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Design Optimization of Diesel Particulate Filter Using CFD

Mr. Y. Rajasekhar Reddy *, Mr. K. Srinivasa Chalapathi ** Mr. S.Jush kumar***

*Asst Prof (Department of Mechanical Engineering, Anurag Group of Institutions, Hyderabad, RR dist, Telangana,)

** Assoc Prof & Head (Department of Mechanical Engineering, Anurag Group of Institutions, Hyderabad, RR dist, Telangana)

***Asst Prof (Department of Mechanical Engineering, Anurag Group of Institutions, Hyderabad, RR dist, Telangana,)

ABSTRACT

The diesel particulate filter (DPF) is a device designed to remove diesel particulate matter or soot from the exhaust gas of a diesel engine. A series of tests have been performed on a downscaled DPF prototype. This prototype had high filtration efficiency. Then the next step is to study the soot and ash handling capacity of DPF system and perform tests on a full-scale prototype. In order to move forward to the next step the functionality of the filter should be investigated. Moreover, a complete model of flow inside the filter can help parameter investigation on both downscale and full-scale prototype. Building up a CFD model using fluent which is capable to simulate the flow through all channels and porous media of the filter plates and tuning the pressure drop parameters for all steps of filtration from clean filter to dirty one are the main achievements of this project. CFD results have been tuned by using experimental data of filtration tests.

Keywords - **CFD, DPF, Filter plates, Solid works.**

I. INTRODUCTION

The first effort at controlling pollution from automobiles was the PCV (positive crankcase ventilation) system. This draws crankcase fumes heavy in unburned hydrocarbons ─a precursor to photochemical smog into the engine's intake tract so they are burned rather than released unburned from the crankcase into the atmosphere. Positive crankcase ventilation was first installed on a widespread basis by law on all new 1961-model cars first sold in California.

As the technology keeps on evolving and emerging, it carries along undesirable effects apart from its broad application and use. One of the main contributors is said to be emissions of automobiles. The number of miles that vehicles travel per year continues to increase as a result of higher demand and needs. Consequently this gives rise to increased pollution every year.

The rapid growth of population and industries in India during the last 2 decades has resulted need for adequate man transport facilities for quick movement of men and material. The diesel engine has always been preferred prime mover for transporting of heavy loads due to its superior fuel economy. The diesel exhaust is objected by the public due to following reasons.

1. It causes reduction in visibility. It may thus constitute a traffic hazard also.
2. It has disagreeable odor due to the presence of aldehydes, ketones and oxygenated compounds.
3. The smooth particle in the exhaust gases settle down on building and trees etc in the vicinity Of sources.
4. The diesel smoke is dangerous for health and cause trouble in breathing.

DIESEL PARTICULATE FILTER

Diesel particulate filters (DPF) are devices that physically capture diesel particulates to prevent their release to the atmosphere. Diesel particulate filter materials have been developed that show impressive filtration efficiencies, in excess of 90%, as well as good mechanical and thermal durability. Diesel particulate filters have become the most effective technology for the control of diesel particulate emissions—including particle mass and numbers—with high efficiencies.

Due to the particle deposition mechanisms in these devices, filters are most effective in controlling the solid fraction of diesel particulates, including elemental carbon (soot) and the related black smoke emission. Filters may have limited effectiveness, or be totally ineffective, in controlling non-solid fractions of PM emissions—SOF and sulfate particulates. To control total PM emissions, DPF systems are likely to incorporate additional functional components targeting the SOF—typically oxidation catalysts—while ultra-low sulfur fuels may be required to control sulfate particulates.

The term "diesel particulate trap" is sometimes used as a synonym for "diesel particulate filter", especially in older literature. The term "trap" covers a wider class of particle separation devices. Several particle deposition mechanisms other than filtration are commonly employed in industrial dust separation equipment. Examples include gravity settling, centrifugal separation, or electrostatic trapping. None of these techniques could be adopted to control diesel PM emissions, due to the small particle size and low density of diesel soot.

It may be noted that *particle oxidation catalysts* (POC)—sometimes called *partial filters*—can also capture diesel particulates, but provide a much lower overall efficiency than diesel particulate filters. In their common designs, POCs capture particulates only from a fraction of the flow, whereas the total flow is filtered in diesel particulate filters. In the case of some filter media, however, the distinction may not be very clear and the devices can be classified as either a POC or a (depth) particulate filter.

The catalytic converter

Diesel particulate filters

Unlike a catalytic converter which is a flow-through device, a DPF retains bigger exhaust gas particles by forcing the gas to flow through the filter however, the DPF does not retain small particles and maintenance-free DPFs break larger particles into smaller ones. There are a variety of diesel particulate filter technologies on the market. Each is designed around similar requirements:

1. Fine filtration
2. Minimum pressure drop
3. Low cost
4. Mass production suitability
5. Product durability

II. DESIGN OF DIESEL PARTICULATE FILTER

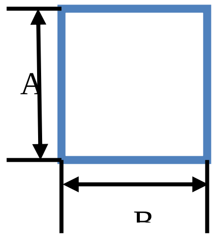
1. Design Calculations

The cylindrical shape was considered due to ease of fabrication, minimum assembly time, rigidity and easier maintenance.

Shell dimensions
The shell is the central cylindrical part between inlet and outlet cone
D= diameter of filter.
L= length of the channels
DIAMETER: 100mm
Length: 150mm
Channel size: 1.5mm, 1.2mm
Thickness of the channels: 4mm, 5mm

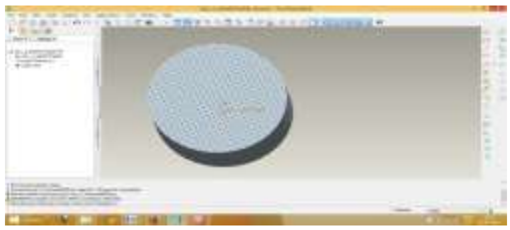
PARAMETERS	At 5mm,4mm Distance between channels	
A(mm)	1.5	1.2
B(mm)	1.5	1.2
Cell Length (mm)	150	150
Cell Density (cpsi)	88	100

Wire mesh Geometry

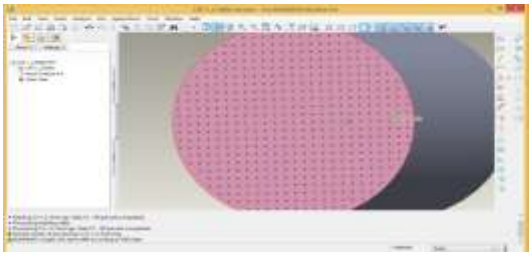


1.2 Models of DIESEL PARTICULATE FILTER

Design of Triangular cells of 1.2mm size and 5mm distance between channels



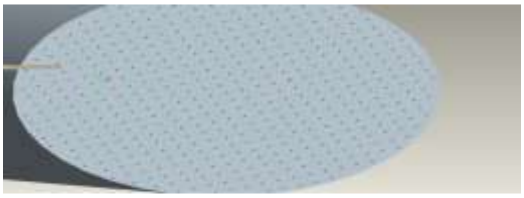
Design of square cells of 1.2mm size and 5mm distance between channels



Design of circular cells of 1.2mm size and 5mm distance between channels

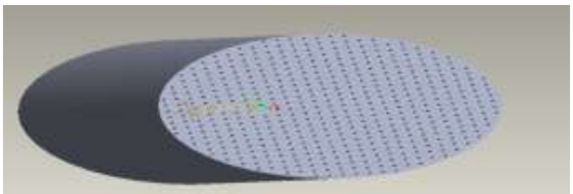
Design of circular cells of 1.2mm size and 4mm distance between channels

Design of square cells of 1.2mm size and 4mm distance between channels

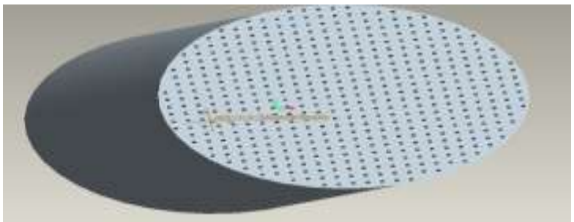


Design of triangular cells1.2mm size and 4mm distance between channels

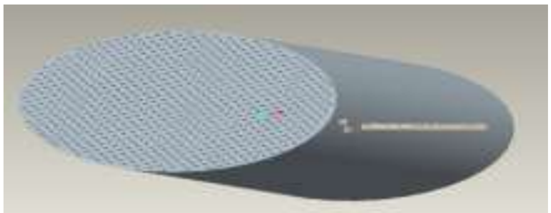
Design of circular cells of 1.5mm size and 4mm distance between channels



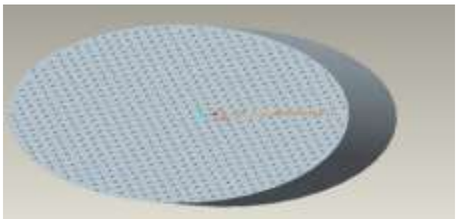
Design of circular cells of 1.5mm size and 5mm distance between channels



Design of square cells of 1.5mm size and 5mm distance between channels



Design of square cells of 1.5mm size and 4mm distance between channels



Design of Triangular cells of 1.5mm size and 4mm distance between channels

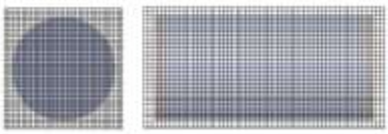
Design of Triangular cells of 1.5mm size and 5mm distance between channels

IV. Optimization of Geometries Using Solid Works Flow Simulation Software

1 Solid work Models

Computational Domain

Four types of honeycomb monolith structures were employed in the current study. One is square-shaped, second is triangular, and third is circular. The channels was built using the solid works flow simulation, which is shows in four channels.



Mesh of Diesel particulate Filter

Fluid cells: 375213
Solid cells: 172658
Partial cells: 268425
Total cells: 816296.

2. Boundary conditions for channels:

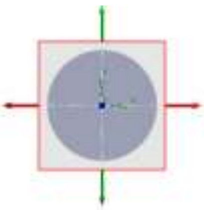
An inlet was defined as the flow regime in the subsonic with an assumed uniform velocity of 10 m/s and an air inlet temperature of 400 °C (673 K). The air inlet temperature was assumed. As the simulation proceeded, the velocity was changed to 20 m/s. The pressure outlet was set at atmospheric pressure. The wall was defined as a no slip condition at the fixed temperature 400°C (673 K). The fluid properties of air used in the proposed model is given in Tables.

Thermodynamic properties (unit)	Properties
Molar mass (kg/mol)	28.96
Density (kg/m3)	1.205
Specific heat capacity (J/kg·K)	1005
Dynamic viscosity (kg/m·s)	18.207 × 10-6
Thermal conductivity (W/m·K)	0.0257

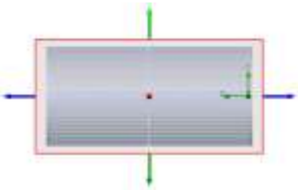
Air properties

Gases	Volume %	Gases pollutants	Volume %
N2 CO2 H2O O2 and noble gas	71 18 9.2 0.7	CO NOx Unburned HCs Particulate Matter Others	0.85 0.08 0.05 0.005 0.115
		Total	100.0

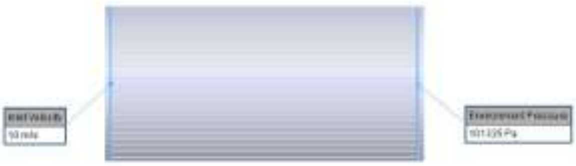
Gases and its Contents



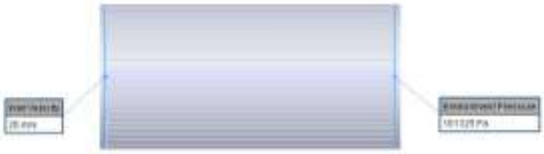
Domain – I



Domain- II



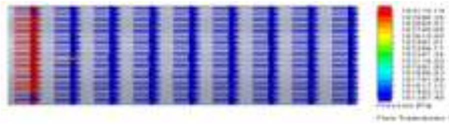
Boundary Condition at 10m/s velocity



Boundary Condition at 20m/s velocity 5.5

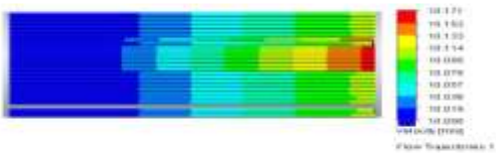
V RESULTS AND DISCUSSIONS

Below figures illustrate pressure counters for 1.5mm size and 5mm distances between channels at 10m/sec velocity

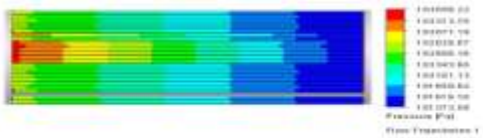


Circular channel at 1.5mm size and 5mm distance between channels at 10m/sec

Square channel at 1.5mm size and 5mm distance between channels at 10m/sec

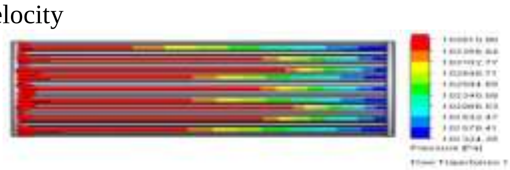


Velocity distribution for Square channel at 1.5mm size and 5mm distance between channels



Pressure drop for Triangular channel at 1.5mm size and 5mm distance between channels

Below figures illustrate pressure counters for 1.5mm and5mm distances between channels at 20m/sec velocity

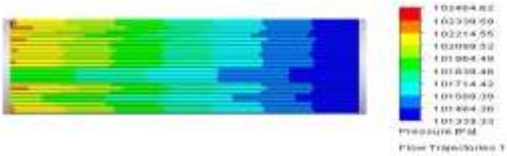


Pressure drop for 1.5mm and 5mm distance between Circular channel at 20m/sec

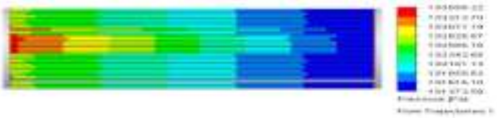
Pressure drop for 1.5mm and 5mm distance between Square channel at 20m/sec

Pressure drop for 1.5mm and 5mm distance between Triangular channel at 20m/sec

Pressure drop for 1.5mm and 4mm distance between circular channel at 20m/sec

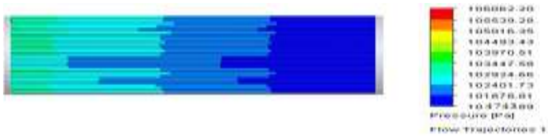


Pressure drop for 1.5mm and 4mm distance between circular channels at 10m/sec



Pressure drop at 1.5mm and 4mm distance between square channel at 20m/sec

Pressure drop for 1.5mm and 4mm distance between triangular channel at 20m/sec



Pressure drop at 1.5mm and 4mm distance between square channel at 10m/sec

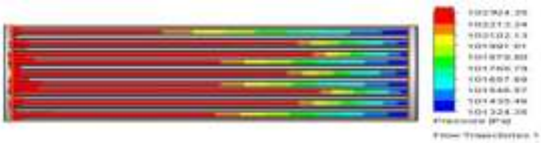
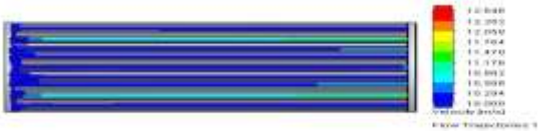
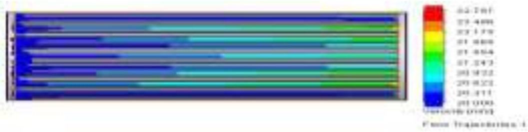


Figure 5.18 Pressure drop for 1.5mm and 4mm distance between triangular channel at 10m/sec

Below figures illustrate velocity counters at 10, 20m/sec for 1.5mm and 4mm distances between channels

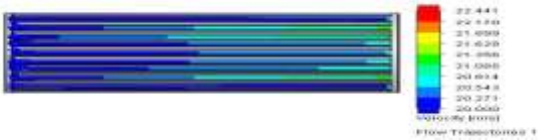


Square channel Velocity distribution at 10m/sec and 4mm distance between channels



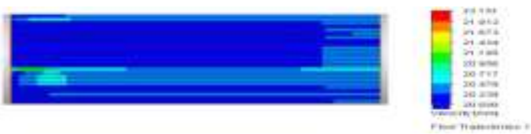
Velocity distribution for square channel at 20m/sec4mm distance between channels

Velocity distribution for circular channel at 10m/sec and 4mm distance between channels

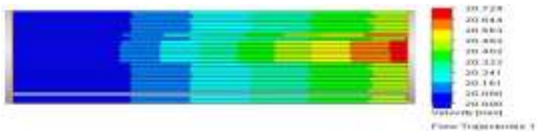


Velocity distribution for circular channel at 20m/sec and 4mm distance between channels

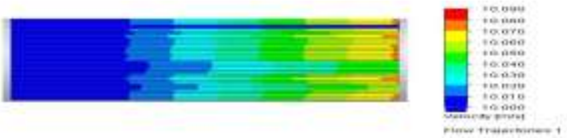
Velocity distribution for Triangular channel at 10m/sec velocity and 4mm distance between channels



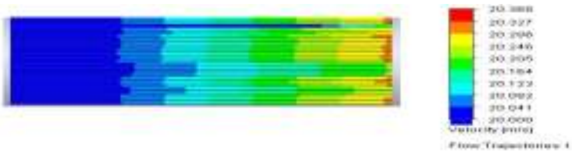
Velocity distribution for Triangular channel at 20m/sec velocity and 4mm distance between channels



Velocity distribution for circular channel at 20m/sec and 5mm distance between channels



Velocity distribution for square channel at 10m/sec and 5mm distance between channels



Velocity distribution for Triangular channel at 20m/sec and 5mm distance between channels

4mm distance between channels with circle, square, triangle: 1.2mm size of circular channel with 10m/s velocity:

Circular channel velocity distribution for 1.2mm size and 4mm distance

Circular channel pressure drop for 1.2mm size and 4mm distance

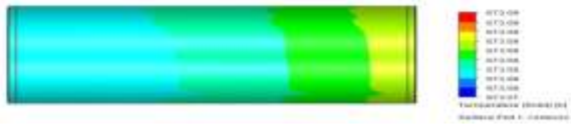
Circular channel temperature distribution

Circular channel Temperature flow trajectory

1.2mm size circular channel with 20m/s velocity

Circular channel velocity distribution for 1.2mm and 4mm distance

circularchannel pressure drop at 1.2mm channel size with 5mm distance between channel



1.2mmcircular channel temperature distribution

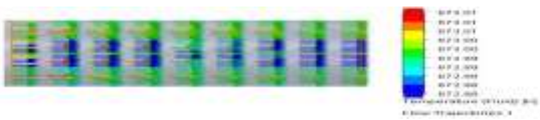
Temperature flow trajectory

1.2mm size of square channel with 10m/s velocity:

Velocity distribution for square channel at 10m/sec velocity

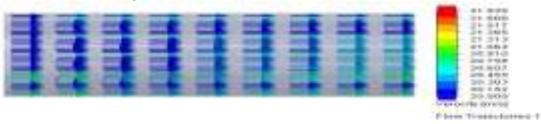
Pressure drop distribution for square channel

Temperature distribution for square channel

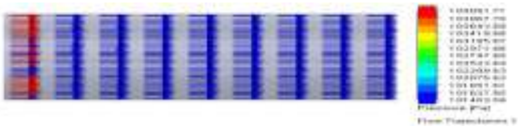


Temperature flow trajectory for square channel

1.2mm size square channel at 4mm distance with 20m/s velocity:

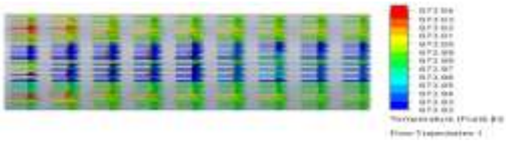


Velocity reduction at 20m/sec



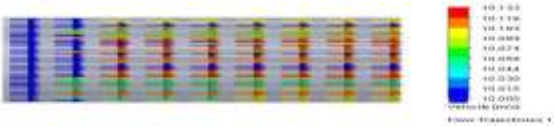
Pressure Drop for square channel at 1.2mm for 4mm distance

Temperature distribution

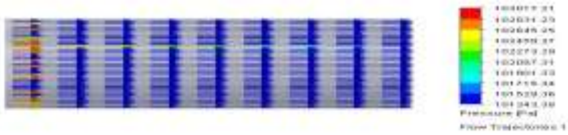


Temperature distribution of fluid

1.2mm size triangular channel with 10m/s velocity:

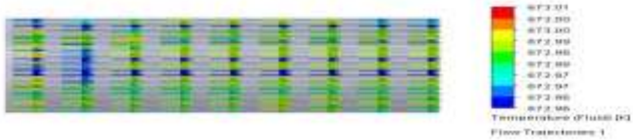


Velocity Reduction for Triangular channel for 1.2mm size channel



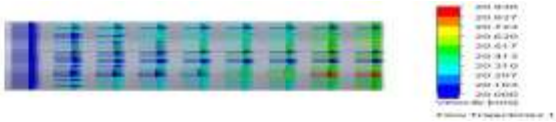
Pressure drop triangular channel at 1.2mm size at 10m/sec

Temperature distribution for triangular channel

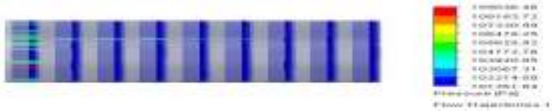


Direction of Temperature distribution

1.2mm size triangular channel with 20m/s velocity

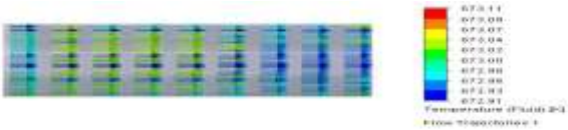


Velocity Flow Trajectory for triangular channel



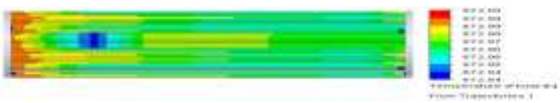
Pressure Drop for triangular channel at 1.2mm size and 4mm distance

Temperature Distribution for triangular channel



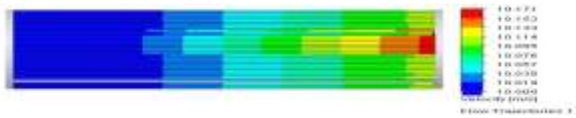
Temperature Flow Trajectory for triangular channel

5mm distance between channels with circle, square, triangle: 1.2mm size of circular channel with 10m/s velocity:

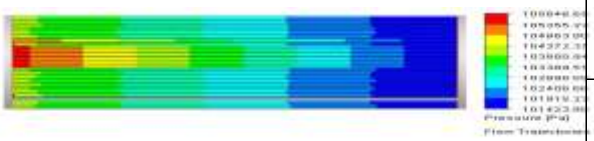


Temperature distribution of fluid for circular channel with1.2mm size and 5mm distance between channels

Temperature distribution for 1.2mm size and 5mm distance between circular channel

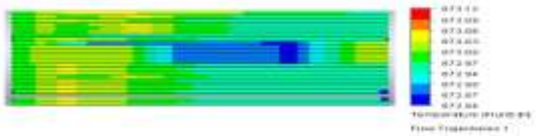


1.2mm size and 5mm distance between circular channel velocity distributions at 10m/sec

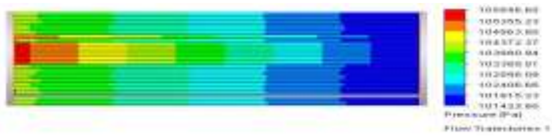


1.2mm size and 5mm distance between square channel Pressure Drop at 10m/sec

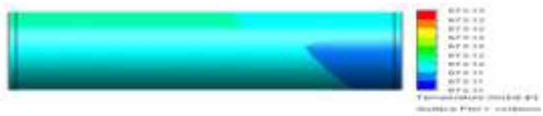
1.2mm size of triangular channel with 20m/s velocity



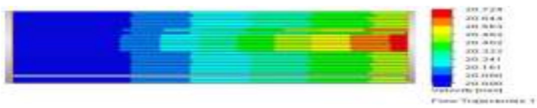
Temperature distribution for triangular channel of 1.2mm size and 5 mm distance between channels



Pressure drop for triangular channel of 1.2mm size and 5 mm distance between channels at 20m/sec

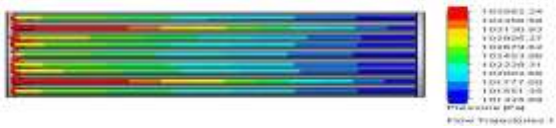


Temperature distribution for triangular channel of 1.2mm size and 5 mm distance between channels



Velocity distribution for triangular channel of 1.2mm size and 5 mm distance between channels

Pressure Drop in 1.2 mm (Pa)						
	At 4mm distance between channels			At 5mm distance between channels		
Inlet velocity	1.2mm channel size			1.2mm channel size		
	Circular	Square	triangular	Circular	Square	triangular
Pressure at velocity 10m/sec	1249	1331.4	1674	999	774	1125
Pressure at velocity 20m/sec	3255.88	3688	7674.62	2256	2832	4706



Pressure drop for circular channel at 10m/sec with 1.2mm and 5mm distance

Pressure drop for circular channel at 20m/sec with 1.2mm and 5mm distance

Pressure drop for square channel at 20m/sec with 1.2mm and 5mm distance

Velocity Reduction(m/sec)						
	At 4mm distance between channels			At 5mm distance between channels		
Inlet velocity	1.2mm channel size			1.2mm channel size		
	Circular	Square	Triangular	Circular	Square	Triangular
10m/sec	1.339	1.495	1.341	2.646	0.919	0.717
20m/sec	2.775	2.820	2.930	2.441	1.615	0.90

Pressure drop for triangular channel at 10m/sec with 1.2mm size and 5mm distance

For the validation, the pressure drop across the channel is measured for different mass flow rates. The results are shown in below table Optimized best channel shape is circular shape.

Pressure Drop in 1.5 mm(pa)						
	At 4mm distance between channels			At 5mm distance between channels		
Inlet velocity	1.5mm channel size			1.5mm channel size		
	Circular	Square	Triangular	Circular	Square	triangular
Pressure at velocity10 m/sec	1126.29	1319.4	1684	1747.71	1408.7	2182.63
Pressure at velocity20 m/sec	4706.31	2182.63	7554.62	2286.55	2812	2615.56

VI CONCLUSIONS

1. Different cross sections of the channels are optimised with help of solid works flow simulation software to find the best cross section channel.
2. It was found that circular channel was best suited for accumulation of diesel particulate as the surface area was maximum.

Velocity	4mm distance between channels	5mm distance between channels	4mm distance between channels	4mm distance between channels
	1.2mm size of channel	1.2mm size of channel	1.5mm size of channel	1.5mm size of channel
Cross section	Circular	Circular	Circular	Circular
Pressure at10m/sec	1249	999	1126.29	1747.71
Pressure at 20m/sec	3255.88	2256	4706.31	2286.55

Pressure drop at 1.2 mm and 1.5 mm

From the above the optimised size of circular cross section is 1.2mm size with 5mm distance between channels.

Velocity	5mm distance between channels
	1.2mm size circular channel
Pressure at10m/sec	999
Pressure at20m/sec	2256

Pressure drop at 1.2 mm and 5 mm

Velocity	4mm distance between channels	5mm distance between channels	4mm distance between channels	4mm distance between channels
	1.2mm size of channel	1.2mm size of channel	1.5mm size of channel	1.5mm size of channel
Cross section	Circular	Circular	Circular	Circular
10m/sec	1.339	2.646	2.389	1.726
20m/sec	2.775	2.441	3.071	2.797

Velocity reduction at 1.2mm size for 4mm and 5mm distance

Velocity Reduction at 1.5 mm (m/sec)						
	At 4mm distance between channels			At 5mm distance between channels		
Inlet velocity	1.5mm channel size			1.5mm channel size		
	Circular	Square	Triangular	Circular	Square	Triangular
10m /sec	2.389	2.927	2.928	1.726	1.150	0.724
20m /sec	3.071	3.368	1.268	2.797	2.151	0.368

3. Velocity reduction is maximum i.e 2.646m/sec at 1.2 size of channel for 5mm distance between channel and also at 1.5mm size of channel with 4mm distance is 3.071m/sec
4. Change in distance between channels from 4 to 5mm causes change in density which helped in finding the pressure drop difference and velocity difference.

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