ADDIS ABABA INSTITUTE OF TECHNOLOGY
ADDIS ABABA UNIVERSITY

EXHAUST GAS REGENERATION SYSTEM DESIGN IN DIESEL PARTICULATE FILTER

BY:-

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Abstract

In this study the diesel vehicle engine exhausts emissions, particularly Diesel Particulate Matter and its impact on health and environment is discussed briefly. The filtration method used to removes this particulate matter from diesel exhaust gases is using wall flow diesel particulate filter through physical filtration. The filter designed for this application has a honeycomb structure with long parallel flow channels and the opposite ends of adjacent channels are alternatively capped, forcing gas to flow through porous side walls leaving soot behind on the surface of the walls that would result in an adverse impact on engine performance.

Therefore the Diesel particulate filter regeneration system strategy (passive type), which promotes the oxidation of carbon soot trapped in diesel particulate filter under normal engine operation condition is applied in this study. This is achieved by catalyst coating on the filter cell membrane to facilitate the soot trap combustion. in addition, Filter design parameters like filter size and filter cell configuration which is responsible for the save regeneration are identified. The mass flow rate of Diesel Particulate Matter Emission from diesel vehicle engine under different operation condition (speed and loading) is considered by using weighting factor for each operation point. Mass based particulate matter emission from diesel engine obtained in this study is 36.01 (g/hr). for filter with 80% ,85% ,90% filtration efficiency of DPF: the Mass of PM released to atmosphere in (g/bkw.hr) are 0.082, 0.062, 0.041 respectively, where the Europe PM emission limit standards is achieved above 85% of filtration efficiency . The pressure drop across Diesel Particulate Filter is predicted (2.81kpa) using soot layer thickness model.

Finally, regeneration behavior of diesel particulate filter using comsol multi physics by coupling the exhaust gas flow(maximum flow velocity 4.2m/s),Particulate matter concentration distribution in DPF model [maximum 12.5 mil (mol/m^3) and 5mil(mol/m^3)]and the filter wall temperature distribution(500 and 705 in K) due to soot trap oxidation reaction in DPF. From the passive regeneration system applied the catalyst coated on the filter porous membrane initiates the burning-off particulate matter in filter channel , reduces the oxidation temperature of soot trap and keeps clean the diesel particulate filters under normal engine operation condition.

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Abbreviation and acronym

DPF Diesel Particulate Filter

PM Diesel Particulate Matter (soot trapped in wall filter DPF)

NOx nitrogen oxide emission from diesel engine

OFA open frontal area

Dh: hydraulic diameter

SFA specific filtration area

BPI back pressure index

V_f filter volume of the diesel particulate filter (m^3)

Df diameter of the diesel particulate filter (m)

L is length of the diesel particulate filter (m)

κ denotes the permeability of the porous medium (m^2),

k_{soot} ,particulate layer permeability

α width of unit cell channel (m)

η soot trapping efficiency of DPF

σ repeating distance in cell configuration of DPF

U_o exhaust gas velocity (m/s)

ΔP in pressure across diesel particulate filter

μ dynamic viscosity of the fluid (kg/ (m·s))

p the pressure (Pa)

u the Darcy velocity (m/s)

ρ is the density of the fluid (kg/m^3)

ε is the porosity of diesel particulate filter membrane (unit less)

Q_m is a mass source term ($kg/(m^3 \cdot s)$)

R is the universal gas constant(8.314 J/ (mol·K))

M the molecular weight of the gas(kg/mol)

T the temperature (K)

∇ $[\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}]$ is differential operator

c_s denote the soot-particle concentration (mol/m3)

i stands for specie

Ds is the diffusivity of soot particles (m2/s)

R_i is soot particle deposition as sink/source per unit area ,

υ species flow rate and cross section area (A).

c_{O2} denotes the oxygen concentration (mol/m^3)

Do_2 is the diffusion coefficient (m^2/s)

Rs equals the reaction rate for the surface reaction (mol/(m^2·s)).

ko_2 the pre-exponential factor,

Ea the activation energy

w_s denote the soot layer's thickness (m

ρs represents its effective density (kg/m3)

Ms is the molecular weight of carbon (kg/mol).

CHAPTER ONE

1. INTRODUCTION

1.1Back ground

Diesel engines combust diesel fuel to convert its chemical energy into mechanical power. The primary combustion products of diesel fuel are carbon dioxide and water. More than 99% of diesel emissions consist of CO2, H2O, and the portion of air left over from the combustion process. As real diesel combustion is not ideal, a fraction of a percent of the total diesel emissions is unwanted combustion byproducts .These pollutants are mainly particulate matter (PM), nitrogen oxides (NOx), hydrocarbons (HC), and carbon monoxide. Of those, PM emissions are seen as perhaps the most critical. They are of major concern regarding negative health and possible climate effects.

1.1.1 Diesel Engine Emissions

Diesel engine, like other internal combustion engines, converts chemical energy contained in the fuel into mechanical power. Indeed, diesel exhaust gases are primarily composed of CO_2, H_2O and the unused portion of engine charge air. Concentrations of these gases in diesel exhaust are typically in the following ranges:

Figure 1.1a exhaust gas emission from diesel vehicles

- CO_2 - 2 ... 12%
- H_2O - 2 ... 12%
- O_2 - 3 ... 17%
- N_2 - balance.

The concentrations depend on the engine load, with the content of CO_2 and H_2O increasing and that of O_2 decreasing with increasing engine load. None of these principal diesel emissions (with the exception of CO_2 for its greenhouse gas properties) have adverse health or environmental effects.

Diesel emissions include also pollutants that can have adverse health and/or environmental effects. Most of these pollutants originate from various non-ideal processes during combustion, such as incomplete combustion of fuel, reactions between mixture components under high temperature and pressure, combustion of engine lubricating oil and oil additives as well as combustion of non-hydrocarbon components of diesel fuel, such as sulfur compounds and fuel additives. Total concentration of pollutants in diesel exhaust gases typically amounts to some tenths of one percent this is schematically illustrated in Figure1.1a. Much lower, “near-zero” levels of pollutants are emitted from modern diesel engines equipped with emission after treatment devices such as NO_x reduction catalysts and particulate filter.

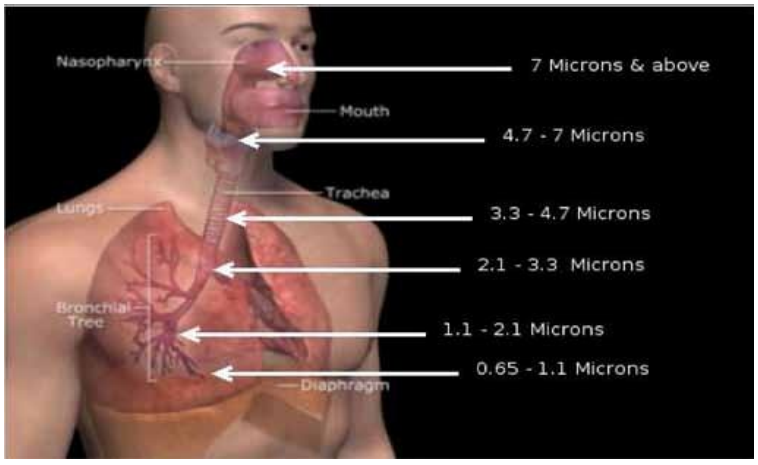

Figure 1.1b) health effects of Emissions of Diesel Exhaust Gas

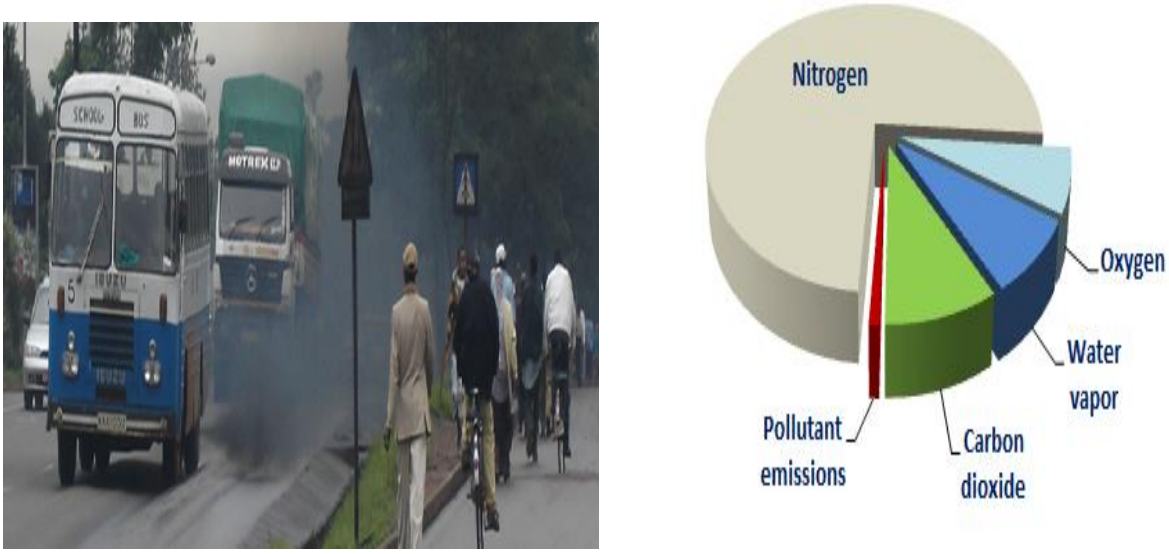

Figure 1.12c environmental and health effects of Emissions of Diesel Exhaust Gas

There are other sources that can contribute to pollutant emissions from internal combustion engines-usually in small concentrations, but in some cases containing material of high toxicity. These additional emissions can include metals and other compounds from engine wear or compounds emitted from emission control catalysts (via catalyst attrition or volatilization of solid compounds at high exhaust temperatures). Formation of new species normally not presents in engine exhaust can also be facilitated by catalysts. This seems to be especially the case when catalysts are introduced into the combustion chamber. For example, some fuel additives so-called "fuel-borne catalysts" used to support the regeneration of diesel particulate filters have been linked to emissions of highly toxic dioxins and furans [25]. A possibility of new emissions must be considered whenever additives (catalytic or not) are introduced into the fuel or lube oil and when fluids are introduced into the exhaust gas. A well known example is urea used as a NOx reductant in SCR catalyst systems emissions from SCR engines can include ammonia, as well as a number of products from incomplete decomposition of urea. Low quality fuels can be still another source of emissions for instance; residual fuels used in large marine engines contain heavy metals and other compounds known for their adverse health and environmental effects.

1.1.2 Diesel Particulate Matters

Particulate matter-perhaps the most characteristic of diesel emissions-is responsible for the black smoke traditionally associated with diesel powered vehicles. The diesel particulate matter

emission is usually abbreviated as PM or DPM, the latter acronym being more common in occupational health applications. Diesel particulates form a very complex aerosol system. Despite considerable amount of basic research, neither the formation of PM in the engine cylinder, nor its physical and chemical properties or human health effects are fully understood. Nevertheless, the existing medical research suggests that PM is one of the major harmful emissions produced by diesel engines.

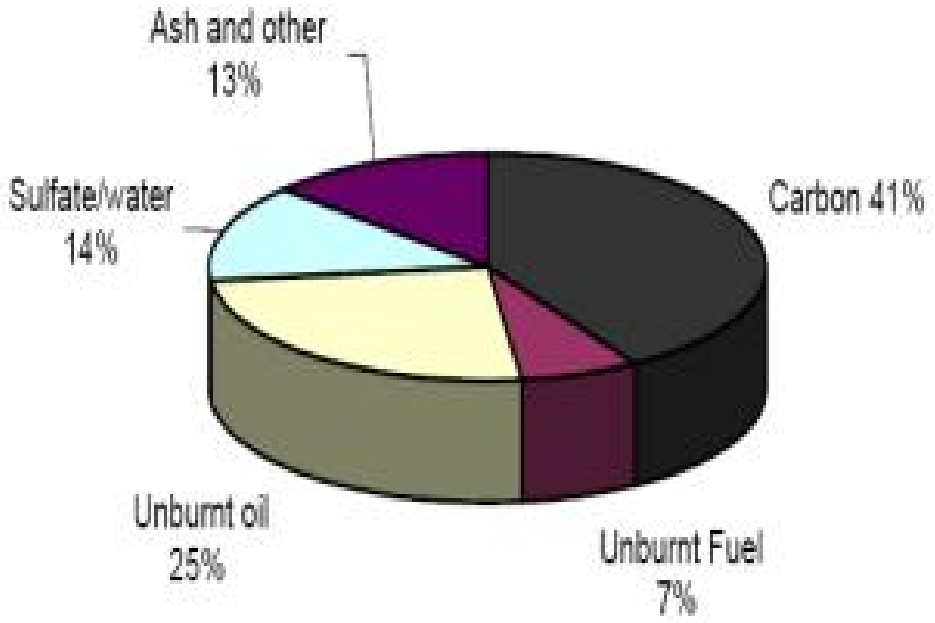

Figure 1.1b Composition of particles from a heavy -duty diesel engine, tested in a transient cycle on an engine test bench [51]

1.1.3 Health and Environmental Effects

Diesel emissions include a number of biologically active substances. In this group, diesel particulates and the associated organic phase became a major health concern. From the environmental perspective, the advantages of diesels are low “greenhouse gas” and hydrocarbons emissions; their drawback is high NO_x emission .

a) Health Effects of Diesel Particulates

The composition of DPM includes many species that are known for their adverse health effects, including several carcinogens. Health effects most often linked with particulate pollution, from diesel and other sources, include an increase in death due to respiratory and cardiovascular disease and worsening of symptoms in people with asthma.

Primary materials found in the solid phase of diesel PM include inorganic carbon and metal ashes, while the liquids include high boiling hydrocarbons, water, and sulfuric acid. According to most legal definitions of diesel particulates and the corresponding sampling and measurement methods, diesel particulates are sampled from exhaust gases that are diluted with air and cooled, typically to 52°C. These sampling procedures have been introduced in an attempt to simulate atmospheric dilution effects on diesel emissions.

Although it is known today that the products of real life atmospheric dilutions may differ from what is sampled in a laboratory dilution tunnel, there has been a consensus in regards to the above definition among worldwide public health authorities. Accordingly, the total particulate matter traditionally includes the following fractions:

1. Solids (inorganic carbon, ash)
2. Organics (soluble organic fraction-SOF)
3. Sulfates (hydrated sulfuric acid, metal sulfates).

There is no such consensus, however, in diesel particulate exposure regulations in various occupational health environments. The elemental carbon definition-which excludes all organic content, sulfates, or inorganic ash-appears to become the preferred representation. Sometimes, the total carbon (TC) definition, which includes both the elemental and organic carbon but no sulfates, is also used.

Once released into the atmosphere, diesel PM becomes a part of the ambient suspended particulate matter, which also includes a number of other components, such as:

- Natural PM material including mineral dust, sea salt, biologic substance (plant/animal debris

- Combustion particles from sources other than internal combustion engines: power plants, industrial plants, heating furnaces
- Secondary particles formed from gaseous precursors in the atmosphere: mostly nitrates and sulfates

Ambient particulates are measured according to a large variety of protocols, but in general they do include both solid and liquid material, just as it was the case with diesel PM.

Health effects from exposure to diesel PM and non-diesel particles are extremely difficult to separate. Since particulates from different sources are often similar, so are the health effects they may cause. In fact, health effects caused by some gaseous pollutants may be also similar to those caused by particles. Despite these challenges, research studies have always attempted to separate the toxic effects of gaseous and particle pollution from different sources. This type of knowledge is essential for the policy makers to establish control strategies that would maximize the public health benefit by targeting the most critical sources of pollution.

b) Environmental Effects of Emissions

Air pollutants are responsible for a number of adverse environmental effects, such as photochemical smog, acid rain, death of forests, or reduced atmospheric visibility. Emissions of greenhouse gases from combustion of fossil fuels are associated with the global warming of Earth's climate. Certain air pollutants, including black carbon, not only contribute to global warming, but are also suspected of having immediate effect on regional climates.

1.2 Problem Statement

Currently, there are many diesel vehicles used for different applications in Ethiopia. The diesel exhaust gas emissions from these have a negative impact on health and environment. Particle pollution contains microscopic solids or liquid droplets that are so small all that they can get deep into the lungs and cause serious health problems. Particles can be carried over long distances by wind and then settle on ground or water. The effects of this settling include: making lakes and streams acidic; changing the nutrient balance in coastal waters and large river basins; depleting the nutrients in soil; damaging sensitive forests and farm crops; and affecting the diversity of ecosystems.

One of the methods used to removes this particulate matter from exhaust gases is using diesel particulate filter through physical filtration. This particulate matter must eventually be removed by exhaust Regeneration strategy of diesel particulate filter to prevent excessive back pressures from occurring, and that would result in an adverse impact on engine performance.Therefore, the design of exhaust gas regeneration system in DPF is important in burning-off particulate matter in filter channel and keeps the diesel particulate filter in proper operation. This will help in controlling the environmental and health problem happen due to particulate matter from diesel exhaust emission.

1.3 Objective

General objective

The main objective of this study is to design Diesel Particulate Matter regeneration system in diesel particulate filter (DPF)

Specific objectives

The research has also the following specific objectives, and these are:

- To select an appropriate diesel particulate filter regeneration system strategy based on diesel oxidation catalyst which promotes the oxidation of carbon soot trapped in DPF
- To analysis Particulate Matter Emission from diesel vehicle/engine under different operation condition (engine speed and loading).
- To analysis the soot layer thickness model on filter wall and pressure drop across DPF
- Expressing the regeneration behavior of diesel particulate filter using comsol multiphysics by coupling the exhaust gas flow, mass concentration distribution

1.4 Methodology

In this study the following methodologies are use to design exhaust regeneration systems of diesel particulate filter.

These are:

- Literature review on diesel particulate filter regeneration system, filter design and catalyst coating technology.
- Use of filter design parameters and diesel vehicle/engine particulate matter emission data for the analysis of regeneration design parameters.

- Analysis of pressure drop across the diesel particulate filter(DPF) and diesel particulate matter mass based accumulation in the filer
- Using comsol multiphysics software package to coupling exhaust gas flow, mass distribution to study the regeneration behavior of diesel particulate filter.

1.5 Outline of the Thesis

This paper is organized in to five chapters. The first chapter contains the back ground of the study which includes a brief discussion of diesel engine particulate matter emission, its health and environmental effects, problem statements and objective of the study. The second chapter is the reviews on the diesel exhaust regeneration systems. Both active and passive case is covered. Also, the reviews of the materials for filter and catalyst are presented. In the third chapter the analysis Particulate Matter Emission from diesel vehicle/engine under different operation condition, pressure drop and soot layer thickness analysis is presented. In addition, the mathematical modeling and the diesel exhaust gas flow; PM distribution in diesel particulate filter modeling using comsol multiphysics software is presented. The fourth chapter provides result and discussion of the study. Finally, in the fifth chapter the conclusion and recommendation of the paper is discussed.

CHAPTER TWO

LITERATURE REVIEW

2.1 Diesel Particulate Filters

Diesel particulate filters are the most effective option to control the particulate matter (PM) missions [1,5]. Today there are several types of DPF available on the market and differing mainly by the method of trapped soot removal usually called filter re generation. It is convenient to classify regeneration methods as active (applying external or engine measures of gas temperature control at DPF inlet) or passive (usually employing catalytic means)[32-36] . Combinations of measures are also common and catalytic means can be applied in active regeneration systems.

The wall-flow monolith DPF is currently the most effective device to reduce diesel particulate emissions (mainly the soot emissions) providing the highest filtration efficiency with the least pressure drop [11]. Figure2.1 shows a typical structure for the wall-flow monolith DPF. While exhaust gases pass through the porous walls between the channels, some of the particulates can be filtered on the wall due to the pore sizes of the walls. The accumulated soot particulates will form soot layers on the walls. As too much particulates are accumulated on the wall, the backpressure in the exhaust system will rise which will increase the engine fuel consumption and reduce the engine power. Thus, it is necessary to clean the filter by oxidizing the collected soot particulates in the DPF.

The filter walls made from silicon carbide are porous. The silicon carbide body is coated with a mixture of aluminum oxide and ceroxide.This mixture serves as a carrier layer for the catalytic converter. The carrier layer is coated with a precious metal, platinum, which acts as the catalyst. A catalyst is a substance that promotes or hinders a chemical reaction without changing Itself [14,7].

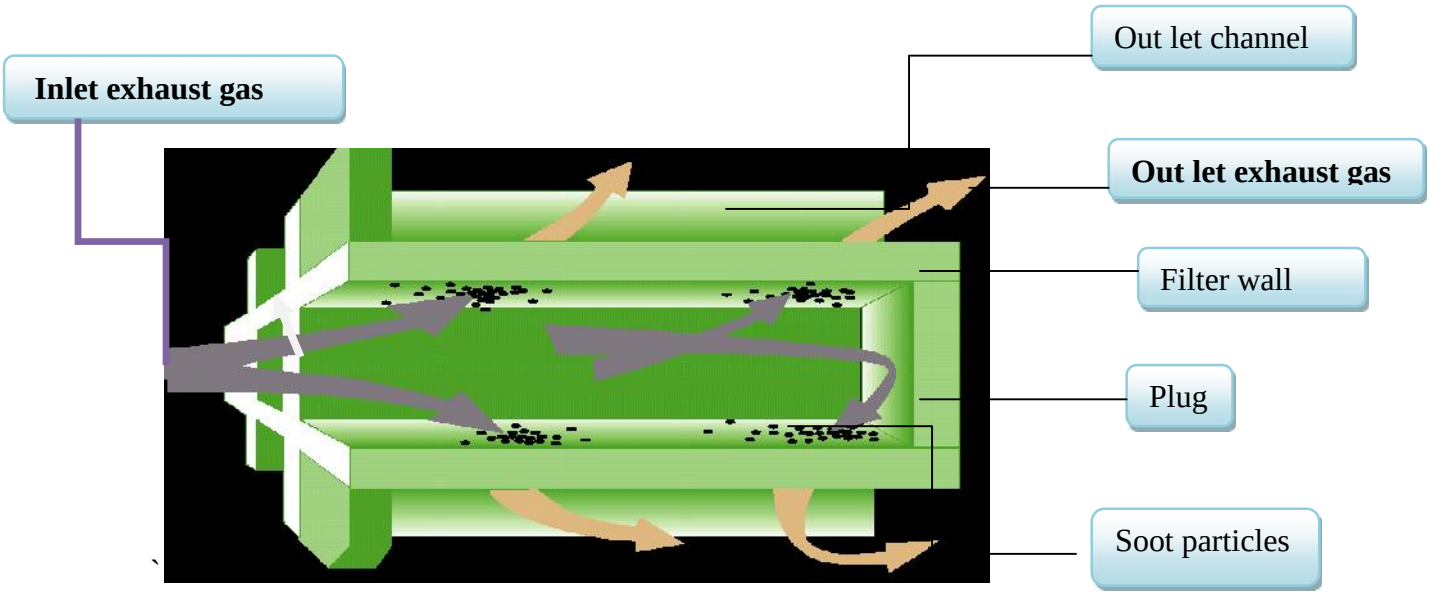

Figure 2.1 A monolithic wall-flow Diesel particulate filter (DPF) from EPA Marine Emissions Seminar Mexico City September 26, 2012 [14]

2.2 Reviews of Exhaust Gas Regeneration Systems in DPF

The diesel particulate filter must be cleaned of the particles of carbon soot regularly to prevent it from becoming blocked and its function thereby being affected. During the regeneration phase, the particulates that have accumulated in the particulate filter are burnt off (oxidized).there are two diesel exhaust regeneration strategies in diesel particulate filter. These are passive and active exhaust gas regeneration systems [8,9, 15,40,41].

Diesel particulate filter systems are designed by combining different filter materials with selected regeneration methods. A classification of diesel filter systems based on the principle of regeneration is shown in Figure 2.2. A diesel filter system must provide reliable means of regeneration, preferably a fully automatic regeneration occurring without an intervention (or even knowledge) of the vehicle operator.

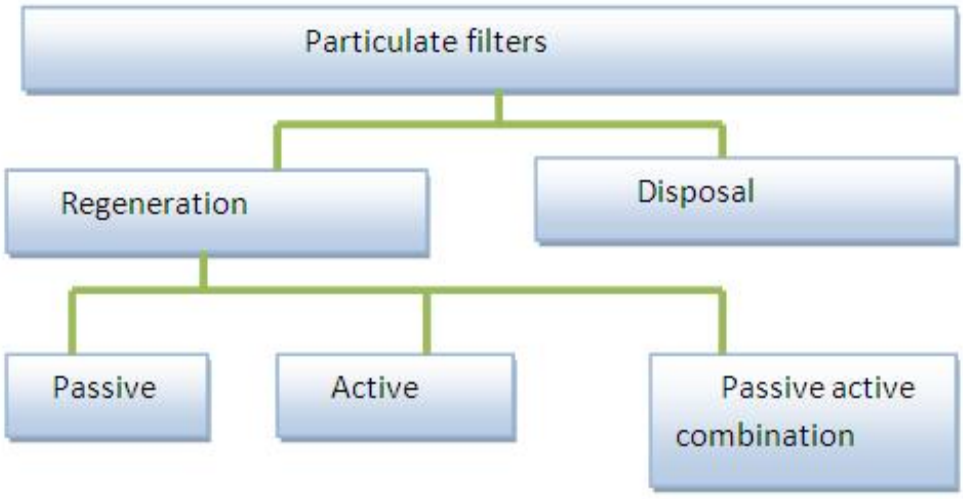

Figure2.2. Classification of Filter Systems by Regeneration Method

2.2.1 Passive Regeneration

With passive regeneration, the carbon soot particles are burnt off continually without intervention from the engine management system. The particulate filter is positioned in close proximity to the engine. This assures that exhaust gas temperatures of 350-500 °C are reached on motorways. The carbon soot particles are thereby converted into carbon dioxide by a reaction with nitrogen oxide. This gradual process occurs slowly and continually through the noble metal catalyst (pt) coating, which works as a catalyst [15].

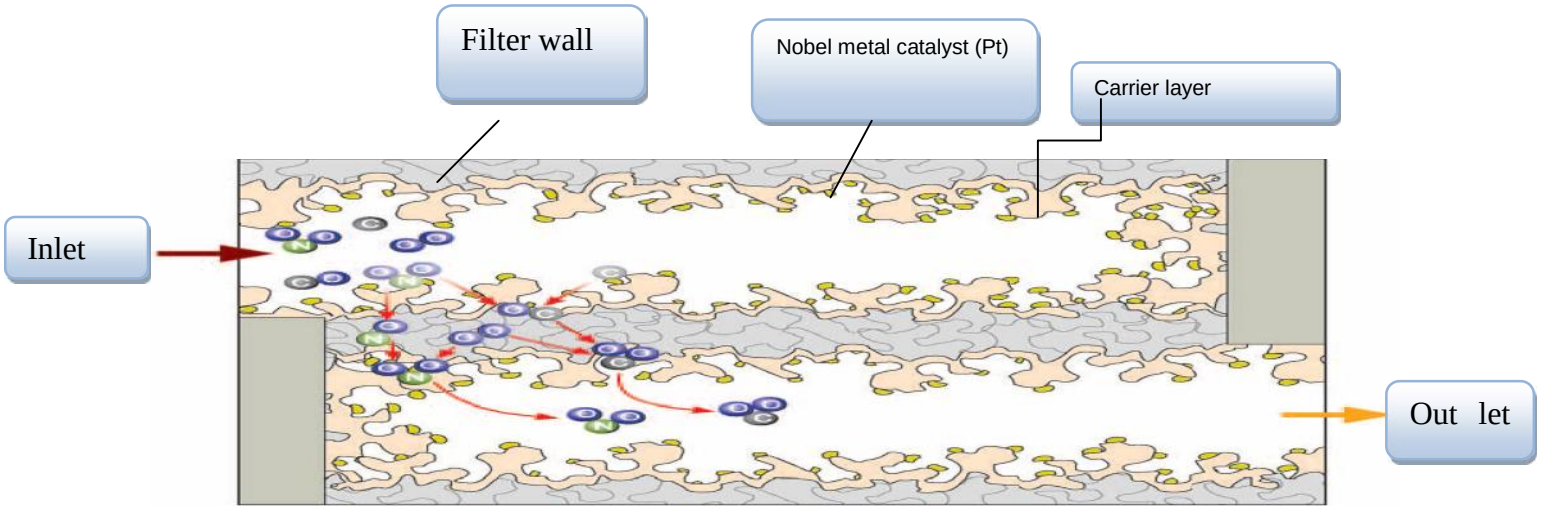

Figure 2.3 Passive exhaust gas regeneration in wall-flow in DPF **[15]**

2.2.1.1 Nitrogen Dioxide Based Soot Oxidation

NO is formed under the high-temperature, high-pressure in-cylinder conditions from the nitrogen and oxygen present in the charge air during the diesel combustion.NO2 forms from NO by reaction with excess oxygen. During the expansion stroke of the piston the temperature decreases rapidly within the combustion chamber, but the NO concentration does not decrease to the NO=O2=NO2 equilibrium concentration as NO is kinetically relatively stable under these conditions [12]. The NO2 concentration at thermo dynamical NO=NO2=O2 equilibrium for the temperature range from 0–700^{o}C under typical diesel O2 concentration levels.

$$NO + \frac{1}{2} O2 \leftarrow \rightarrow NO2$$

The concentration of nitrogen oxides in diesel exhaust gas is around 0.01–0.1%. That is 2–3 orders of magnitude lower than the O2 concentration.80–95% of the nitrogen oxides leave the engine as NO and only 5–20% as NO2. The presence of an oxidation catalyst can speed up the NO oxidation reaction and increase the NO2-share of NOx downstream of the catalyst, where the NO2 can then be utilized for soot oxidation. An alternative, but not yet commonly applied way to increase the rate of the NO oxidation is the application of a non-thermal-plasma reactor [18, 42-44].

2.2.1.2 Oxygen Based Soot Oxidation

The oxygen comes from the charge air left over from the diesel combustion process and its concentration in diesel exhaust emissions is in the order of around 10%.Exhaust temperatures above 550^{o}C are required for soot oxidation by O2. With the application of so-called ‘‘fuel borne catalysts’’, which precursors are added to the diesel fuel, the required temperature can be lowered to around 400–450^{o}C. Alternatively oxygen could be ‘‘activated’’ by applying non-thermal plasma to generate ozone [17,37], which could then be used to combust soot at low temperatures.

2.2.1.3 Continuously Regenerating Diesel Particulate filter

This particulate filters include the john Matthew Continuously Regenerating trap, contain a precious metal catalyst and a particulate filter (figure2.4).the systems consists of two chambers; the first is an oxidation step and is kept separate from the particle collection phase.

The NO2 production in the first chamber to combust the trapped particles [40,41] and so does so at approximately 250^{o}c, which is much lower than the temperature achieved by using oxygen

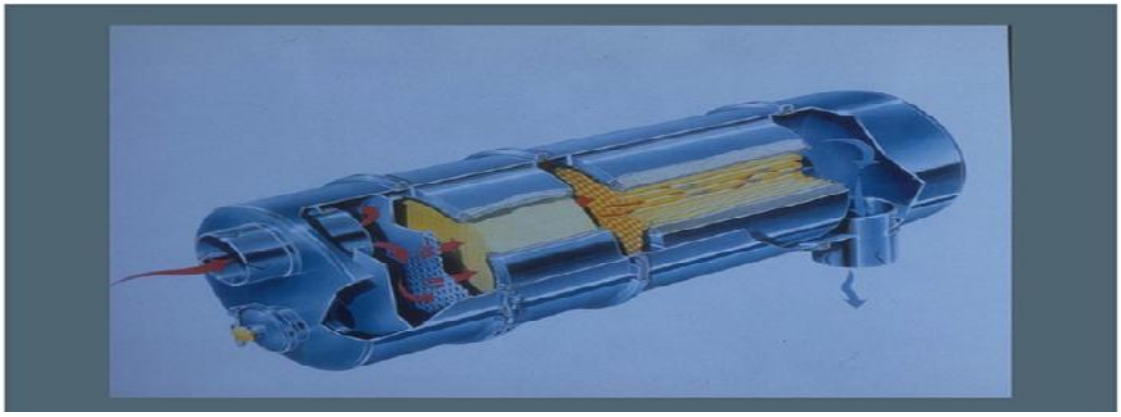

Figure 2.4. John Matthew Continuously Regenerating traps systems [19]

2.2.1.4 Fuel–Borne Catalyzed Particle Filter

The use of fuel additive is another method of lowering the soot oxidation temperature. The fuel borne catalyst additives reduces the particle ignition temperature. The main advantage with this method is having the catalyst incorporated into the PM and not just on the surface of the filter. The main disadvantages are related to the on board storage of the additive.

The following issues need to be addressed by designers of fuel additive regenerated DPFs:

- Introducing the catalyst to fuel

In most fuel distribution systems, doping the fuel with additive is not practical. On- board automated dosing devices are being developed to introduce the additive directly to the vehicle's thank after the vehicle is fuelled. However, such devices increase the system complexity and, in effect, turn passive traps into more complicated and expensive active systems.

- Impact on the engine or its components

Some additives are cause fuel injector fouling. Generally, additives have to be tested for engine wear problem.

- Fuel stability

Blending the additive with fuel may result in deposit formation, an increase in sedimentation from the fuel itself and /or increased deposit formation when water is added to the doped fuel.

PSA have introduced a fuel borne regenerated system into passenger car. The system uses a cerium based fuel additive but application on heavy –duty vehicles is still being investigated.

There are concerns over the possible health hazards should the catalysts escape from the vehicle exhaust [12].Road test conducted by RhodiaTerresRares on a medium heavy duty vehicle show trap efficiencies higher than 90% under all engine operating conditions and undetectable particle emission [20].other tests also using a cerium additive have suggested that the additive has no effect on the PM emissions [21].

2.2.2 Active Regeneration

With active regeneration, the carbon soot particles are burnt off through a targeted increase in the exhaust gas temperature by the engine management system. As shown in figure 2.5,the carbon soot particles are retained in the inlet channels. The engine control unit can detect the level of carbon soot in the particulate filter by evaluating the signals from the air mass meter, the temperature sender before and after particulate filter and the exhaust gas pressure sensor 1.When the carbon soot level reaches a predetermined limit, the engine management system initiates active regeneration[15].

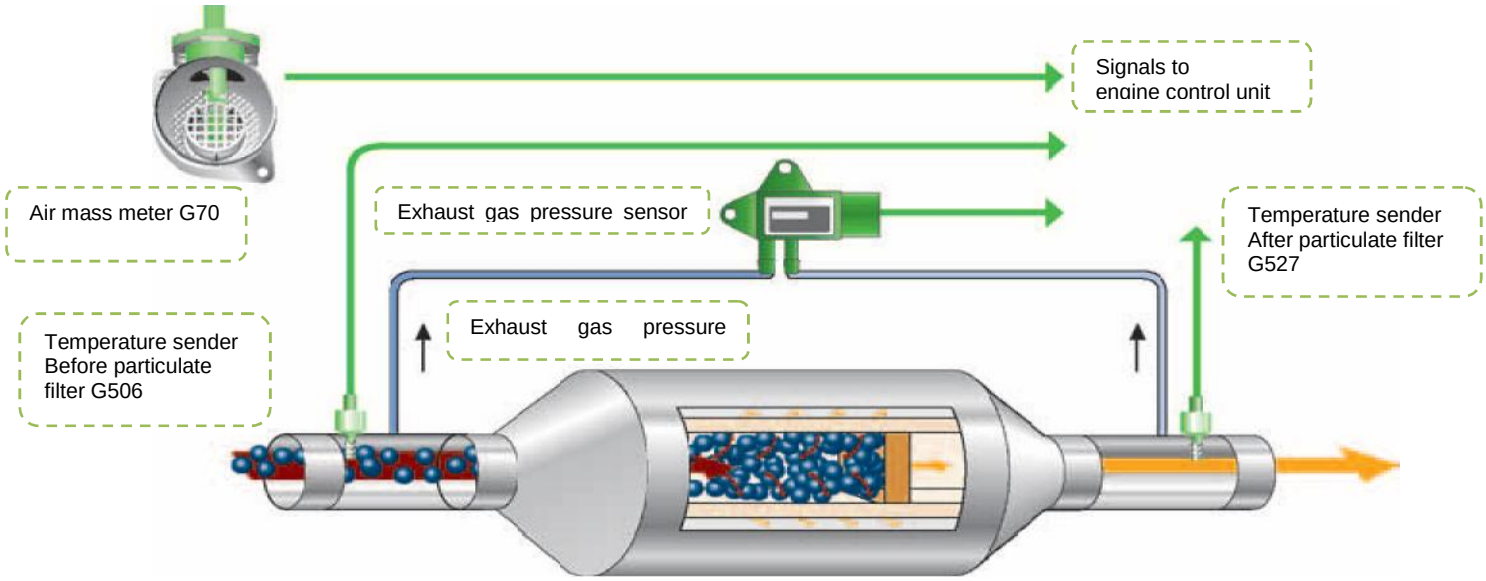

Figure 2.5 Particulate filter full = high resistance to flow [15]

2.2.2.1Fuel Burner Regenerated Traps in DPF

A fuel burner can be used to increase the temperature of exhaust gas stream to the that would facilitate regeneration of the trap via oxidation. The main components of the system are the

ceramic monolith, the mixing chamber and the integrated chamber. Burner related problem contributed to failures of several early DPFS systems. To prevent intrusion of soot particles on the burner and contamination of the air blast atomizer, the burner required cleaning after every 50hours operation.

External energy regeneration systems like these are not currently seen as viable due to their increased cost, complexity and reliable issues [22].

2.2.2.2 Electrically Regenerated traps in DPF

The use of an electric heater is to increase the temperature of either exhaust gas or stream of regeneration air is a relatively simple method of triggering the regeneration of a soot laden diesel filter. The Donaldson Company has developed the most advanced ceramic trap system with electric regeneration for city bus. On board regeneration system draw the power needed for regeneration from the vehicle electrical system. This method is suited to heavy –duty only.The primary concern related to electric regeneration system is energy consumption. The energy required by the heater puts an extra load on the vehicle electrical system, presenting a significant fuel consumption penalty. Electrical demand must be reduced before this can be seen as a viable regeneration solution.

Laboratory tests have shown reasonable efficiencies for the regeneration of but system reliability has yet to be stablished.PM efficiencies of up to 85% have been achieved[1].and fuel consumption penalties of around 3.5% are expected[23].

2.2.2.3 Microwave Regenerated traps in DPF

Diesel soot can be heated directly by microwave irradiation within the particulate filter. When a material is heated conventionally, the heat is first transferred to its surface, typically by a combination of convention and radiation mechanisms, the inside of the material is then heated through conduction from the surface. However, when heated through microwave irradiation, the energy and therefore heat is concentrated in the center of material itself.

Microwave heating is selective. Microwaves most effectively heat material of high dielectric constants and high dielectric loss factors such as water, carbon blacks, and diesel soot. Most ceramic ‘materials, due to their low dielectric constant and loss factor, are practically transparent to radio frequency (RF) energy. Metals, on the other hand, are near perfect reflectors of microwave energy.

The main advantages of microwave heating are its capability to concentrate energy directly into diesel particles, which are collected through the volume of the filter. If a satisfactory degree of control over the RF energy deposition could be achieved, the microwave regeneration would offer much more flexibility in designing and controlling the regeneration than can be achieved by the electric and burner approaches.

One of the problems reported with microwave - regenerated filters are related to difficulties in achieving a satisfactory degree of control over the process. as a result, the filters tend to show uneven regeneration patterns, incomplete regeneration, or expensive exothermal heat release leading to substrate damage. Microwave leakage was encountered in some studies. Leak of micro energy can cause interface with external electronic circuits and decrease energy efficiency. In test an 80-95% PM removal efficiency and a 95% microwave cleaning efficiency have been achieved [24].currently major development work is concentrating on durability and reducing cost of application to heavy duty vehicle.

2.3 Back Pressure Limits

All engines have a maximum allowable engine back pressure specified by the engine manufacturer. Operating the engine at excessive back pressure might invalidate the engine warranty. To facilitate retrofitting of existing engines with DPFs, especially using passive filter systems, emission control manufacturers and engine users have been requesting that engine manufacturers increase the maximum allowed back pressure limits on their engines.

Engine Size	Back Pressure Limit
Less than 50kw	40kpa
50-500kw	20kpa
500kw and above	10kpa

Table2.1 VERT Maximum Recommended Exhaust Back Pressure [29]

Mufflers generally result in maximum back pressures in the range of 6 kPa. In exhaust systems with a DPF, the back pressure can rise to significantly higher levels especially if the filter is heavily loaded with soot. The Swiss VERT program determined maximum back pressure limits in order to allow DPFs to be fitted to a wide variety of equipment Table2.1 outlines the VERT recommended back pressure limits for a range of engines sizes. The exhaust pressure for large engines was limited to low values due to valve overlap and high boost pressure

Engine manufacturers are usually much more conservative on their back pressure limits. For example, diesel generator set engines from Caterpillar, Cummins, John Deere and DDC/MTU ranging in size from 15 to over 1000 kW have back pressure limits ranging from 6.7 to 10.2 kPa.In setting back pressure limits, many factors must be taken into consideration. These include the effect on turbocharger performance, exhaust emissions, fuel consumption and exhaust temperature. The limit that a particular engine can tolerate will depend on specific design factors and making general recommendations is difficult.

2.3.1 Literature review on Pressure drop

The total pressure drop of the filter channel can be divided into four parts: inlet channel pressure drop, pressure drop across the soot deposit, the pressure drop across the substrate wall, and the outlet Channel pressure drop [6, 10,17, 36]

$$\Delta P_{total} = \Delta P_{porous\ wall} + \Delta P_{Soot\ cake} + \Delta F_{riction} + \Delta P_{const/expans}$$

Recently, most of the DPFs are made of refractory ceramics. The two most common materials are: Cordierite (Cd) and Silicon Carbide (SiC). Cordierite filters are manufactured through an extrusion process so that it is a single piece monolithic filter. On the other hand, many SiC filters are extruded in smaller 'segments' and the joined together to form the filter full .For the same DPF cross - section, wall thickness, and cell density, there is a higher flow Resistance in the segmented filter and therefore a larger pressure drop

From Darcy law of pressure drop due to flow through a porous wall, one can obtain:

$$\Delta P = \frac{\mu U w s}{k o}$$

The total pressure drop for the segmented DPF the summation of the pressure drop across filter wall, soot layer ,inlet channel and out let channel

$$\Delta P = \frac{\mu Q}{2Vtrap}(\alpha + w_s)^2\left[\frac{ws}{ko\alpha} + \frac{1}{2ksoot}\ln\left(\frac{\alpha}{\alpha-2w}\right) + \frac{4F}{3}L^2(1/(\alpha\text{-}2w)^4 + 1/\alpha^4)\right]$$

Segmented filters generate higher pressure drop than monolithic filters by up to 30% for clean cases and up to 35% for the loaded filters. A higher cell density filter could results in the reduction of this higher pressure drop.

In both loaded segmented and loaded monolithic filters, 80% or higher of the pressure drop is due to the substrate wall and the deposit layer . The impacts of channel friction and flow contraction / expansion are less important . For the clean filter, the opposite is true, as the majority of the pressure drop is from flow in the channel.

2.4 Materials2.4.1 Diesel particulate filter substrate

Table2.2 below shows a selection of candidates comparing properties of pure (dense) materials. The properties of the filter materials are described in detail in the filter materials section. A comprehensive article about material attributes concerning ceramic DPF materials has been published recently.

The properties of the different filter materials can only be compared directly, if they show the same pore volume and mean pore size. Unfortunately, there is a lack of reliable and comparable data in the literature, mainly regarding strength. Most of the materials are produced in thin-walled honeycomb shape, which cannot be measured by common standards with good accuracy, and most of the filters differ in honeycomb cell size and wall thickness and cannot be compared properly.

Material	Cordierite	Sic	silicon	Mullite	Al-Titanate	FeCrNi
Density(g/cm^3)	2.1	3.1-3.2	2.33	2.9	3.3	8.1
thermal conductivity(W/Mk)	1-3	90	120	4-5	1.5-3	14
CTE 20-1000^oC(10^{-6}1/K)	0.9-2.5	4.7-5.2	4.4	4.4	-0.5-3	17
young's modulus(GPa)	130	410	110	150	20	200
Thermal limit for application (air)(^oC)	1350	1500	13502	1600	1500	1250

Table 2.2 Material candidates for Diesel Particulate Filters; properties are of pure (Dense) Materials[7].

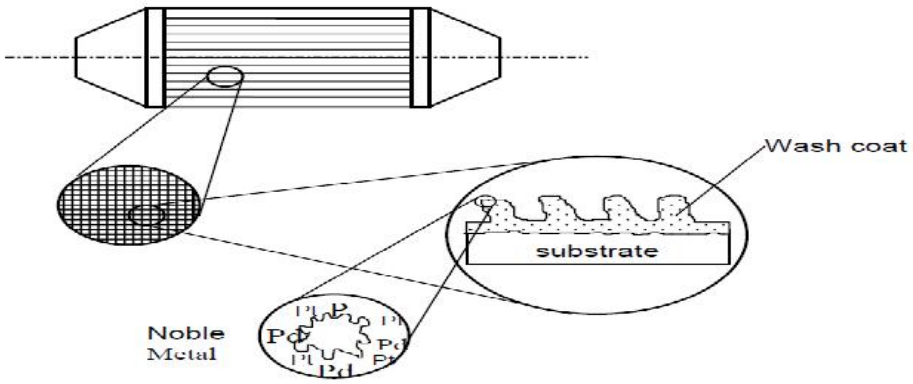

Figure2.6. Structure of the monolithic catalytic coated DPF

2.4.2 Catalysts

Various catalyst systems used for diesel filters. Catalyzed Diesel Particulate Filter catalysts can be divided into two categories :

(1) platinum-based, and

(2) base metal catalysts.

Base metal catalyst:

Base metals tend to be less active in promoting filter regeneration (thus requiring higher regeneration temperatures) and have low activity for the oxidation of CO and HC. On the positive side, they form little or no sulfate particulates and/or nitrogen dioxide emissions. Vanadium used to be one of the most popular base metal catalysts used in diesel particulate filters. The CDPF commercialized in Mercedes cars in California in the mid-1980s was coated with vanadium pentoxide (V2O5) catalyst by Degussa. This catalyst promoted filter regeneration at temperatures of 380-400°C.

Nobel metal catalyst:

Platinum (usually combined with promoters) is typically more active in supporting filter regeneration and for oxidizing CO and HC. The latter function is important in applications where gaseous emission reductions are also required. The disadvantages of Pt include production of sulfate particulates (which limits its applicability with high sulfur fuels) and increased levels of tailpipe NO2.

Although a number of noble metals are named as filter catalysts in the patent literature-including platinum, palladium, rhodium, and others-most commercial noble metal based filters utilize platinum, typically with such promoters as alkaline earths. Ceria has been introduced as a promoter in more recent catalyst formulations.

2.4.3 Catalyst Coating Methodology

Catalysts can be applied on wall-flow diesel filter substrates using one of two methods[43]:

a. impregnation with water-based solutions of catalyst precursors, or

b. Wash coating with suspensions (slurries) of insoluble oxides or salts.

The first method using water solutions of catalyst precursors, noble and/or base metals, followed by drying and calcining is indeed a very convenient way of applying a catalyst onto the ceramic monolith as shown in (figure 2.7). A common method of coating is to apply a predetermined quantity of solution based on a water absorption test of the substrate by pouring it over the inlet

face of the filter. The solution soaks throughout the substrate resulting in a uniform distribution of the catalyst throughout the porous filter walls. Hence, the filter has no preferred direction of flow for exhaust gases and can be reversed in the exhaust system (of course, one could use less solution than needed to soak through the part to apply more catalyst near one end of the filter, resulting in a non-symmetrical coating). The final catalyst, usually metal or metal oxide, is formed from the precursor at elevated temperatures (typically 500-600°C) during the calcining process.

If wash coat technologies are used, there are three possible methods of applying noble metal catalysts (each producing somewhat different catalyst):

- Platinum (or other noble metal) can be impregnated after the wash coat is calcined, Followed by a second calcinations
- Platinum catalyst precursor can be added to the slurry platinum can be fixed on the wash coat powder (e.g., on alumina) and calcined before the slurry is prepared.

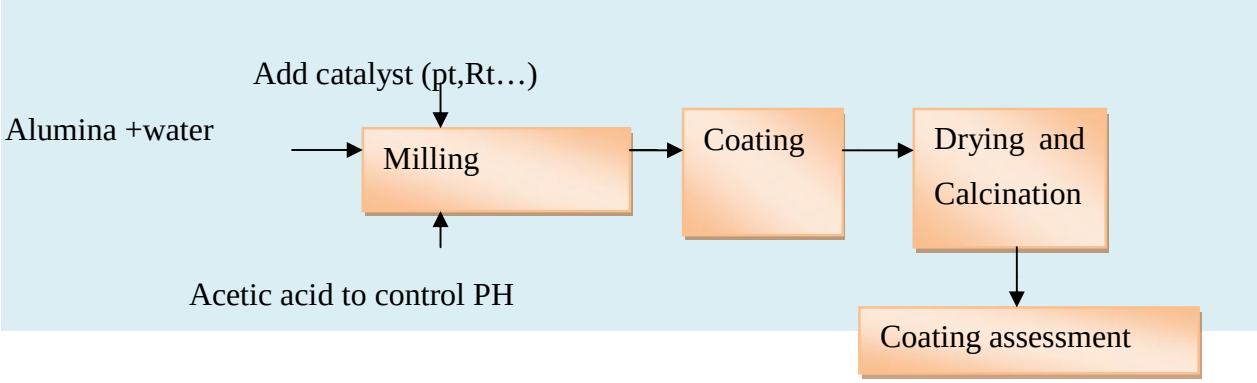

Figure 2.7. Preparation path for catalyst coatings on filter membrane [43]

Milling: The coating slurry containing alumina is adjusted to a suitable pH which produces the best particle dispersion, and is then comminuted in a mill until the required particle size distribution is achieved.

Coating: There are two industrial methods of coating slurry onto substrates. The first method involves coating the already formed into a monolith by pouring the slurry through or by sucking the slurry into the monolith channels. The second method involves coating the before the monolith is constructed by dipping in the slurry (dip-coating), painting or spraying .

Drying and calcinations: The coatings are dried at a temperature above 100 ^{o} C for 1 – 2 h and calcined at 350 – 700 ^{o}C for 1 – 3 h to prevent cracks and ensure good coating adherence [6, 10]The technique for assessing coating thickness and homogeneity should have a high degree of accuracy and resolution, and SEM clearly outperformed other techniques in these areas judging by its predominant use.

2.5 Diesel emissions legislation

Due to the adverse effects of diesel emissions on health, environment, vegetations, materials, climate, etc.; Government legislations for permissible exhaust emission standards [70] were first introduced in both Europe and the United States of America in 1982, only for light-duty vehicles and not until 1990 for heavy-duty engines.

The first Indian emission regulations [51] were idle emission limits which became effective in 1989. These idle emission regulations were soon replaced by mass emission limits for both gasoline (1991) and diesel (1992) vehicles, which were gradually tightened during the 1990's. Since the year 2000, India started adopting European emission and fuel regulations for four-wheeled light-duty and for heavy-duty vehicles.

Emission regulations of DPM and NO_x have become more and more stringent as indicated in Table 2.4. The limits are defined in mass per distance (g/km, light-duty vehicles) or mass per energy (g/kW h, heavy-duty engines) over a defined test cycle. Because of greater air pollution problems, California has its own, more stringent standards. The trends in the DPM legislation apparent in the table make it clear that effective emissions control devices need to be developed to enable vehicles to meet the increasingly stringent limits [52]. Up-to-date information of the various diesel emission standards and vehicle certification tests can be found on the Internet [53].

Year	reference	Light duty diesel engine(g/km)		Heavy duty diesel engine(g/kWh)	
		NOx	DPM	NOx	DPM
2000	Euro I	-	0.14	8.0	0.36
	India 2000		0.25		
	Bharat		0.17		
2008	Euro III	0.50	0.05	5.0	0.10
	Bharat	0.78	0.1		
2010	Euro Iv	0.25	0.025	3.5	0.02
	Bharat	0.33	0.04		
2011	Euro v	0.18-0.235	0.005	0.235-0.28)	0.005

Table2.4 diesel emission standards for different countries

CHAPTER THREE

3.EXHAUST GAS REGENERATION SYSTEMS DESIGN IN DPF

Diesel particulate filters are the most effective option to control the particulate matter (PM) missions .Today there are several types of DPF available on the market and differing mainly by the method of trapped soot removal usually called filter re generation. It is convenient to classify regeneration methods as active (applying external or engine measures of gas temperature control at DPF inlet) or passive (usually employing catalytic means). Combinations of measures are also common and catalytic means can be applied in active regeneration systems.

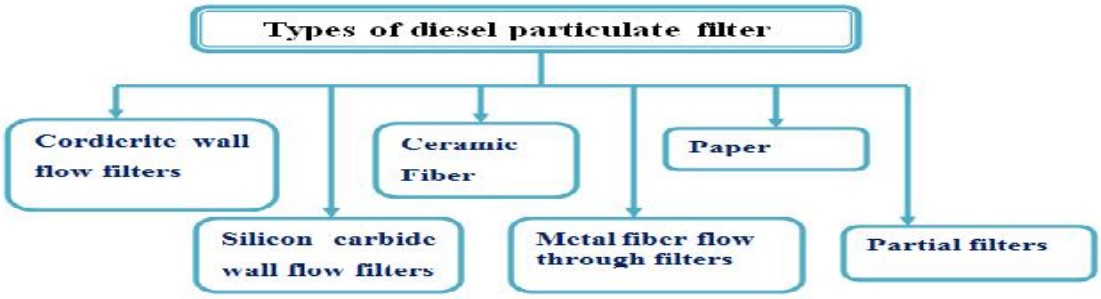

Figure3.1 types of diesel particulate filters may use in PM filtration

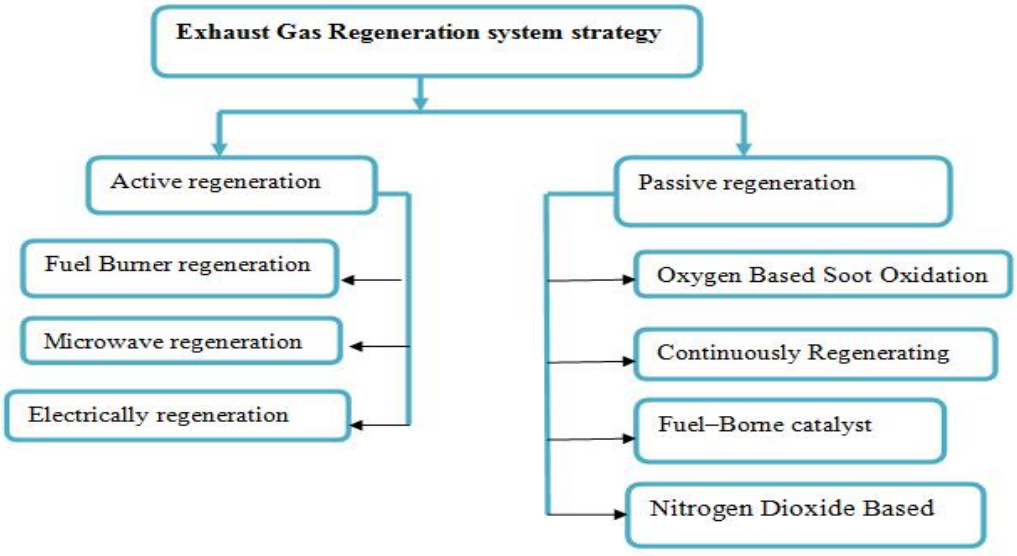

Figure3.2 alternative method for exhaust gas regeneration

3.1 Introduction

Diesel particulate filter is a device which removes particulate matter from exhaust gases through physical filtration. DPF has a honeycomb ceramic structure with long parallel flow channels. Opposite ends of adjacent channels are alternatively capped, forcing gas to flow through porous side walls leaving soot behind on the surface of the walls (figure 11). Since every filter has a finite capacity, the soot build-up must eventually be removed to prevent excessive back pressures from occurring, that would result in an adverse impact on engine performance. In this work the design of exhaust gas regeneration system in diesel particulate filter is presented.

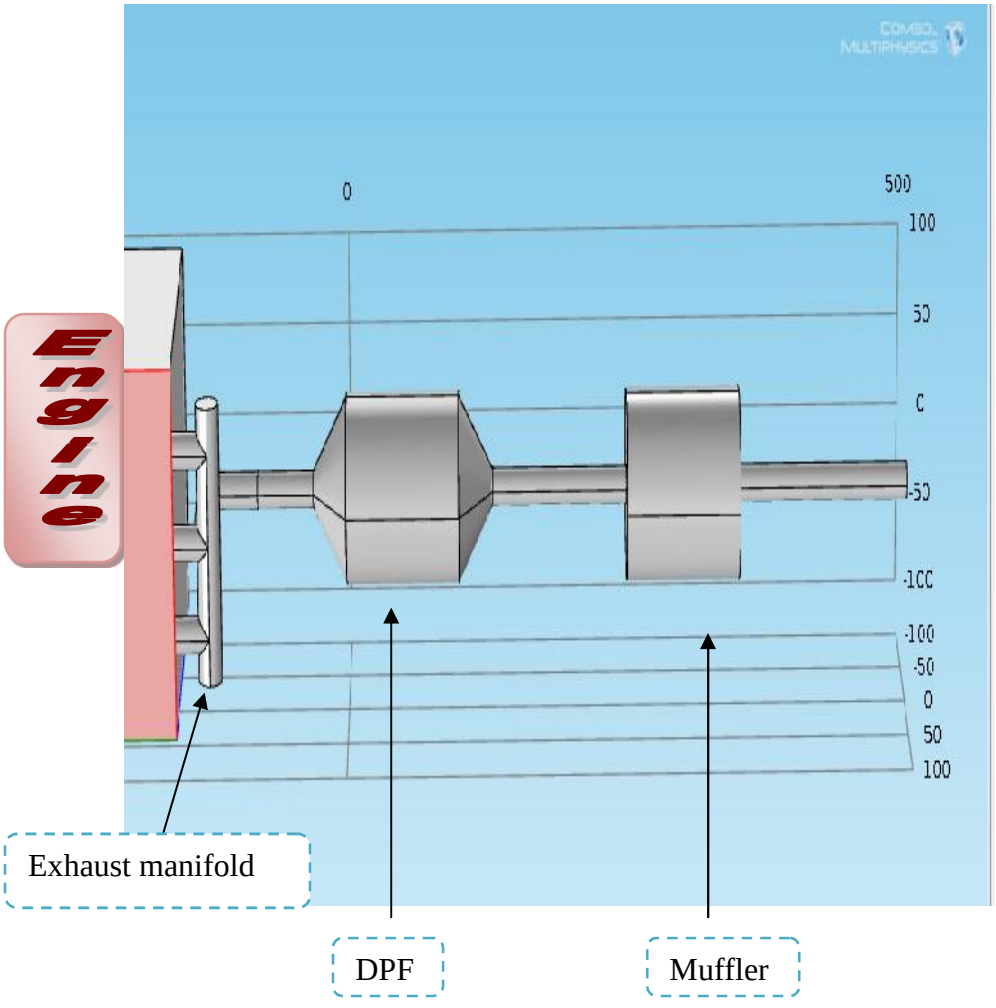

Figure3.3 Diesel engine exhaust line integrated with DPF

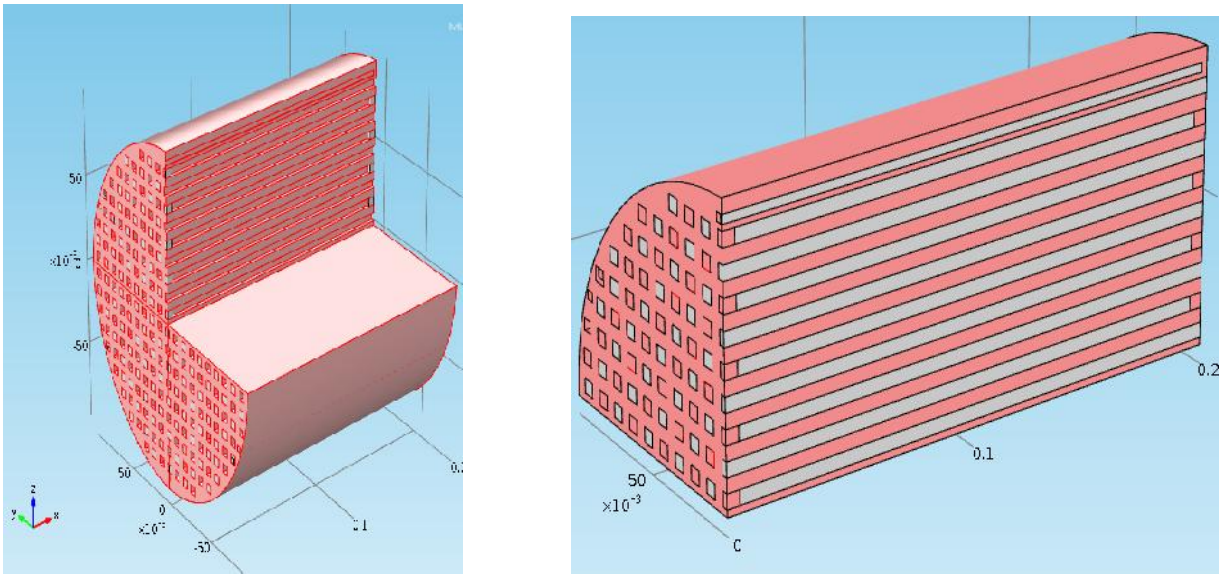

Figure 3.4 diesel particulate filter model and cell arrangements.

3.2 Material Selection

3.2.1 Material for substrate

The material should possess high-temperature stability, resistance against thermal strain, corrosion stability, and sufficient mechanical strength to fulfill all the requirements on filtration, regeneration, and application in a system. It should have a low Young's modulus, low coefficient of thermal expansion and good thermal conductivity to lower the effects of thermal stresses. Availability for mass production at low prices and low weight is a prerequisite for automotive applications. Considering all common materials substances, there is no material that covers all these demands perfectly. The diesel particulate filter substrates are made from Silica sand material. It manufactured through extrusion method and the surface porosity is obtained by re crystallization process of silica sand substrate at its re crystallization temperature.

3.2.2 Catalysts

Various catalyst systems used for diesel filters utilize noble metals, base metals, as well as mixtures of noble and base metals. Platinum is the most active and the most commonly used noble metal (palladium, rhodium or ruthenium catalysts and their mixtures are possible but uncommon). The list of common non platinum-group metals that have or had been used in diesel filters includes vanadium, nickel, cerium, magnesium, calcium, strontium, barium, manganese,

iron, copper, and silver. Noble gas metals palladium and Activated base metal catalyst (nickel /cu as primary active catalyst coated on substrate of DPF).

3.2.3 Wash coating material

Emission control catalysts are typically manufactured by applying wash coat onto catalyst supports. The wash coat, which serves as the carrier for a precious metal catalyst, is a porous refractory oxide layer which is applied to the substrates from acidified aqueous slurry, dried and calcined as stated in [17]. Other materials, used either as catalyst carriers or as promoters and stabilizers, include silicon oxide, cerium dioxide, titanium dioxide, zirconium oxide, and zeolites. Aluminum oxide ($Al_2O_{3)}$ is used in this case as wash coat material.

Figure3.5 Wash coat material (aluminum oxide)

3.3 Diesel Particulate Filter Geometry and Description

The filter has the honey comb and square cell configuration and Individual channel open and plugged at opposite ends. The diesel Exhaust gases enter the open end, flow through the pores the walls, and exit through the adjacent channel**.**

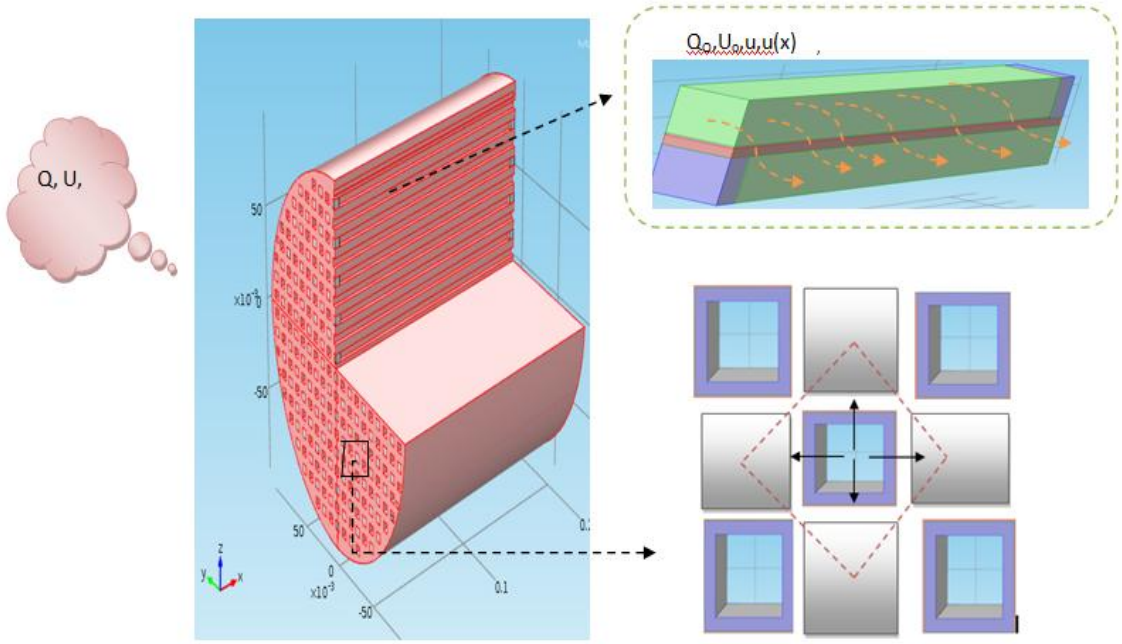

Figure 3.6 Cell configuration pattern in wall flow DPF

Engine capacity	Direct injection /turbo-charged/intercooler
Cylinder arrangement	6/in-line
displacement	6.871cm3
Compression ratio	16.5:1
Max.power @rated speed	169kw2,400min^{-1}
Max.torque @ intermediate speed	860Nm,1440min^{-1}
max.BMEP	15.5bar
Min.BSFC	198g/kw-h
Calibrated for exhaust regeneration	EURO II

able 3.1 Diesel engine tested data calibrated for exhaust regeneration for EURO II

3.3. Theoretical analysis

3.3.1 Filter size

Filter size is generally dictated by engine capacity and is normally equal to engine volume. It helps control soot collection and regeneration without impairing filter durability and imposing high back-pressure penal as per indicated in table 2.1.

- The relation used to design the volume of DPF is give by

Diesel particulate filter volume ≥ engine displacement volume (V_d)

3.3.2configuration

- The wall –flow filter with square cell geometry used.
- These properties can be defined in terms of repeat distance or cell spacing ℓ, and wall thickness(ws)
- Common type(100/17and 200/12)

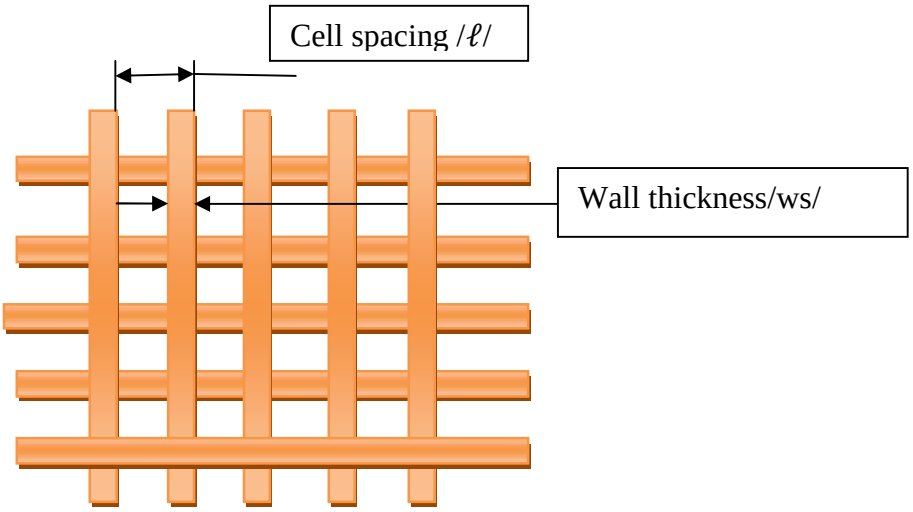

Figure 3.7 Wall flow Filter with Square Cell Geometry [30]

In view of identical open frontal area, filters with 100/17and 200/12 cell configuration will have identical open cross–sectional area and gas flow velocity through their respective channels under constant flow rate conditions.

Thus, the pressure drop will now be proportional to l/α^2, we define this ratio as “back pressure index”

Property and performance parameter		100/17 cell	200/12 cell
Cell spacing distance	(in)	0.100	0.071
Filter wall thickness	(in)	0.017	0.012
Cell density N	(cells/in^2)	100	200
OFA		0.345	0.345
MIF		0.035	0.035
α	(in)	0.083	0.059
SFA	(In^2/in^3)	16.6	23.5
BPI	(in^{-1})	1.0	1.17
Filter length(l)	(in)	L	0.585l

Table 3.2 Properties and performance parameters of diesel filter with two different cell configuration [30]

Where Uo,in is the velocity of the flow inlet channel given by

$$Uo, in = Q/A_O$$

Where, Q = engine displacement*No of cylinders*rpm

$= 6.9[L]*1440[1/60s]*6$

$= 828[L/s]*10^{-3}$

$= 0.9936[m^3/s]$

$A_O = \frac{\pi}{4}d^2 * OFA = 0.7854*(0.2)^2*0.345$

$= 0.0108385m^2$

Here Q is the flow rate through the filter, n is the numbers of cylinders, and A_o is the open cross - sectional area

Therefore, $Uo, in = Q/A_O$

$= 0.9936[m^3/s] /0.108385[m^2]$

$= 9.2m/s$

Total numbers of cells (n cells) = total open inlet area (Ao)/hydraulic area (α^2)

$= Ao/\alpha^2$

$= 0.0108385m^2/0.00000625m^2$

= 1734 cells

- The diesel engine data from specification given in table is used for medium to heavy duty truck of diesel engine:

Cylinder displacement = 5.9 liter

Max.power = 169kw

@Rated speed(rpm) = 2440

Max.torque = 860Nm

@Intermediate speed(rpm) = 1440

Numbers Cylinder/ arrangement =6/in-line

Min.BSFC =198g/kw-h

Diesel Particulate Filter Specification

For filter efficiency = 80%

For filter efficiency = 85%

For filter efficiency ≥ 90%

3.3.3 Diesel particulate matter emission under different engine operating condition

A) Diesel engine operating condition (6-mode Test)

Mode#	Speed(%of rated)	Torque(% of Max)	Weighting factor(W.f)
1	idle	idle	0.355
2	40%	100%	0.071
3	40%	25%	0.059
4	60%	100%	0.107
5	60%	25%	0.122
6	80%	75%	0.286

Table 3.3 Ideal Test Mode points for the Japanese 6-mode Test [from appendix B)

B) Diesel Engine Exhaust emission under different operation condition(6-mode Test)

Mode#	CO	CO2	HC	NOX	O2	Filter soot
	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)
1	-	-	-	-	-	-
2	11.2	740	0	6.42	321	1.23
3	0.91	1000	0	13.1	1190	2
4	4.80	700	0	6.54	401	0.7
5	1.06	1050	0	15.0	1430	0.58
6	0.98	990	0	12.7	1320	0.8

Table3.4 Emission in grams/kW.h for older Detroit Diesel engine on 6-mode Test(from appendix B)

PM emission from Diesel Engine(per Brake Power [kW])

This is the measured output of the engine. This power from the engine drive shaft is measured by a Dynamometer (also known as Brake power).

Brake Power = 2*π*T2*(N2/60)

= 2*π*860Nm (976/60)

= 87.853kW

Therefore, the (DPM) emission Engine for mod2:

= 1.23g/(bkW.hr)*87.853bkW)

=108.0592g/hr

Similarly the brake power and emission level for the corresponding mode of operations are presented as follow

- brake power for mode 1(since at idle, the load is not coupled, we express in terms of soot emission in g per hour = 3.7mg/hr as shown in table 2.3)
- brake power for mode 2=2*3.14*860(976/60) = 87.853kW
- brake power for mode 3=2*3.14*215(976/60) = 21.963kW
- brake power for mode 4=2*3.14*860(1464/60) =13.2kW
- brake power for mode 5=2*3.14*215(1464/60) = 32.95kW
- brake power for mode 6=2*3.14*645/1952rpm =13.18kAnd the corresponding DPM emission will be given as:

Therefore, the (DPM) emission from diesel Engine at different modes of operation in (g/hr) is presented as follow:

The table 3.5 shows that the PM matter emission at each six mode of engine operation are different. It depending the corresponding brake (bkw) and the rate of PM emission is the summation of emission under all modes per hour.

In general: mass of PM emission in gram per hour = 36.01 g/hr

Mass PM emission in gram per filter volume = 36.01g/5.9Lhr

= 6.034g/Lhr

- The (DPM) emission from diesel Engine exhaust for mod2

  1.23g/(bkW.hr)*87.853bkW)=108.0592g/hr

- the (DPM) emission from Engine exhaust for mod3

  2g/(bkW.hr)*21.963kW=43.926g/hr

- the (DPM) emission from Engine exhaust for mod4

  0.7g/(kW.hr)*13.2kW=9.24g/hr

mode	Brake power(bkW)	PM emission(g/hr)	PM emission with operation weighting factor(g/hr)
1	idle	13.32	2.66
2	87.853kW	108.0592	24.422
3	21.963kW	43.926	2.5922
4	13.2kW	9.24	0.989
5	32.95kW	19.11	2.3314
6	13.18kW	10.544	3.0156
Rate of PM emission $= \sum_{i=1}^{6} PM\ i * (W.f)i$			36.01

Table 3.5 Summary of mass based diesel particulate matter emission analysis

- the (DPM) emission from Engine exhaust for mod5

  0.58g/(kW.hr)*32.95kW=19.11g/hr

- the (DPM) emission from Engine exhaust for mod 6

  0.8*13.18=10.544g/hr

i) Mass flow rate of diesel particulate matter collected by dpf

- Filtration Efficiency = 80%

  = 36.01g/hr*80%

  = 28.81g/hr or 28.81g/ (filter volume)

  = 4.883g/l per hr

- Mass of PM released to atm = 36.01g /hr -28.81g /hr

  =7.2g/hr

- For proposed PM emission limit (g/bkw-hr) = 7.2g/87.853kWhr)

  = 0.082 g/bkw-hr

  - Filtration Efficiency = 85%l

    = 36.01 /hr*85%

    =30.61g/hr or5.2l/ hr

- Mass of PM released to atm = 36.01g /hr -30.61g/hr

  =5.4g/hr

For proposed PM emission limit (g/kw-hr) = 5.4g /87.853kw-hr)

=0.062g/bkw-hr

Filtration Efficiency = 90%

mass flow rate of PM collected in filter :

= 36.01g /hr*90%

= 32.41g/hr or 6.68g/l per hr

= 9mg/s per volume of filter.

Mass of PM released to atmosphere :

= 36.01g /hr – 32.41g/hr

= 3.6g/hr

For proposed PM emission limit (g/kw.hr) :

≤ 3.6g/87.853kw-hr)

≤ 0.05g/bkw.hr

3.4 Pressure Drop and Soot Layer Thickness in DPF

When the pressure drop is too high, there is a significant amount of particulate accumulated on the filter wall. The additional particulate needs more thermal energy to complete the regeneration. This energy is often provided by combusting diesel fuel, which leads to a lower fuel economy, which is an issue that should be considered at the same time. Therefore, a reasonable pressure drop is required for the DPF during both filtration and regeneration.

a) Mass flow rate of Diesel Particulate Matter terms of soot layer thickness:

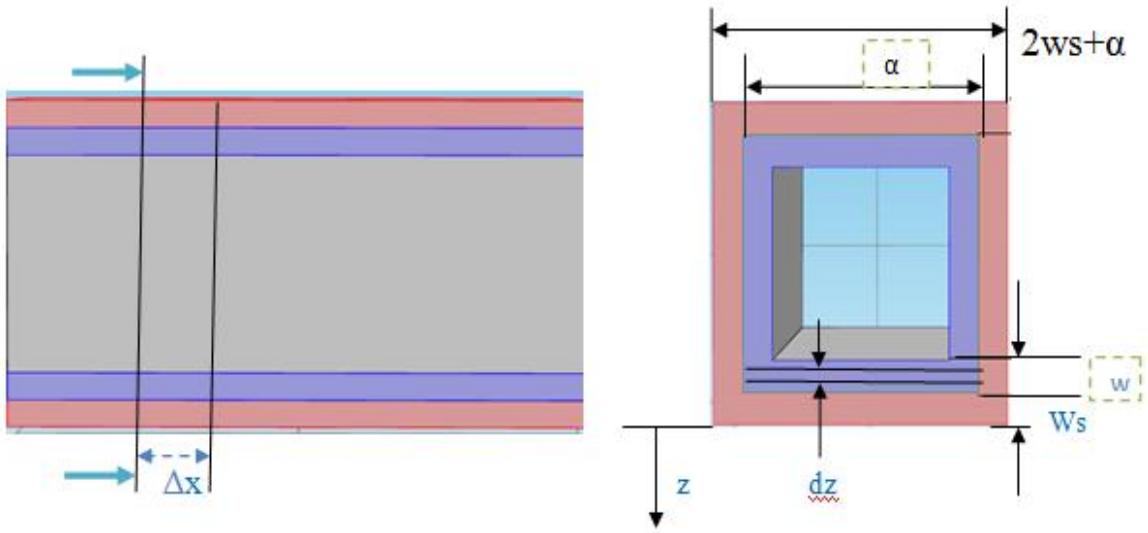

Figure 3.8 Diesel Particular matter deposit layer thickness

Deposit soot layer thickness w can be calculated from the soot volume soot volume for single channel

$$Vsoot = \frac{mc}{ncell * \rho soot,c} \qquad (a)$$

For a loaded filter the volume of particulate mass deposited in one inlet channel

$$Vsoot = (\alpha^2 L - (\alpha - 2w)^2 L$$

$$= 4w(\alpha - w)L$$

$$= 4w\alpha - 4w^2 L \qquad (b)$$

Combine equation a and b gives the particulate layer thickness in terms of

$$4w\alpha - 4w^2 L = \frac{mc}{ncell * \rho soot,c}$$

$$w^2 - w\alpha + \frac{mc}{4ncell * \rho soot,c * L} = \mathbf{0}$$

This has quadratic equation form of $ax^2\ bx + c = o$ where a=1,b=-α and $c=\frac{mc}{4ncell * \rho soot,c * L}$

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

The solution for unknown x=w, which is the thickness of soot layer is

$$ws = \frac{\alpha - \sqrt{\alpha^2 - \frac{mc}{ncell * \rho soot,c * L}}}{2} \qquad (c)$$

The first two hours of soot trapped on the wall flow filter of 90% filtration efficiency the PM collected in filter is 36.01g /hr*90%.Which is 32.41g/hr *2hr, equal to (18.011mg/m^3) PM deposited per volume of filter.

Therefore, for filter length and filter channel width 30cm and 0.254cm respectively. The soot layer thickness in the equation 4.3.3c will be ws=14µm.

Total pressure drop equation (soot loaded)

$$P = \frac{\mu}{k0} u_w w_s + \beta \rho u_w^2 w_s + \frac{\mu}{k\,soot} \int_0^w u\ x\ dx + \left(\frac{\mu F}{2(\alpha - w)2} Uo, inL + \frac{\mu F}{2\alpha 2} Uo, outL\right) \ldots\ldots\ldots\ldots\ldots\ldots 3.1$$

Where velocity terms are :

$$uw = \frac{Qo}{Afilt} = \frac{UoAo}{4\alpha L} = \frac{Uo\ \alpha 2}{4\alpha L} = \frac{Uo\,\alpha}{4L}$$ clear filter condition for A

$$\int_0^w u\ z\ dx = \int_0^w \left(\frac{Qo}{Afilt}\right) dz = \int_0^w \left(\frac{Qo}{4(\alpha - 2\ W - X\ L}\right) dz = \frac{Qo}{8L} \ln \frac{\alpha}{\alpha - 2w}$$

$$U_{In} = Q / \sum_{inlet} A_o$$

$$= \frac{Q}{\frac{\pi D2}{4}\ 1/2(\ \alpha - 2W\ 2\ \alpha + wS\ 2)} = \frac{8Q}{\Pi D2\sigma\ \alpha - 2w\ 2}$$: soot cake thickness (w) for A_o

$$Q_O = \frac{QAo}{\sum inlet\, Ao} = \frac{Q(\alpha - 2W)2}{\frac{\pi D2}{4}\ 1/2(\ \alpha - 2W\ 2\ \alpha + ws\ 2} = 8Q\ (\alpha + w_s)^2 / \pi D^2\, U$$

length	L1=	L2=	L3=	L4=	L5=	L6=
thickness	0.05	0.1	0.15	0.2	0.25	0.3
ws1 = 0.00002	8.44E+01	1.69E+02	2.53E+02	3.38E+02	4.22E+02	5.07E+02
ws2 = 0.00003	1.27E+02	2.54E+02	3.81E+02	5.09E+02	6.36E+02	7.63E+02
ws3 = 0.00004	1.69E+02	3.37E+02	5.06E+02	6.75E+02	8.43E+02	1.01E+03
ws4 = 0.00005	2.14E+02	4.28E+02	6.42E+02	8.56E+02	1.07E+03	1.28E+03
ws5 = 0.00006	2.58E+02	5.15E+02	7.73E+02	1.03E+03	1.29E+03	1.55E+03
ws6 = 0.00007	3.02E+02	6.03E+02	9.05E+02	1.21E+03	1.51E+03	1.81E+03

Table 3.7a pressure drop relation across DPF channel as function of soot later thickness and channel length

Pressure drop	$\Delta P_{orous\ wall}$	$\Delta S_{oot\ cake}$	$\Delta P_{\ inlet\ channel}$	$\Delta P_{\ out\ let\ channel}$	Δp_{total}
Loaded filter	0.72kpa	1.55kpa	0.31kpa	0.23kpa	2.81kpa

Table 3.7b total pressure drop across D PF

Modeling in Comsol

3.5 Diesel Particulate Matter Regeneration Modeling In DPF

Mathematical modeling provides a powerful tool for investigating diesel particulate filter regeneration critical parameters under a wide range of operating conditions.

3.5.1 Soft ware description

Here the COMSOL Multi physics soft ware is used to solve the coupled flow and mass transport equations describing the transport/reaction /phenomena in a diesel particulate filter. Procedure needed for the model analysis in comsol4.3 multi physics soft ware is presented under appendix-A.

3.5.2 DPF Model description

The channels and porous membrane with their true geometry with the only simplification being the membrane description. The membrane could be described with a porous-media approach using effective transport properties. Flow in the channels is expected to be close to fully developed laminar flow.

Darcy's Law Equation Formulation

Darcy's law states that the velocity field is determined by the pressure gradient, the fluid viscosity, and the structure of the porous medium:

$$u = -\frac{k}{\mu}\Delta p \quad \text{.....3.2}$$

In this equation, κ (m^2) denotes the permeability of the porous medium, μ (kg/(m·s)) the dynamic viscosity of the fluid, *p* (Pa) the pressure, and **u** (m/s) the Darcy velocity.

The Darcy's Law interface combines Darcy's law with the continuity equation:

$$\frac{\partial}{\partial t}\ \rho\varepsilon\ +\ \nabla.(\rho u)\ = Q_m \quad \text{.....3.3}$$

In the above equation, ρ (kg/m^3) is the density of the fluid, ε (unit less) is the porosity, and Q_m (kg/(m^3·s)) is a mass source term. Porosity is defined as the fraction of the control volume that is occupied by pores. Thus, porosity can vary from zero for pure solid regions to unty for domains of free flow.

If the Darcy's Law interface is coupled with an energy balance, then the fluid density can be a function of the temperature, pressure, and composition (for mixture flows). For gas flows in porous media, the dependence is given by the ideal gas law:

$$\rho = p\frac{M}{RT}$$

$$\rho_1 = p_{in} * \frac{Mgas}{RgTin} \quad \text{, gas density in the inlet channel}$$

$$\rho_2 = p_{out} * \frac{Mgas}{RTout} \quad \text{, gas density in the outlet channel}$$

Where R= 8.314 J/(mol·K) is the universal gas constant, M (kg/mol) is the molecular weight of the gas, and T (K) is the temperature.

3.5.3 mathematical modeling for mass balance equation in DPF

The soot particles are present only in the inlet channel because they are deposited as a film on the Porous membrane. Mass transport by convection, diffusion and reaction, this gives the transport equation

$$\frac{\partial ci}{\partial t}\ +\ \nabla.(-D_s\nabla + c_i + u.\nabla c_i) = R_i \quad \text{.....3.4}$$

Where $\nabla = [\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}]$ is differential operator, c_s denote the soot-particle concentration (mol/m3), i, stands for species, Ds is the diffusivity of soot particles (m2/s) , R_i is soot particle deposition as sink/source per unit area , υ species flow rate and cross section area (A).

3.5.3.1 Soot species (cs) in the exhaust stream

A balance for soot particles introduces the deposition of soot particles as a sink to the flux of particles in the open channe1

$$\frac{\partial cs}{\partial t} + \frac{\partial}{\partial z}(-D_s\frac{\partial}{\partial z}c_s + c_s u_1) = \frac{4}{\alpha}\ c_s\ \upsilon \quad \text{.....3.5}$$

3.5.3.2 Oxygen species (O2) in the exhaust stream

The model defines the concentration of oxygen using two material balances, one for the inlet and another for the outlet channel. The material balance in the inlet channel contains the term where oxygen reacts in the combustion reaction with soot.

- The species material balance in the inlet channel is represented by the equation

$$\frac{\partial c}{\partial t} o_{2,1} + \frac{\partial}{\partial z}(-D_{o2,1}\frac{\partial}{\partial z}c_{o2,1} + c_{o2,1}u_1) = \frac{4}{\alpha} c_{o2,1}\upsilon + \frac{1}{\alpha} RS \quad \text{.....3.6}$$

Where c_{O2} denotes the oxygen concentration (mol/m^3), Do$_2$ gives the diffusion coefficient (m^2/s), and Rs equals the reaction rate for the surface reaction (mol/(m^2·s)).

The corresponding species mass balance for oxygen in the outlet channel yields

$$\frac{\partial c}{\partial t} o_{2,2} + \frac{\partial}{\partial z}(-D_{O2}\frac{\partial}{\partial z}c_{O2,2} + cO_{2,2}u_2) = \frac{4}{\alpha} c_{O2,2}\upsilon \quad \text{.....3.7}$$

The reaction rate is described by an Arrhenius law according to:

$$r = ko_2 * \exp\left(\frac{-Ea}{RgT}\right)$$

$$Rs = r * co2,1$$

Where ko$_2$, the pre-exponential factor, Ea, the activation energy, R$_g$ is the gas constant, 8.314 J/(mol·K), and T the temperature (K).

The balance of soot results in an expression for the growth or consumption of the soot layer:

$$\rho s * \frac{\partial ws}{\partial t} + (Ms\ Rs - c_s\upsilon) \quad \text{.....3.8}$$

Whereas denotes the soot layer's thickness (m), ρs represents its effective density (kg/m3), and Ms equals the molecular weight of carbon (kg/mol).

The boundary condition for co2,1 sets the concentration at the inlet, while insulation is used for all other boundaries. For co2,2, use a convective flux condition at the outlet and set all other boundaries to insulation. The initial conditions for both co2,1 and co2,2 are 0.

3.5.4 energy balance

These are:

The balance for the inlet channels

$$\rho_1 C_{p1}\frac{\partial T1}{\partial t} + \nabla.q_1 + \frac{4}{\alpha}\rho_1 C_{p1} T_1 \upsilon - \frac{4}{\alpha}h(T - T_1) = 0 \quad \text{.....3.9}$$

$$q_1 = -\kappa_1 \nabla T_1 + \rho_1 C_{p1} T_1 \mu_1$$

Where *T*1 is the temperature in the inlet channels (K), T is the temperature in the membrane (K), *Cp*1 gives the heat capacity of the gas in the inlet channel (J/(kg·K)), *h* equals the heat transfer coefficient (W/(m2·K)), and **q**1 is the flux vector.

b) In the membrane, the energy equation is given by

$$\rho C_p \frac{\partial T}{\partial t} + \nabla.q1 + \frac{\upsilon}{w}(\rho_2 C_{p2} T - \rho_1 C_{p1} T_1) + \frac{h}{w}(2T - T_1 - T_2) = 0 \quad \text{.....3.9}$$

$$q1 = -\kappa \Delta T$$

Here *T* is filter temperature, *T*2 equals the temperature in the outlet channel (K), *Cp*2 refers to the heat capacity of the gas in the outlet channels (J/(kg·K)),and *h* is the heat transfer coefficient between the membrane and the channels.

The last equation determines the temperature in the outlet channel:

$$\rho_2 C_{p2}\frac{\partial T2}{\partial t} + \nabla.q_2 + \frac{4}{\alpha}\rho_2 C_{p2} T_2 \upsilon - \frac{4}{\alpha}h(T - T_2) = 0 \quad \text{.....3.10}$$

$$q_2 = -\kappa_2 \Delta T_2 + \rho_2 C_{p2} T_2 \mu_2$$

The boundary conditions for the inlet channel are a given temperature at the inlet and insulation at all other boundaries.

At the outlet channel, use a convective flux condition at the outlet and set all other boundaries to insulation. The initial condition specifies a temperature equal to the inlet temperature of the gas.

For the membrane, the heat flux through the boundaries is given by

$$q_{m}.n = h_{outer}(T - T_{amb})$$

Where h_{outer} denotes the heat transfer coefficient and Tamb equals the ambient temperature.

CHAPTER FOUR

Results and discussion

4.1 Mass flow rate analysis of Diesel Particulate Matter (DPM) from diesel vehicle/engine

The basic approach to testing was to run each engine at 6 steady-state test modes which were chosen to cover a range of speed and power levels. The speed and power levels were chosen to generally comply with the Japanese 6-mode test procedure which is a certification test standard formerly used in Japan.

Mode#	Speed(%of rated)	Torque(% of Max)	Weighting factor(W.f)
1	idle	idle	0.355
2	40%	100%	0.071
3	40%	25%	0.059
4	60%	100%	0.107
5	60%	25%	0.122
6	80%	75%	0.286

Table 4.1 a) diesel engine modes of operation and their weighting factors

It is still generally useful for representing an engine at a range of test loads and speeds which covers normal operation.

Maximum torque (T_{max}) = 860Nm Rated speed(N) = 2440rpm			
mode	Brake power(bkW)	PM emission(g/hr)	PM emission with operation weighting factor(g/hr)
1	idle	13.32	2.66
2	87.853kW	108.0592	24.422
3	21.963kW	43.926	2.5922
4	13.2kW	9.24	0.989
5	32.95kW	19.11	2.3314
6	13.18kW	10.544	3.0156
Rate of PM emission $= \sum_{i=1}^{6} PM\ i * (W.f)i$			36.01

Table 4.1 b) diesel engine modes of operation and their weighting factors

As indicated in the table 4.1b the mass of particulate matter emission level from diesel engine exhaust level is directly proportional the engine loading condition. Which means the maximum soot emitted at higher load (mode 2) and minimum emission level at lower load (mode 6)

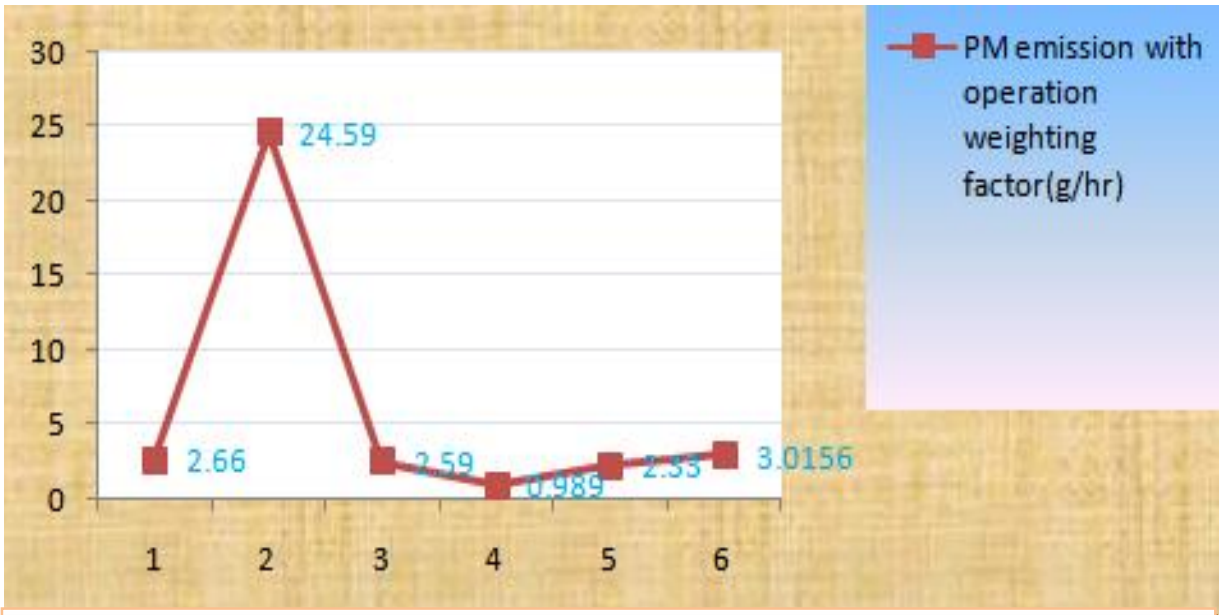

Figure 4.1 DPM emission from Diesel Exhaust under different modes of operation condition

The total PM emission from the diesel exhaust gas per one hour under six mode operation conditions is the summation of the products of soot filter emission and weighting factor for in each mode of operation. As indicated in the table 4.1b Rate of PM emission $= \sum_{i=1}^{6} \text{PM i} * \text{W.f)i}$, which is 36.01g/hr. About 69.5% mass of PM emitted from diesel exhaust was during mode 2 of engine operation condition.

In general: mass of PM emission in gram per hour = 36.01 g/hr

Mass PM emission in gram per filter volume = 36.01g/5.9Lhr

= 6.034g/Lhr

4.1.1mass flow rate of diesel particulate matter collected by DPF

Filter PM trapping efficiency (%)	The (DPM) emission from Engine exhaust with w.f(g/hr)	Mass of PM released to atmosphere(g/bkw.hr)	Proposed (DPM) emission standards (For EUIV to EUV standards (g/bkw.hr))
80	36.01	0.082	. ≤ 0.05
85	36.01	0.062	
90	36.01	0.041	

Table 4.1c the proposed (DPM) emission standards

The table 4.1c above shows that the mass of PM released to the atmosphere for filter filtration efficiency above the 85% is meet the Proposed (DPM) emission standards.

4.1.1Soot layer thickness and Pressure drop across diesel particulate filter

W hen the pressure drop is too high; there is a significant amount of particulate accumulated on the filter wall. The additional particulate needs more thermal energy to complete the regeneration. This energy is often provided by combusting diesel fuel, which leads to a lower fuel economy, which is an issue that should be considered at the same time. Therefore, a total pressure drop across the filter is predicted from equation 3.1. the results are presented as per in the following table.

Pressure drop	$\Delta P_{orous\ wall}$	$\Delta S_{oot\ cake}$	$\Delta P_{\ inlet\ channel}$	$\Delta P_{\ out\ let\ channel}$	Δp_{total}
Loaded filter	0.72kpa	1.55kpa	0.31kpa	0.23kpa	2.81kpa

Figure 4.2a pressure drop across unit cell channel of diesel particulate filter due to soot deposition $\Delta P_{\ soot\ layer} = \mu Q_o/(8k_{soot}L\ )*\ln(\alpha/\alpha-2w)$

The graphs in the figure above shows that the relationship between pressure drop and soot layer thickness developed due to diesel soot particles trapped continuously on the porous membrane of the filter wall. At each soot layer thickness the pressure drop predicted is increased in logarithm function graphs. The soot deposited should be removed/regenerated before the back pressure limit reached.

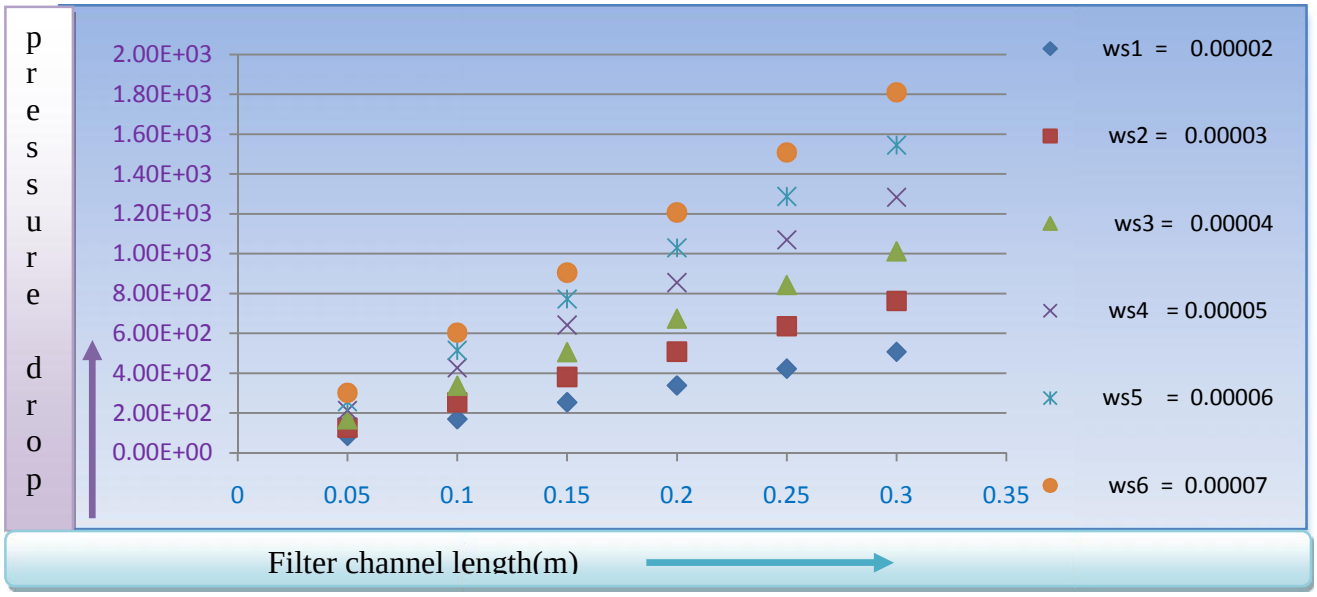

Figure 4.2b pressure drop across unit cell channel of diesel particulate filter due to soot deposition

The maximum pressure drop when the soot layer thickness is at 60µm, the pressure drop is 1.55kpa.the total pressure drop across the filter channel as indicated table 3.7, and it is 2.81kpa.

4.1.3 diesel particulate matter regeneration modeling in DPF

Here the COMSOL Multi physics soft ware is used to solve the coupled flow and mass transport equations describing the transport/reaction /phenomena in a diesel particulate filter.

4.1.3.1 exhaust gas flow velocity in DPF

The channels and porous membrane with their true geometry with the only simplification being the membrane description. The membrane could be described with a porous-media approach using effective transport properties.

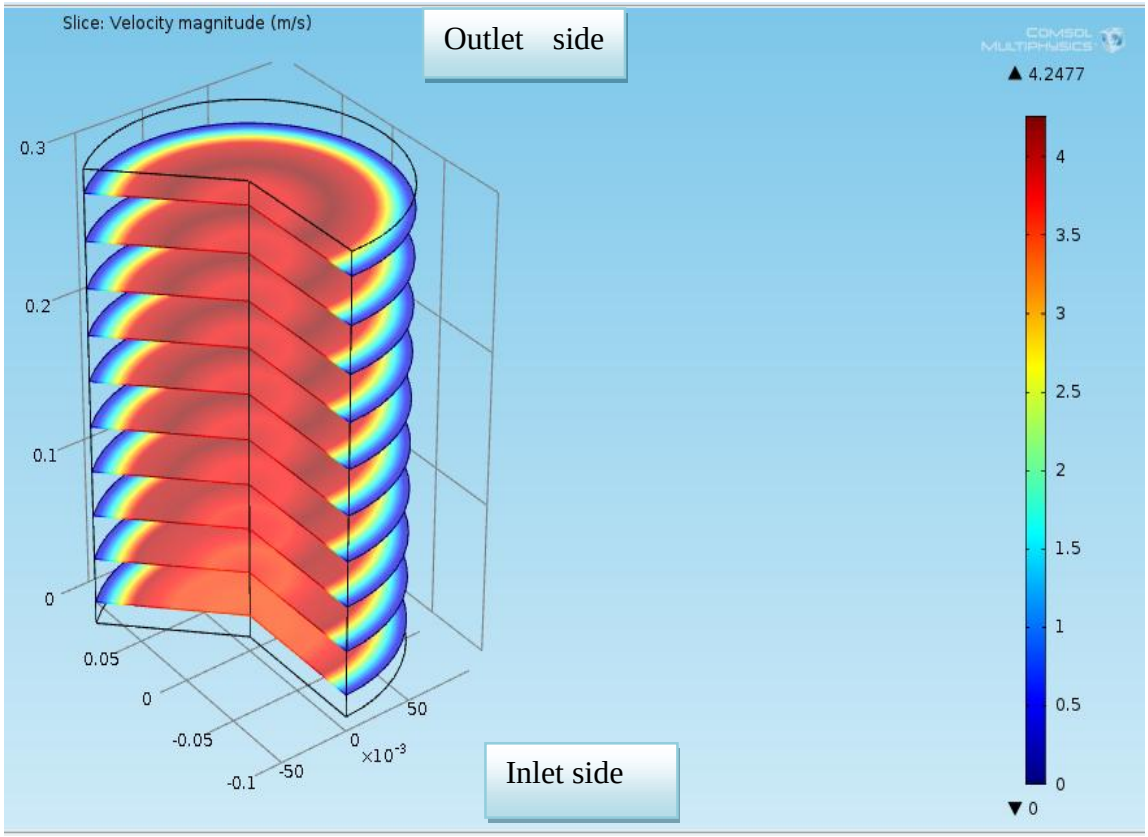

figure 4.3 exhaust gas velocity and its flow profile in DPF

Flow in the channels is expected to be close to fully developed laminar flow. Darcy's law states that the velocity field is determined by the pressure gradient, the fluid viscosity, and the structure of the porous medium:

As shown in figure4.3 above the Maximum flow velocity values obtained at the center of filter and decreases toward the radial direction of the DPF.The values of the flow velocity near the outer surface of the filter is zero due to fully developed laminar flow velocity profile of exhaust gas in DPF.

4.1.3.2 diesel exhaust gas mass distribution in DPF

The soot particles are present only in the inlet channel because they are deposited as a film on the Porous membrane. The model defines the concentration of oxygen using two material balances, one for the inlet and another for the outlet channel. The material balance in the inlet channel contains the term where oxygen reacts in the combustion reaction with soot. The general concept of equation 3.4 is used to find concentration of species in the filter.

4.1.3.3 Oxygen species concentration distribution in DPF

The figure 4.4 and4.5 indicates that the maximum values concentration distribution is at the inlet and center part of the DPF. The minimum values of the concentration distribution are near the filter out let and outer. This shows that the filter channel cell at the center of the filter is regenerated quickly before the cell located at outer one.

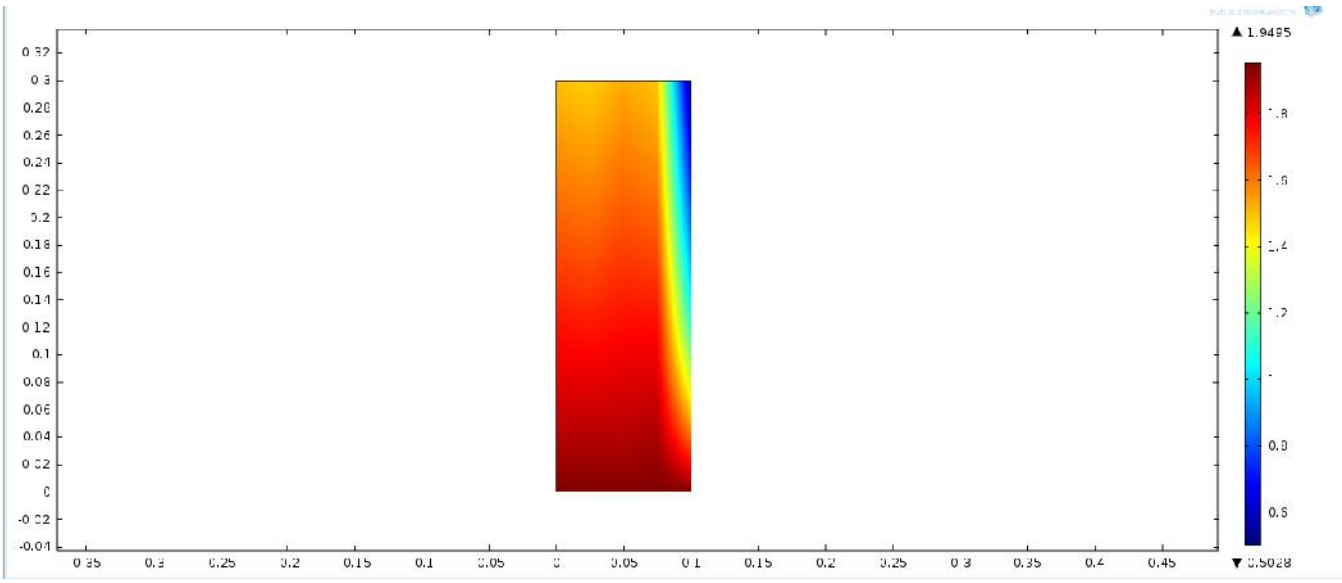

Figure 4.4 Oxygen species concentration distribution in 2D model of DPF

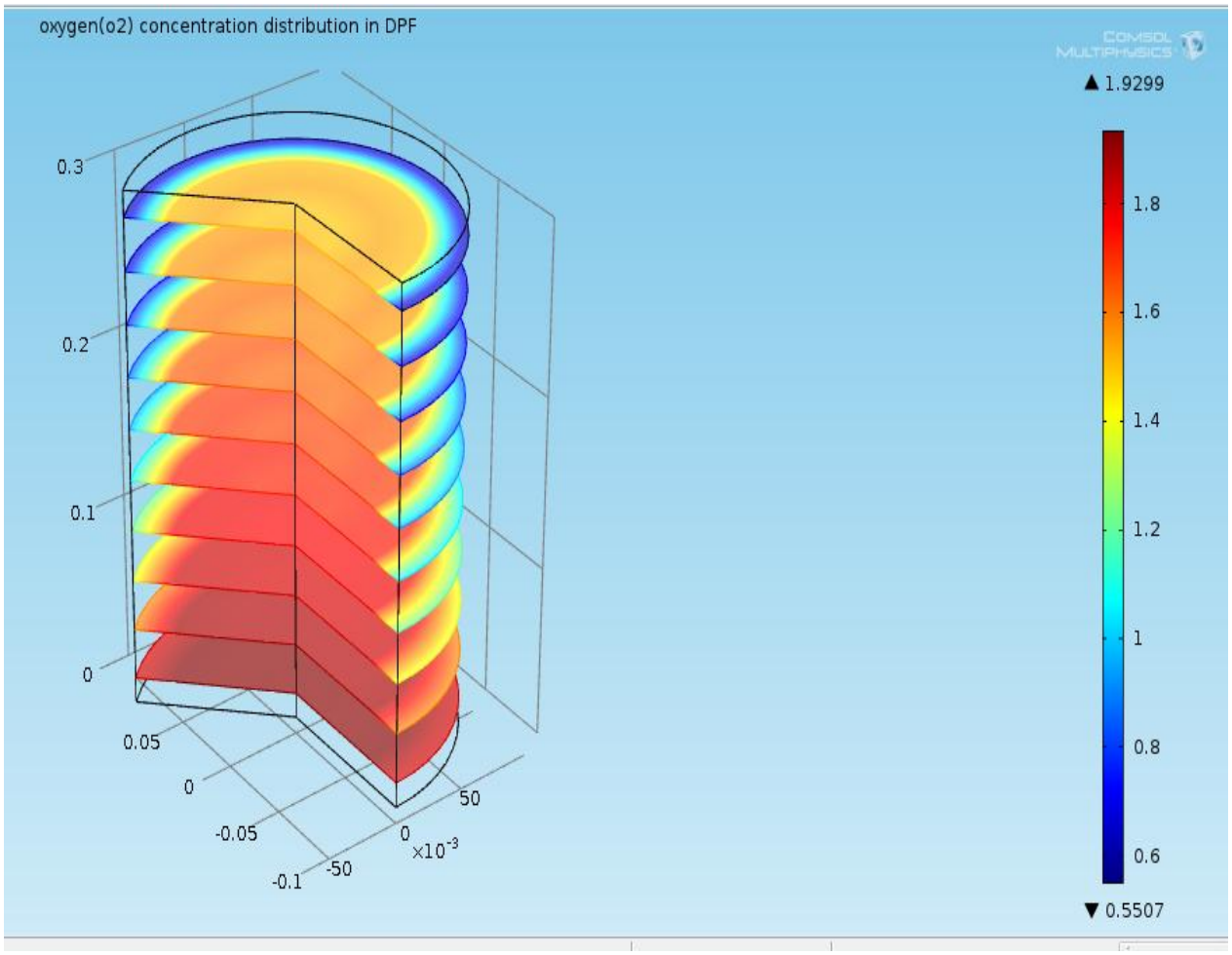

Figure 4.5 Oxygen species concentration distribution in 3D model of DPF

4.1.3.4 Soot species concentration distribution in DPF

The soot trap concentration in DPF model as shown in figure 4.6 and 4.7, near the out let and the outer surface part of the filter model high soot trap concentration seen and at inlet and filter channel located near center is less soot trap concentration distribution.

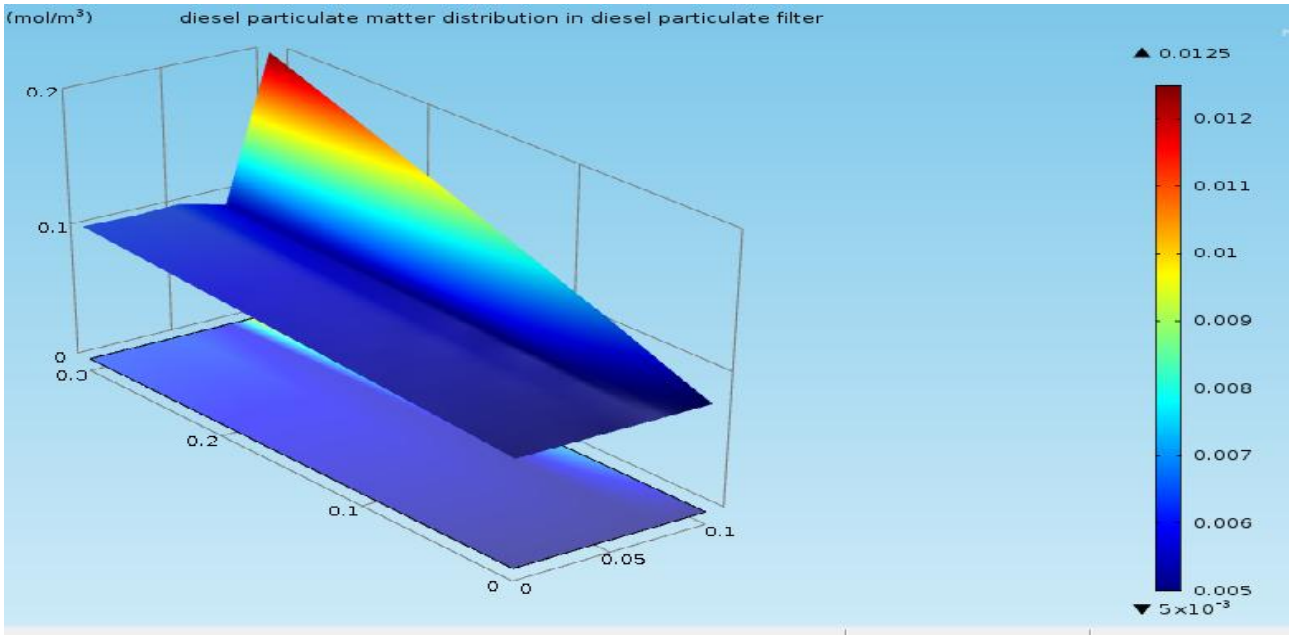

Figure 4.6 soot trap species concentration distribution in 2D model of DP

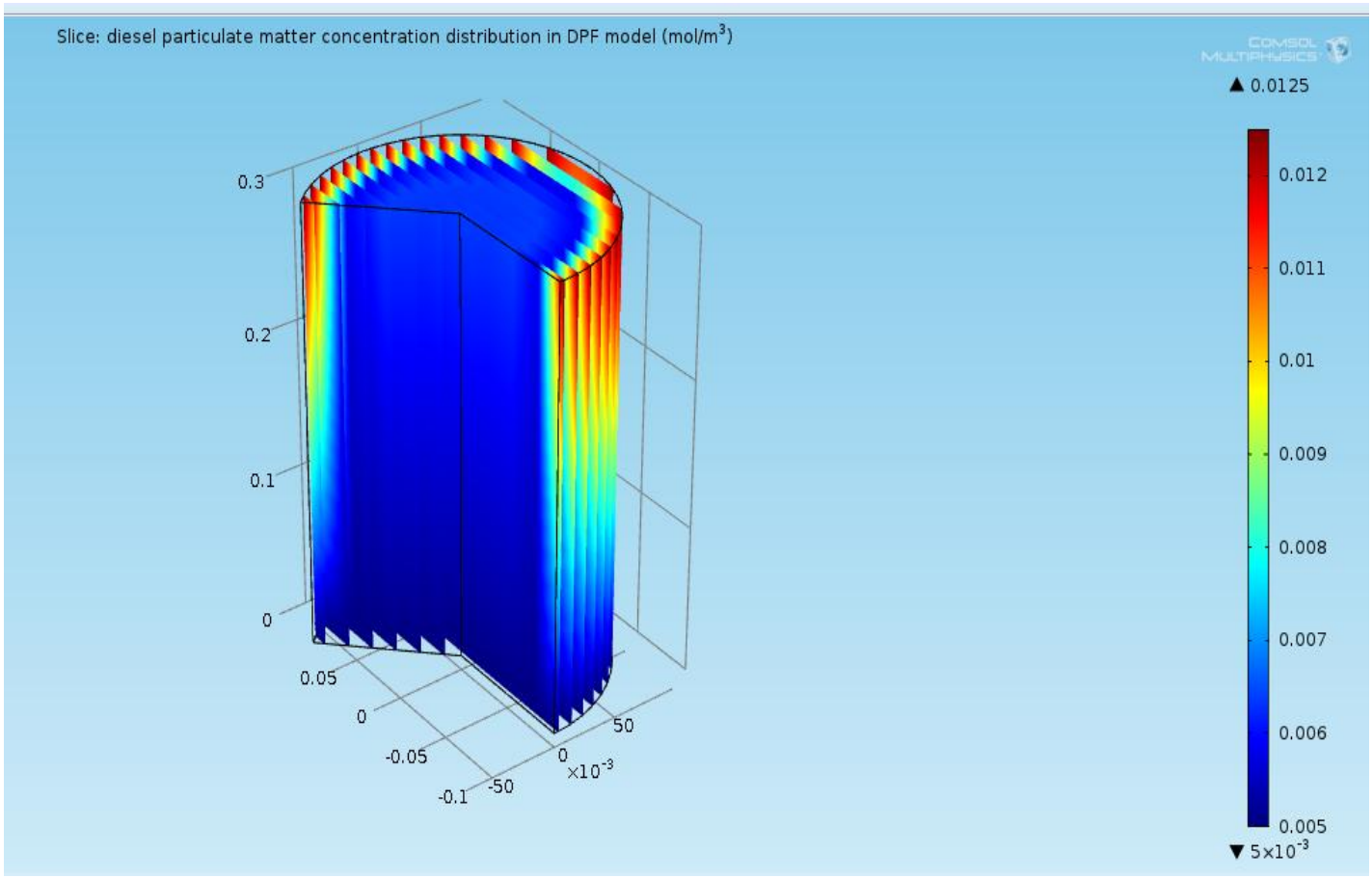

Figure4.7 soot trap species concentration distribution in 3D model of DPF

4.1.3.5 Temperature distribution in diesel particulate filter

The values for the temperature distribution in diesel particulate filter below shows that in addition to the temperature of exhaust gas(500K), there is increase in values due to oxidation of soot trap to 705K. In other ways from passive regeneration strategy applied the activation energy desired for soot oxidation is lower, which implies lowed oxidation temperature than the normal condition.

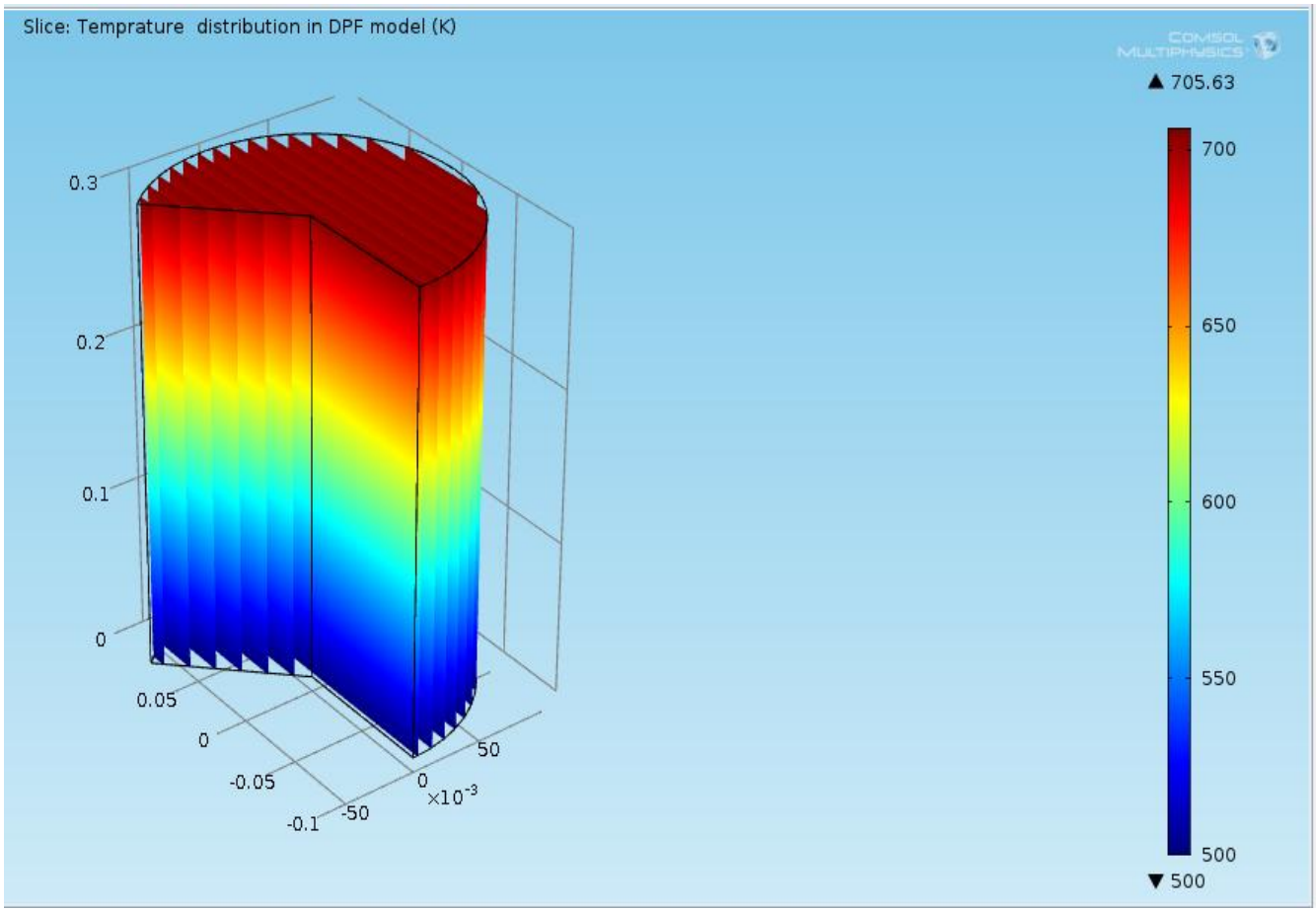

Figure 4.8a temperature distributions in diesel particulate filter model

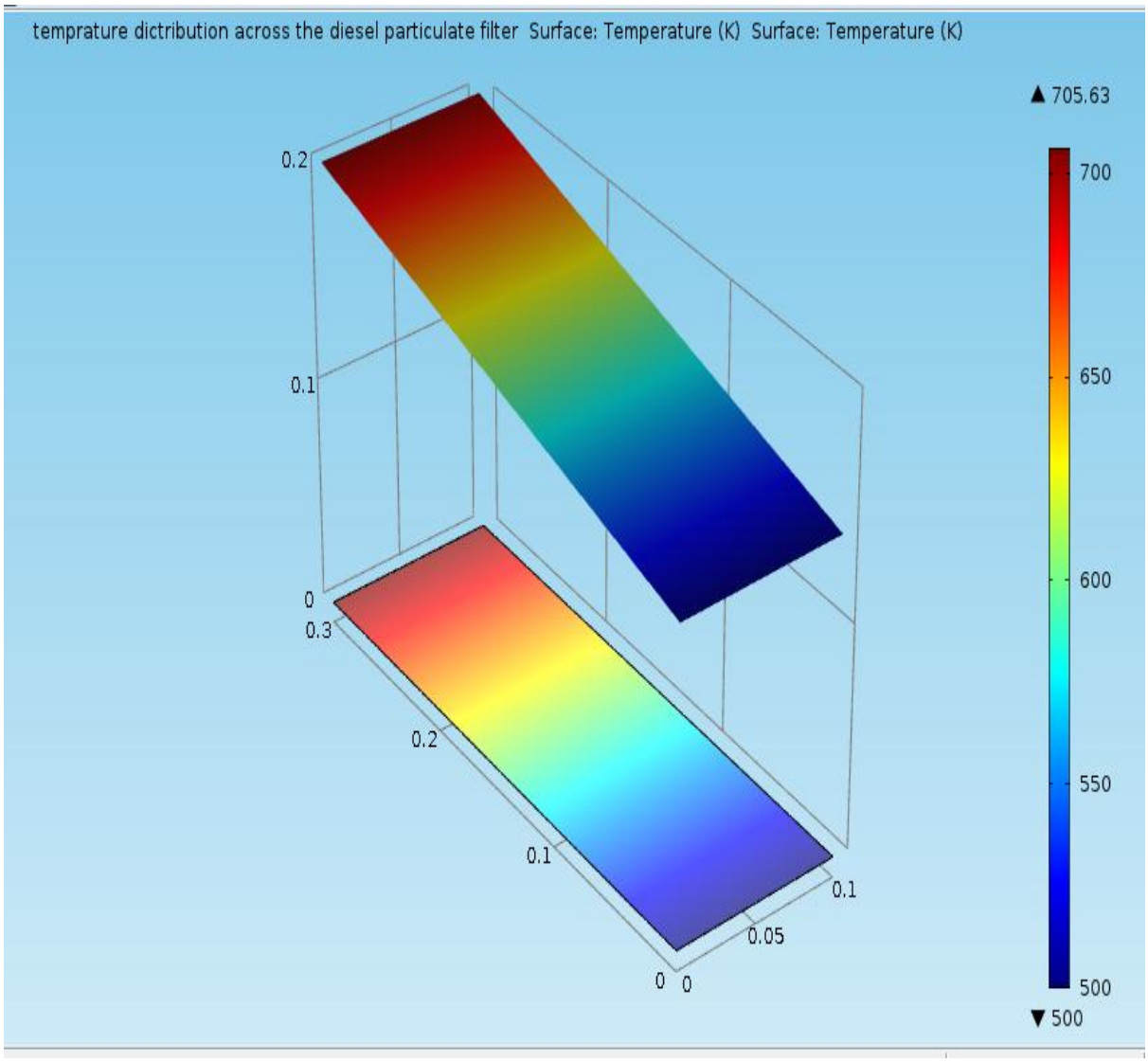

Figure 4.8b surface plot of temperature distribution across diesel particulate filter

CHAPTER FIVE

5.1Conclusion

This paper gives clear understanding of diesel engine particulate matter emission and its negative impact. In addition, the application of diesel particulate filter in particulate matter emission control and the need for diesel particulate matter regeneration system design in diesel particulate filter is studied. The filter design parameters for save exhaust gas regeneration of diesel particulate filter like filter size and cell density and configuration are considered. The mass based particulate matter emission is analyzed, which means (36.01g/hr) or 5.2(g/l) is collected per volume of filter in one hour. For filter filtration efficiency above 85% the amount of PM released to the atmosphere ($\leq$ 0.06 g/bkwhr) so, agreed with Europe emission standards (0.05g/bkwhr) on diesel particulate matter emission control legislation.

Using the soot layer thickness model on filter wall, the pressure drop (2.81kpa) across Diesel particulate filter channel is predicted. As described in Mayer, A., 2004 of reference [29] the Mufflers generally result in maximum back pressures of 6 kPa and diesel engines ranging in size from 15 to over 1000 kW have back pressure limits ranging from 6.7 to 10.2 kPa.so that The result obtained with the muffler‘s is in range of recommended back pressure limits. Therefore, this used as an input for studying the particulate matter regeneration systems/ removing condition in diesel particulate filter. And the regeneration behavior of diesel particulate filter using comsol multiphysics is analyzed. The effects of exhaust gas velocity flow profile and its effects on mass concentration distribution (maximum of 12.5 mil (mol/m^3) and 5mil (mol/m^3) the oxidation of particulate matter trapped is visualized in the filter model.

Therefore since the oxidation reaction of particulate matter trap in filter generates heat in addition to diesel exhaust gas temperature, the overall temperature of the system is increased (705K/430^{o}c). As Explained by J.lemaire and M.khaire, 1994, the Exhaust temperatures above 550^{o}C are required for soot oxidation by oxygen. With the application of “oxidation catalysts”, the required temperature can be lowered to around 400–450^{o}C which is in similar range.

From the passive regeneration system applied the Nobel metal catalyst coated on the filter porous membrane initiates the burning-off particulate matter and lower the oxidation temperature

of PM .finally this overall regeneration system provides the filter channel in normal filtration without over loaded with PM and clean the diesel particulate filters under normal engine operation condition. This will help in controlling the environmental and health problem happen due to particulate matter emission from diesel engine exhaust.

5.2 Recommendation

The experimental part of this work should be conducted by using passive type regeneration system strategy. The filter substrate material and design, the catalyst material and catalyst coating methodology should be applied as per described in literature review. By considering the soot mass distribution behavior, the filter part should be coated with catalyst based on the regeneration profile obtained. Since the life of filter depends on the life catalyst used,It should be take service periodically to keep in clean condition from ashes . this makes it active when in contact with the soot trap at the temperature of the exhaust gases. The PM emission level from diesel engine in Ethiopian should be experimentally conducted and the Ethiopian PM Emission control legislation standards should be proposed.

REFERANCES

[1] Majewski WA (2004) What are Diesel emissions (Ecopoint Inc. Revision 1999.09a) In: DieselNet Technology Guide www.dieselnet.com=tech=emi_into.hmtl (accessed 26. 04. 014)

[2] Maynard RL, Howard CV (eds) (1999) Particulate Matter: Properties and Effects upon Health, Oxford

[3] Wichmann HE et al (2000) Daily mortality and fine and ultrafine particles in Erfurt, Germany.Part I: Role of particle number and particle mass. Health Effects Institute Research Report 98

[4] IPCC, Climate Change (2001) The Scientific Basis, Cambridge University Press, New York

[5]Johnson, T. V., Review of diesel emissions and control, international Journal of Engine Research 2009 10: 275

[6]Johnson, Diesel emission control in review. US Dept. of Energy Diesel Engine Efficiency and Emissions Reduction (DEER) Conference, Detroit, August 2006.

[7] Joerg Adler, Ceramic Diesel Particulate Filters, Int. J. Appl. Ceram.Technol., 2 [6] 429– 439 (2005)

[8] K. Theinno , S. S. Gill,A. Tsolakis, A .P. E. York and A. Megaritis Diesel Particulate Filter Regeneration Strategies: Study of Hydrogen Addition on Biodiesel Fuelled Engines , American Chemical Society January 20, 2012

[9] Athanasios G. Konstandopoulos, Fundamental Studies of Diesel articulate Filters: Transient Loading, Regeneration and Aging ,SAE 2000 World Congress Detroit, Michigan March 6-9, 000

[10]Yeon Hwang, Dae-Sik Kang, Hyoung-Gwon Choi, and ChoongHoon Lee ,Ceramic Diesel Particulate Filter Structure with Inclined Gas Paths,Journal of the Korean Ceramic Society Vol. 49, No. 3, pp. 226~230, 2012.

[11]Koltsakis, G., Stamatelos, A., “Catalytic Automotive Exhaust After treatment”, Progress in Energy and Combustion Science, v 23, n 1, 1997, p 1-39.

[12] Law M.C., Clarke, A., Garner, C.P.,“A Diesel Particulate Filter Regeneration Model with a Multi-step Chemical Reaction Scheme”, Proc. Imech E. Part D: Automobile Engineering. v 219.

[13]Johnson M.“Catalytic Coatings for Active and Passive Diesel Particulate Filter regeneration”,, Environmental Catalysts and Technologies, Royston,SG8 5HE, United Kingdom Royston,SG8 5HE, United Kingdom, MonatsheftefeurChemie 136, 91–105 (2005)

[14] Joe K. “Clean Diesel Emission Control Technologies”, Manufacturers of Emission Controls Association,EPA Marine Emissions Seminar: Mexico City September 26, 2012

[15]OLKSWAGEN AG. “Self-study programme336 on the catalytic coated diesel particulate filter”, Wolfsburg, VK-21 Service Training

[16]Herzog P et al. (2000) “Exhaust After treatment Technologies for HSDI Diesel Engines”, ATA Conference, Olbia

[17] Majewski WA (2004) “Plasma Exhaust Treatment”. In: Diesel Net Technology Guide (Ecopoint Inc. Revision 2002.12a) http: www.dieselnet.com:tech=plasma.html#pm 11.

[18] PenetranteBMet al (2000) “Plasma Regenerated Particulate Trap and NOx Reduction System”, US Patent (Lawrence Livermore National Laboratory) 6,038,854

[19] J.Hoard “plasma –catalyst for Diesel Exhaust Treatment: current state Of ART”SAE paper 2001-01-0185;Detroit USA 2001.

[20] T.seguelong and P.Fournier-Bidoz “use of Diesel Particulate Filter and Cerium –based Fuel borne catalyst for low temperature –low load application.

[21] J.lemaire and M.khaire “effect of cerium additive on the emission characteristics of a heavy -duty diesel engine” SAE paper 942067; Detroit USA 1994.

[22]Bosch automotive Hand book -4th edition SAE;ISBN 1560919183;Germany 1996.

[23]T.Jonson “Diesel emission control in Review ”SAE paper 2000-01-0184;Detroit UAS2000

[24] J.Green, J.Stoney ,and R.wagner “Macro wave regenerated Diesel Exhaust particulate filter” SAE paper 2001-01-0903;Detroit USA 2001

[25] Heeb, N.V., Zennegg, M., Haag, R., Seiler, R., Schmid, P., Wichser, A., Ulrich, A., Honegger, P., Zeyer, K., Emmeneggererb, L., Zimmerli, Y., Czerwinski, J., Kasper, M. and Mayer, A., 2011. “Parameters affecting the dioxin formation in diesel particle filters”, Proc. 15th ETH Conference on Combustion Generated Nanoparticles, Zurich, June 26-29, 2011

[26] ARB, 2011. “LEV III PM Technical Support Document: Appendinx P”, California Air Resources Board, December 7, 2011,

[27] Kittelson, “Engines and Nanoparticles: A Review”, J. Aerosol Sci., 29(5/6), 575-588, 1998.

[28] elles, S.J. 1999. Development of catalytic systems for diesel particulate oxidation, Ph.D. Thesis, Delft University of Technology, Delft.

[29] Www.DieselNet.com. Copyright © Ecopoint Inc. Revision 2004.07c ,2007.03a

[30] Stefan Ebener,Ceramic catalyst supports and particulate Filter for Diesel Engine Exhaust Aafter traeatmen,internal combustion engine,volume-7,No 1-2,2000

[31] avid C., Emad A., Jason H," particulate matter emission profiles of Alberta heavy duty vehicles, " Environment Research Group Department of Mechanical Engineering University of Alberta " Pub. No: T/610, ISBN: 0-7785-1728-4

[32]A.G. Konstandopoulos, E. Papaioannou,"Update on the science and technology of diesel particulate filters",Hosokava Pow der Technology Foundation, KONA Powder and Particle Journal,vol.26,pp.36-65, 2008.

[33] L. Tartakovsky, S. Hausberger, M. Gutman, M. Veinblat, and Y. Zvirin,"Retrofit aftertreatment systems for diesel engines", in Proceedings of the 14th International Scientific Symposium on Transport and Air Pollution, pp.221 -230,2005.

[34] K Sung, J Kim, R D Reitz,"Experimental study of pollutant emission reduction for near -- toichiometric diesel combustion in a three -way catalyst",SAGE Journals, International Journal of Engine Research, vol.10, no.5,pp.349-357, 2009.

[35] J. Warner, D. Dobson, G. Cavataio,"A Study of Active and Passive Regeneration Using Laboratory Generated Soot on a Variety of SiC Diesel Particulate Filter Formulations", SAE International Journal on Fuels &Lubricants, vol.3, no.1, pp.149 -164, SAE Paper 2010 -01 -0533,2010.

[36] H Kato, K Ito, H Suda, J Kusaka, T Mori, F Tsurumi, N Masaki, K Hirata, H Akagawa, "Development of a Quasi-Two -Dimensional Model for Analyzing Continuous Regeneration—Diesel Particulate Filter States during Continuous and Active Regeneration", SAGE Journals, International Journal of Engine Research, vol.12,no.1,pp.1 -13,2011.

[37] P. Roth, T. Eckhardt, B. Franz, J. Patschull,"H2O2-assisted regeneration of diesel particulate traps at typical exhaust gas tempe ratures", Elsevier, Combustion & Flame,vol.115, p.28,1998.

[38]H. Christensen, J. Dinesen, H. Engell, K. Hansen,"Electrochemical reactor for exhaust gas Purification", SAE Technical Paper, 1999 -01-0472, 1999.

[39] B. W. L. Southward, S. Basso, M. Pfeifer,"On the de velopment of low PGM content direct soot combustion catalysts for diesel particulate filters", SAE Technical Paper, 2010-01-0558, 2010.

[40] L. Rocher, T. Seguelong, V. Harle, M. Lallemand, M. Pudlarz, M. Macduff,"New generation fuel borne catalyst for reliable DPF operation in globally diverse fuels", SAE Technical Paper, 2011 -01 -0297, 2011.

[41]P.Hawker, N. Myers, G.Huthwohl, H. Vogel, B.Bates, L. Magnusson, P. Bronneberg,"Experience with a new particulate trap technology in Europe", SAE Technical Paper, 970182,1 997.

[42] A. Messerer, R. Niessner, U. Posch,"Comprehensive kinetic characterization of the oxidation and gasification of modeland real diesel soot by nitrogen oxides and oxygen under engine exhaust conditions: measurement , Langmuir Hinshel wood and Arrhenius parameters",Elsevier, Carbon,vol.44,pp.307 -324, 2006.

[43] Avila, P., Montes, M. and Miro, E., 2005, Monolithic reactors for environmental applications - a review on preparation technologies, Chemical Engineering Journal, 109 (1-3),

[44] M.Ahmadinejad,Becker,C.F.Goersmann,A.D.Newman,T.C.Watling,"Modeling of soot oxidation by NO2 in a Diesel Particulate Filter", SAE 2011-01-2083, pp. 115-125, 2011.

[45] Johnson JH, Konstandopoulos AG. A Study Describing the Performance of Diesel Particulate Filters During Loading and Regeneration- A Lumped Parameter Model for control Applications. SAE Journal. 2003; 2003010842.

[46]Masoudi M. Pressure Drop of Segmented Diesel Particulate Filters . SAE Journal. 2005;2005010971.

[47] Johnson JH, Naber JD, Bagley ST. A Methodology to Estimate the Mass of Particulate Matter Retained in a Catalyzed Particulate Filter as Applied to Active Regeneration and On-Board Diagno stics to Detect Filter Failures . SAE Journal. 2008;2008010764.

[48] A.G. Konstandopoulos, J.H. Johnson,"Wall-flow diesel particulate filters – their pressure drop and collection efficiency", SAE Technical Paper, 890405,pp.625-647,1989.

[49] A.G. Konstandopoulos, M. Kostoglou,"Reciprocating flow regeneration of soot filters", Elsevier , Combustion and Flame, vol.121, pp.488-500, 2000.

[50] P. Darcy, P. Da Costa, H. Mellottee, J.M. Trichard, G. Djega-Mariadassou,"Kinetic of catalyzed and non-catalyzed oxidation of soot from a diesel engine",Elsevier, Catalysis Today,vol.119, pp.252-256,2007.

[51]Maricq, M.M. 2007.Chemical characterization of particulate emissions from diesel engines: A review, Aerosol Sci. 38: 1079-1118. [13] Kittelson, D.B.1998. Engine

[52]ECMA-Indian Emission Standards. 2010. http://www.ecmaindia.in.

Appendix –A

Diesel particulate filter regeneration system modeling in comsol multiphysics Starting comsol multi physics.

In the Model Navigator go to the Space dimension list and select 3D.

From the Application Modes list, select Chemical Engineering Module>Mass Transport>Convection and Diffusion> time dependents

- Type $co_{2,1}$,$co_{2,2}$ in the Dependent variables edit field, and Type o_2 in the Application mode name edit field. Click Add.
- From the Application Modes list, select Chemical Engineering Module>Mass Transport>Convection and Diffusion>time dependent analysis
- Type c_s in the Dependent variables edit field and soot in the Application mode name edit field.
- Click the Add Geometry button. Select 2D from the Space dimension list, and then click OK. Click OK to close the Model Navigator and launch the main user interface.

Options and setting

From the Options menu, select Constants. Click the Import Variables from File button in the lower left of the Constants dialog box and

- Select the DPF file .txt to import parameters of exhaust gas, filter and soot trap which located in the same Model Library folder as the MPH-file(as shown in the table below).

Click Open.

- Alternatively, enter the parameter names and values in the Constants dialog box given:

NAME	EXPRESSION	DESCRIPTIO
p_{atm}	1.013e5[Pa]	Ambient pressure
P_1	0.31[kPa]	Pressure , inlet channel
P2	0.23[kPa]	Pressure , outlet channel
T_{inlet}	500[K]	Inlet temperature to filter channel

R_g	8.314[J/(mol*K)]	Gas constant
M_{gas}	29[g/mol]	Molar mass, gas
k_{gas}	0.025[W/(m*K)]	Thermal conductivity, gas
$Cp_{gas.}$	1.2[kJ/(kg*K)]	Heat capacity, gas
k_m	50[W/(m*K)]	Thermal conductivity, membrane
rho_m	4e3[kg/m^3]	Density, filter membrane
Cp_m	2[kJ/(kg*K)]	Heat capacity, filter membrane
k_m	1e-12[m^2]	Permeability, filter membrane
α	2.54[mm]	Channel height
μ	3e-5[Pa*s]	Viscosity, gas
T_{atm}	300[K]	Ambient temperature
hg	1500[W/(m^2*K)]	Heat transfer coefficient, filter/gas
Ds	1e-5[m^2/s]	Diffusion coefficient, soot
k_{appas}	1e-13[m^2]	Permeability, soot layer
rho_s	2e3[kg/m^3]	Density, soot layer
Ms	12[g/mol]	Molar mass, soot
Ds	1e-8[m^2/s]	Diffusion coefficient, soot layer
Do2	1e-5[m^2/s]	Diffusion coefficient, O_2
c_o2in	$0.08*p_{atm}/(Rg*T_{inlet})$	Concentration of O_2 at inlet
H_{ox}	30[kJ/mol]	Reaction enthalpy

- From the Options menu select Expressions>Global Expressions.
- Enter the following parameter names and values in the Global Expressions dialog box.

name		expression		description
rho_1		$(p_{atm}+p1)*M_{gas}/(Rg*T1)$		Gas density, inlet channels
rho_2		$(p_{amb}+p2)*M_{gas}/(R_g*T2)$		Gas density, outlet channels
v_1		$-\frac{k}{\mu}\Delta p_{\text{inlet}}$		Velocity, out let channel
v_2		$-\frac{k}{\mu}\Delta p_{\text{out let}}$		velocity, outlet channels
k_{ox1}		Ko2*T*exp(-Eact(Rg*T))		Oxidation rate constant with catalyst
k_{ox2}		Ko2*T*exp(-Eact(Rg*T))		Oxidation rate constant without catalyst
Rs1		$k_{ox}*c_{o21}$		Oxidation rate
Rs2		$k_{ox}*c_{o21}$		Oxidation rate
Q_{ox1}		Rs*H_{ox}		Heat generated by oxidation

Geometry modeling

- Click the Geom2 tab.
- From the Draw menu, select Work-Plane Settings.
- In the Work-Plane Settings dialog box, click the y-z option button. Click OK.
- Press the Shift key and click the Rectangle/Square button on the Draw toolbar.
- Type the following values in the corresponding edit fields for the rectangle
    - dimensions:

Width x	0.1	position	0
Height z	0.3	position	0

    - Click OK.

Meshing the model

From the Mesh menu, select Boundary Layer Mesh Parameters. In the dialog box that appears, go to the Boundary page.

- Select Boundary 3 from the Boundary selection list.
- Type 1.5 in the Stretching factor edit field.
- Type 3 in the Number of layers edit field.
- Clear the check boxes for boundaries 1 and 2 in the Boundary selection list.

- Click the Sub domain page.
- Select Sub domain 1 from the Sub domain selection list, then select Extra coarse from the Predefined mesh sizes list.
- Click the Re mesh button.
- When the mesh has finished, click OK.

Physics Settings

Sub domain Settings-Convection and Diffusion, From the Multiphysics menu, select Convection and Diffusion (oxygen species) .

- Select all entries in the Sub domain selection list
- On the c_page, click the D (anisotropic) option button, then access the Diffusion Coefficient matrix by clicking in the edit field.
  - Type D_{o2} in the first column of the first row. Set all other matrix elements to 0 .
  - Type $-(4/\alpha)*v_m*co_{2,1} - (4/\alpha)*Rs$ in the R edit field.
  - Type v1 in the u edit field. Click the Artificial Diffusion button.
  - Select the Isotropic diffusion check box and type 0.1 in the Tuning parameter edit Field.Click the $co_{2,2}$ tab.
  - Click the D (anisotropic) option button, then access the Diffusion coefficient matrix by clicking in the edit field.
    - Type Do_2 in the first column of the first row. Set all other matrix elements to 0 .
    - Type $(4/\alpha)*v_m*co_{2,1}$ in the R edit field.
    - Type v_2 in the u edit field.
    - Click the Artificial Diffusion button.
    - Select the Isotropic diffusion check box and type 0.1 in the Tuning parameter edit field. Click OK.
- Click OK to close the Sub domain Settings dialog box.

Boundary Conditions setting

From the Physics menu, select Boundary Settings. Convection and Diffusion

- Enter boundary conditions for $co_{2,1}$ according to the following table:

Settings	boundary 1(inlet)	all others
Boundary condition No	Flux co_{2in}*v1	Insulation/Symmetry

Enter boundary conditions for $co_{2,2}$ according to the following table:

Settings	boundary 4 (outlet)	all others
Boundary condition	Convective flux	Insulation/Symmetry

- Click OK.
  - Sub domain Settings-Convection and Diffusion
  - From the Multiphysics menu, select Convection and Diffusion (soot) .
  - From the Physics menu, select Sub domain Settings .
  - Click the D (anisotropic) option button, then access the Diffusion coefficient matrix by clicking in the edit field.
  - Type Ds in the first column of the first row. Set all other matrix elements to 0 .
  - Type $-(4/\alpha)*cs*v_m$ in the R edit field.
  - Type v1 in the u edit field.
  - On the Init page, type cs0 in the Concentration, c_s edit field. Click OK.
  - Boundary Conditions-Convection and Diffusion
  - From the Physics menu, select Boundary Settings.
  - Enter boundary conditions according to the following table; when done, click OK.

Settings	boundary 1	all other boundaries
boundary condition	concentration	insulation/symmetry
c_{so}	c_{so}	

Boundary From the Physics menu, select Boundary Settings .

Enter boundary conditions according to the following table; when done, click OK

boundary condition	te m p e r a t u r e	thermal insulation
	T0	T_{inlet}

- From the Multiphysics menu, select Convection and Conduction for filter membrane.
- From the Physics menu, select Boundary Settings.
- Enter boundary conditions according to the following table; when done, click OK.
- Boundary conditions-convection and conduction
- From the Physics menu, select Boundary Settings
- Enter boundary conditions according to the following table; when done, click OK.

settings	boundary 1	all other boundaries
boundary condition	te m p e r a t u r e	thermal insulation
T0	T_inlet	

From the Multiphysics menu, select Convection and Conduction (E_mem) .

From the Physics menu, select Boundary Settings

Enter boundary conditions according to the following table; when done, click OK.

settings	boundary 1	boundary 4	boundary 5
boundary condition	heat flux	heat flux	heat flux
q_0	-hg*(t -t1)	-hf*(t -tamb)	-hg*(t -t2)

settings	boundaries 2, 3
Boundary condition	Thermal Insulation

- From the Physics menu, select Boundary Settings. Enter boundary conditions according to the following table; when done, click OK

SETTINGS	BOUNDARY 5	ALL OTHER BOUNDARIES
Boundary condition	Convective flux	Thermal Insulation

Adding Study to the model

- Click the Solver Parameters button on the Main toolbar.
- Delete all the predefined groups in the segregated groups area by clicking the Delete button of each group.

group	group component
1	co21 , co22
2	cs
3	T

- for the first group, click the Settings button, then select Direct (PARDISO) from the Linear system solver list. Click OK
- On the Solve for page of the Solver Manager, select all the application modes.
- Go to the Initial Value page, and click the Store Solution button at the bottom of the page.
- Click the Stored solution option button in the Initial value area.
- Click OK to close the Solver manager dialog box.
- Click the Solver Parameters button on the Main toolbar.
- From the Solver list, select Time dependent.
- In the Times edit field, type range(0,90,900)s.
- Type 1e-5 in the Relative tolerance edit field and 1e-6 in the Absolute tolerance edit
    - Select Direct (PARDISO) from the linear system solver list. Click OK. Click the Solve button on the Main toolbar.

Result visualization

To generate the velocity-field boundary plots in Figure 4.3, follow these steps:

- Click the Plot Parameters button on the Main toolbar.
- On the General page, clear the Slice check box and select the Boundary check box.
- From the Solution at time list, select 0.
- On the Boundary page, type u in the Expression edit field.
- Similarly, reproduce the plots in Figure 4.6,Figure 4.5 and figure 4.8 by typing cs ,co_{21} and T in the Expression edit field, respectively

Appendix-B

Emission test vehicles / engines under 6-mode

The test vehicles and engines were chosen to cover a range of vehicle technologies and age. Five diesel-powered, currently licensed road vehicles were rented briefly for testing and one diesel engine was tested on an engine dynamometer [31].

These six test vehicles / engines tested, (in chronological order of testing), were:

1. 1999 Ken worth T800 Tractor unit with Cummins N14 460 engine
2. 1999 Ken worth T800 Tractor unit with Detroit Diesel Series 60 engine
3. 1994 Ken worth T800 Tractor unit with Caterpillar 3406 engine
4. 1993 Ken worth T800 Tractor unit with Detroit Diesel Series 60 engine
5. 1992 Dodge 3/4 Ton pickup with Cummins turbo diesel engine
6. 1993 Isuzu 4BE1 3.6L, naturally aspirated engine (from Isuzu ELF 250 2 ton truck)

This range of vehicles was chosen to cover a representative range of manufacturers, technologies and vehicle ages typical of the current diesel-powered fleet. The first five engines are all turbocharged and intercooled while the sixth is naturally aspirated. Fuel injection systems range from mechanical pump injection to electronically controlled unit injection systems. Age ranged from two to eight years covering the majority of active, high-mileage vehicles. For one of the more modern engine types,(Detroit Diesel Series 60), both a relatively new unit and a higher-mileage unit were tested, giving a measure of the effect of age on newer vehicles.

Emission test standards and conditions

The basic approach to testing was to run each engine at 6 steady-state test modes which were chosen to cover a range of speed and power levels. The speed and power levels were chosen to generally comply with the Japanese 6-mode test procedure which is a certification test standard formerly used in Japan. (The test is no longer used for certification, having been replaced with a 13-mode test during the 1990's. However, it is still generally useful for representing an engine at a range of test loads and speeds which covers normal operation.) For the formal test, the six test modes would be chosen as in Table3.3.

Mode	CO	CO2	HC	NOx	O2	Filter Soot
	(g/s)	(g/s)	(g/s)	(g/s)	(g/s)	(g/s)
1	0.01	0.92	0	0.010	13.3	3.73
2	0.61	40.1	0	0.347	17.3	66.5
3	0.02	17.2	0	0.226	18.8	34.9
4	0.31	44.8	0	0.417	25.6	44.6
5	0.02	17.8	0	0.255	24.3	9.90
6	0.02	22.1	0	0.284	29.6	17.8

Emission in grams/second for older Detroit Diesel Engine on 6-Mode Test Using shell Diesel (water ous, 9:00AM, March 1, 2001).

Declaration

I hereby declare that the work which is being presented in this thesis entitled, **‘‘Exhaust Gas regeneration system Design in Diesel Particulate Filter’’** work of my own, has not been presented for a degree of any other university and all the resource of materials uses for this thesis have been duly acknowledged.

Beruna Bayisa Date

_____ _____

This is to certify that the above declaration made by the candidate is correct to the best of my knowledge.

Prof .Eyassu Woldesenbet Date

_____ _____