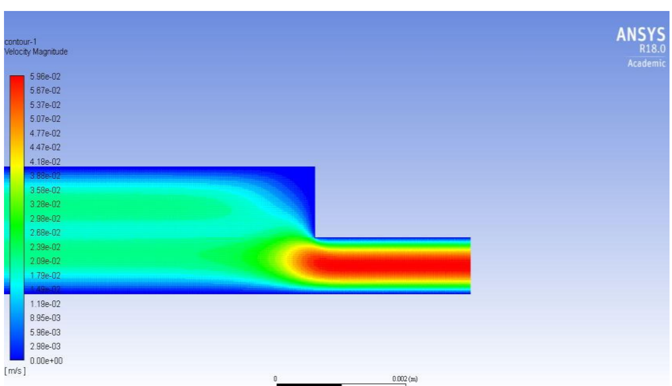



Fig. 6. Filter wall with porous medium




(a)




(b)

Fig. 7. Velocity contour at intel side (a) and outlet side (b) of channel with porous medium

in Eq. (2) [27], where $u$ is fluid velocity, $K$ represents the permeability of medium, $\mu$ is dynamic viscosity of fluid and $(p_1 - p_2)$ is pressure drop across the filter.

$$u = \frac{K(p_1 - p_2)}{\mu L}. \tag{2}$$

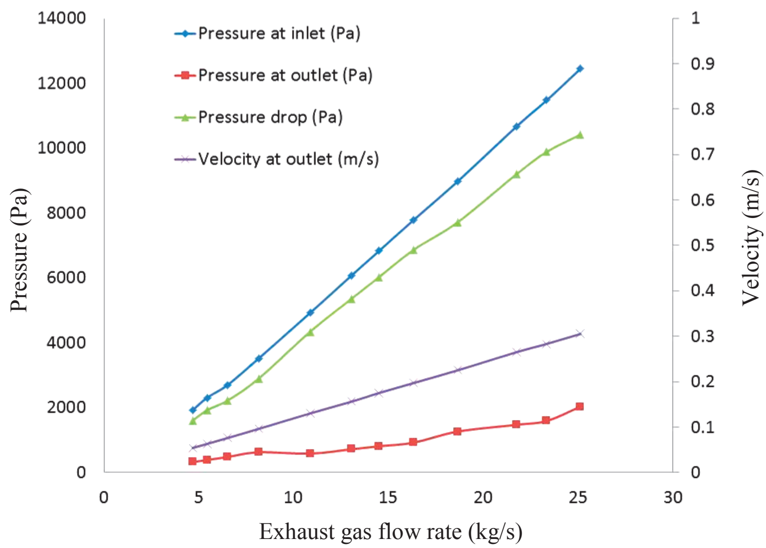



Fig. 8. Flow behaviour of a single DPF channel

### 3.2. Obstruction model of regeneration control simulation

The three components namely DOC, DPF and SCR have to be modelled separately for simulation of pressure drop. DOC filter has open channels and it can be modelled by a simple gain as shown in Eq. (3), where the pressure loss inside DOC is assumed to increase linearly with the engine speed. DPF has alternately plugged channels, so it is modelled by a first order transfer function as shown in Eq. (4), since it gets more and more blocked as the engine runs.

$$DOC_{(s)} = \frac{\Delta P_{(s)}}{RPM_{(s)}} = K_{DOC}, \tag{3}$$

$$DPF_{(s)} = \frac{K_{DPF}}{1 + \tau_{DPF_{(s)}}}. \tag{4}$$

The SCR involves injection of fluid inside the exhaust line, so it is associated with a constant pressure loss that will be included as a disturbance. $K_{DOC}$ and $K_{DPF}$ is the gain and $\tau_{DPF}$ is the time constant whose values can be improved by regeneration process.

### 3.3. Regeneration model

The regeneration process is modelled by a second order model as shown in Eq. (5). The function transfer linking the step source (related to the power of microwaving) and coefficient of pressure decrease. The regeneration does not have any overshooting since it is linked to pressure reduction, thus the overshooting coefficient will be equal to one, as shown in Eq. (6).

$$R_{(s)} = \frac{C_{p(s)}}{PWR_{(s)}} = \frac{K\omega_o^2}{s^2 + 2\xi\omega_o s + \omega_o^2} = \frac{K}{s^2 + as + b}, \tag{5}$$

$$\xi = \frac{1}{2\tau_2\omega_o} = 1 \quad \Rightarrow \quad \omega_o = \frac{1}{2\tau_2}. \tag{6}$$

The models can be combined to obtain the Simulink model as shown in Fig. 9. A switch is added with a threshold to 60 kPa to activate regeneration process.

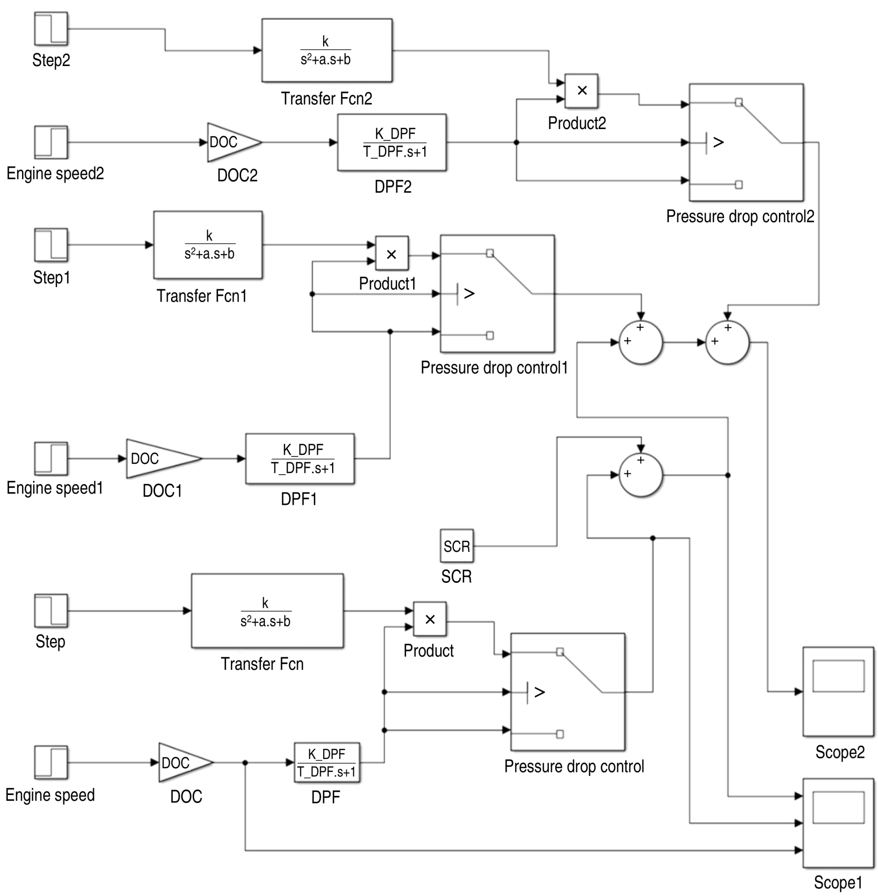



Fig. 9. Simulink model

Simulation is run for 24 hour duration and the results of simulation are plotted showing the variation in pressure drop with time as shown in Fig. 10.

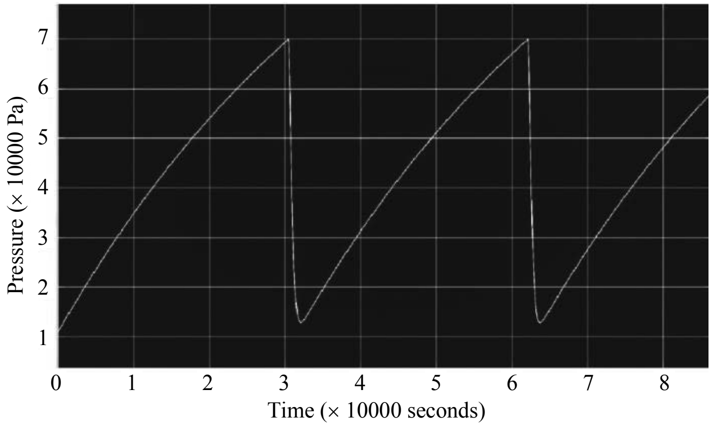



Fig. 10. Pressure drop simulation curve

The graph shows that there will be three regenerations required if the vehicle runs continuously for 24 hours. Usually in the vehicles with fuel-based regeneration system which is currently used undergoes regeneration after every 450 km [28]. The curve generated by simulation can be used for designing of experiments in real conditions. The results of simulation analysis can be also used for development of a prototype of the composite regeneration system. The future scope of this work includes development of such a system with the application of magnetron as source of microwave radiations for regeneration purpose. The temperature to which the microwave radiations can heat the soot particle depends on the exposure time to radiations. The active regeneration of soot particles will initiate at a temperature of 600°C in case of non-catalyzed DPF and at a temperature of 400°C in case of catalyzed DPF [29].

## 4. Conclusions

Three dimensional model of the emission control system comprising of DOC and DPF was developed using PTC CREO software. The dimensions of the commercially available filter substrate were considered for the modelling purpose. Single channel flow analysis of the designed DPF substrate was done in ANSYS FLUENT 16.0 software. Simulations were carried out for different mass flow rate of exhaust gas both in case of DPF channel with porous medium and without porous medium. The results of simulation showed that the presence of porous medium is causing a pressure drop of around 60%. Also, the results showed that the mass flow rate has direct proportionality with the inlet and outlet pressure. Mathematical model for regeneration control was developed in MATLAB/SIMULINK where the model simulates the case of an engine with a volume of 1.5 l and running at 1500 rpm for a period of 24 hours. The results of simulation showed that there will be three regenerations required if the vehicle runs continuously for 24 hours. Experiments on emission control system can be designed with inference from results of simulation. The future scope of the work involves development of functional prototype of composite regeneration system with microwave based active regeneration and fuel additive based passive regeneration.

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