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Design and Simulation of a Hollow Cylindrical Ceramic Air filter using Finite Volume Technique

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Abstract

Background/Objectives: The commercial hollow air filters mostly used in automobiles are made out of cotton gauge, paper, fibrous materials, foam, etc. These filter's initial cost is low but maintenance cost of these is much higher than their initial cost with lower life span. The aim of this research work is design and simulation of a hollow cylindrical air filter fabricated using a ceramic material such as Silicon Carbide. **Methods/Statistical Analysis**: Research on air filters have focused on four main criteria, viz. less pressure drop, high air flow, superior dirt protection and less overall cost. Hence the major parameters were designed based on these factors and also by using Ergun's equation by considering the air filter as a packed column/bed. The important design parameters considered are particle size and pore size of the ceramic powder in order to have control over porosity. The filter model is designed using CATIA V5R16 and simulated using ANSYS FLUENT software. **Findings:** Ceramic air-filters can replace the existing air-filters with even better pressure drop. The thickens of these filters are in the range of 5 mm to 10 mm which will result in huge savings compared to the existing vary large filters in terms of space required. A stack of this hollow air filters can also be effectively used for superior dirt protection. However using these filters with thickness more than 20mm will have higher pressure drop and hence it is not recommended to go beyond this thickness. As the filters are made out of ceramics the life span of the filter will be very high. Damage of the filter due to either the harder and sharp particles or due to cleaning process is avoided. **Application/ Improvements:** The proposed ceramic air filters can be used in automobiles particularly in heavy vehicles which work in harsh and dusty environment such as quarries, cement and process industries. The improvements achieved as compared to current air-filters are the increase in life of the filters and efficiency of the engine.

Keywords: Hollow Air-filter, Particle Size, Pore Size, Porosity, Sphericity, Superficial Velocity

1. Introduction

The hollow air filters mostly used in automobiles and other application are made out cotton gauge, paper, fibrous materials, foam, etc. These types of filters needs maintenance and cleaning in a preset period of time and have lower span of life. They are subjected to damage during the service and cleaning. The clogging of dirt in these filters affects the flow of air and thereby affects the combustion efficiency which results in power reduction. Therefore the maintenance cost of these filters is much higher than their initial cost with lower life span.

A ceramic hollow air filter as shown in Figure 1, will have properties such as high porosity (ε), narrow pore size distribution, lower pressure drop (ΔP), high air flow and superior dirt protection. These air filters may be costlier, but the cost of maintenance will be low associated with a longer life span and other benefits. The important parameter to be considered in designing the filter are particle size, particle shape, pore size, packing arrangement of the particle and surface topology of the powder particle[1].

The filter produced can be assumed as packed bed[2] and modelled accordingly. Majority of the earlier studies

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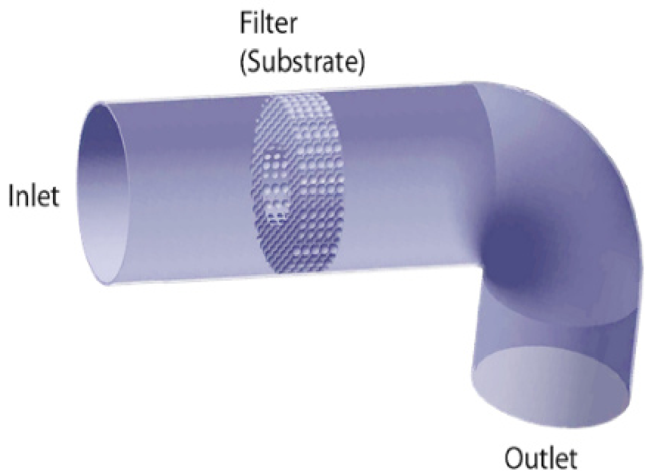

Figure 1. Ceramic Hollow Air filter.

dealing with pressure drop in packed beds are mostly based on the empirical correlations suggested by earlier researchers[3-6], which mainly concentrates in the applications based on adsorption, stripping and distillation operations[7]. Research works which uses the packed bed concept for design and fabrication of hollow air filters using ceramic powders were not found in the known literatures.

Most of the applications which are based on the packed columns are manufactured by considering the diameter of the particle (d_p) and pressure drop as the input factors to get the output velocity[7], whereas, an application such as an air filter will have range of velocities that must be maintained. So, a modified Ergun's equation was formulated by the authors in this research work based on the superficial velocity (V) and pressure drop as major input parameters and output as a relation between thickness (L) and diameter of the filter (D).

The appropriate particle diameter is decided based on the average dust particle size in the application environment of the filter. In order to identify and examine the flow of the air in the packed bed, the designed parameters are modelled using CATIA V5R16 and simulated using ANSYS-FLUENT software. Such a design and simulation work was carried out based on three different thickness of the bed sizes and three diameters of the particles for both non-spherical and spherical particles with low particle to tube ratio1.667[8].

Erguns pressure drop correlation[6] shown in Equation (1) is based on the ratio of air flow rate and pressure drop across packed bed which was practically used in many applications like absorption, distillation, and Fluidized bed reactors etc.

$$\Delta P = \frac{150\mu(1-\epsilon)^2 LV}{\epsilon^3 d_p^{\,2}} + \frac{1.75(1-\epsilon)LV}{d_p \epsilon^3} \tag{1}$$

But it is[9] predicted that using Erguns equation below D/d_p=16.5, will show a 9% deviation between theoretical and experimental pressure drop. Ergun's equation is based on the equation of Blake-Kozeny and Burke-Plumber and is valid for laminar flow and turbulent flow through the packed bed. They also observed that Ergun formulated the correlation for spherical particles and not considered the influence of side wall friction.

It is also predicted that Ergun's equation is not valid for predicting pressure drop of the smooth spheres above 700 Reynolds number (R_e)[10]. It is stated that Erguns equation should not be used between 500-600 Reynolds numbers because the pressure drop in a finite packed bed is not proportional to the square of the flow speed[5]. Ergun's correlation is modified for a similar objective and reported[11]. It is also reported that the Reynolds Number for fluid flow based on Erguns equation for a cylindrical bed using smooth spheres with different particles is $50<Re<100$. Hence, Ergun's equation is modified by many researchers in order to fit it to their research requirements and conditions.

Many studies based on the Ergun's equation discussed about the values of empirical constants involved in the equation. The empirical proportionality constant will be 150 for change of pressure at low flow rates[12]. The empirical proportionality constant for inertial flow in pressure drop through packed bed is 1.75[13]. When non spherical particles are used the empirical constant based on the viscous resistance is 180[8], and based on inertial resistance is 1.85. The bed porosity is affected by the packing mode, the ratio between diameter of the tube, diameter of the particle, particle shape, and particle size distribution, roughness of the particle surface and by the bed thickness[1]. The empirical relationship (2) for calculation of porosity based on the diameter of the duct (D_d) and diameter of the particle (d_p)[14].

$$\epsilon = A\left(\frac{D_d}{d_p}\right)^m e^{n\left(\frac{D_d}{d_p}\right)} \tag{2}$$

Where the proportionality constants A= 12.6, m = 6.1 n = −3.6.

It is explained that airflow rate is based on the engine displacement and horse power[15]. The analytical correlations suggested are useful for establishing superficial velocity. It is reported that vacuum pressure is developed during suction strokes[16].

A computational study on packed bed using FLUENT software was conducted[7] in order to identify and examine the aspects of transitional air flow behaviour through spheres. It is reported that pressure drop per unit depth correlates with the theoretical equations accurately.

A CFD flow simulation on a T-junction pipe was conducted[18] and reported that pressure loss coefficient depends upon the flow rate ratio, but not upon the Reynolds numbers for this particular model. Packed bed of cylinders was investigated using CFD simulation[17] which is modelled based on the scan IP and Scan FE and reported that finite volume method is an executable alternative to Lattice Boltzmann methods. Packed columns are computationally generated[17] using Macro Pac software package and meshed with IBM techniques.

2D CFD simulations was used to investigate[19] flow structure for a range of sphere sizes and separations numerically using a finite element technique. Flow around a linear array of 8 spheres was studied[20] using the finite element package FIDAP. A similar work with 3D studies was performed on an array of spheres[21]. Further improved model was developed and simulated using CFD code and the flow structure was investigated in FLOTRAN software with 4 spheres in two columns which are perpendicular to direction of the fluid flow[22]. A simulation based on a simple uniform cubic unit cell, using finite volume code using k – ε model was also conducted[23]. It is observed that the flow structure can be studied by 3D model[7,17].

2. Design and Simulation Premises

The following design and simulation premises are considered based on the literature survey and the requirements of the air-filter;

- Ergun's equation shall be modified to fit to this research requirements.
- The Filter is considered as a packed bed.
- The Flow through filter is either laminar or turbulent.
- The Porosity of the packed bed is constant over the length.
- The Orientation or packing arrangement is considered as cubical.
- The simple unit cell structure shall be considered.
- The Surface topology of the particle is considered as smooth.
- The ratio of the diameter of the tube to particle diameter (D/d_p) shall be between 15-17.
- The Reynolds number of the fluid flow through the air-filter shall be low.
- The velocity profile has minimal effect on pressure drop except possibly at high Reynolds numbers.
- Increasing the thickness of the packed bed results in increasing pressure drop.
- Negative pressure/vacuum will be created at the exit of the tube.
- Finite Volume Method shall be considered.

3. Theoretical Design

The flow through packed bed mainly depends on the following aspects; Porosity of the bed, Diameter of the particle, Sphericity (Ø) of the particle and Roughness of the particle. Pressure drop is the major factor causing pressure difference between the inlet and outlet of the pipe. Pressure drop in the flow of a fluid is caused due to the resistance to flow in the fluid network. Fluid velocity and viscosity are the governing factors of the resistance to flow. Lower the fluid flow velocity and higher fluid viscosity results in larger pressure drop. Ergun's empirical relation (1) based on pressure drop in a packed bed for a fully developed flow with spherical particles with $D/d_p = 16.5$ is used for deriving a modified equation for determining the pressure drop. The Modified Ergun's equation formulated[8] is shown below.

$$\frac{\Delta P}{2} = \frac{180\vartheta(1-\epsilon)^2 L}{\theta^2 \epsilon^3 d_p{}^3 V} + \frac{1.85L(1-\epsilon)}{\epsilon^3 \theta d_p} \qquad (3)$$

Here the superficial velocity is the velocity of the fluid in the pipe in the absence of the packing or any obstructions. The velocity of the air flow through the filter is considered as the ratio between the air flow rate ($\dot{m}$) and the cross sectional area (A_{cs})of the tubular vessel as shown below.

$$V = \frac{\dot{m}}{A_{cs}} \qquad (4)$$

The air filter used in automobiles has a fluid flow rate that depends on the combustion air requirement of the engine. The air flow rate can be established from;

$$\text{Air Flow}\left(\frac{m^3}{min}\right) = \frac{\text{Engine size}(\text{lit}) \times RPM \times VE}{2000} \quad (5)$$

Where VE = Volumetric Efficiency. In an ideal mode, calculation of combustion air requirement of the engine is based on Engine's displacement or power. Hence the engine displacement is used for determining the flow rate. The Engine Displacement for a 4-stroke Engine can be arrived as shown below.

Engine size (ES) in lit = Cubic Inch Displacement (CID) X 0.0163871Where CID = Number of Cylinders (NOC) X 0.7854 X Bore Size X Stroke Length.

Note: The constants are conversion factor from Imperial to metric units.

The RPM, NOC, Bore diameter, and Stroke length is based on a specific engine. Generally the porosity for the filter should be higher in order to have less pressure drop. So a cubical packing with 47% porosity[11] is considered. Also considering the Kinematic Viscosity of the air at 300k as $1.343\times10^{-5} m^2/s$, the superficial velocity can be replaced with engine air flow (5) that will yield the generalised equation for design and simulation of an air filter for a 4-stroke engine. Based on all the above correlations the pressure drop equation is further modified which is shown below.

$$\Delta P = \frac{7.68\times(1-\in)^2 L\times A_{cs}}{\theta^2(\in)^3 d_p{}^3 \times([ES\times RPM]\times VE)} + \frac{1.61L(1-\in)}{(\in)^3 \theta d_p} \quad (6)$$

The pressure drop values based on the above correlation (6) for the proposed hollow ceramic air-filter were designed by varying four control factors with multiple levels viz., four different particle diameters (d_p), two different porosities ($\in$), two different Sphericity values (Ø) and four different filter thickness (L) for a specific engine with 5000 rpm, 3 Cylinders, 68.5 mm Bore and 72 mm stroke length. For the design work, Taguchi based Design of Experiment was implemented. The method provides a set of sixteen well-balanced designs which are presented in Table 1.

The designed pressure drop values based on the modified equation (6) for the 16 designs are presented below in Table 2.

4. Simulation

The fluid flow through the sixteen different hollow air filters with the control factors as mentioned in Table 1, and the resulting pressure drops were simulated using FLUENT software in ANSYS 14.0 package. Usually for manual 2D, 3D fluid flow calculations for a packed bed, Navier–Stroke equations is used which requires lot of computational time. In order to reduce the manual computational effort and time, a three-dimensional model with the help of software package is used to study the velocity and pressure drop across the air filter. The proposed ceramic air filter model is shown in Figure 2.

Table 1. Sixteen Well Balanced-Designs

No	Control Factors			
	Particle Diameter (d_p)	Filter Thickness (L)	Sphericity ($\in$)	Porosity (Ø)
D1	400	05	1.000	0.4700
D2	400	10	1.000	0.4700
D3	400	15	0.531	0.5545
D4	400	20	0.531	0.5545
D5	600	05	1.000	0.5545
D6	600	10	1.000	0.5545
D7	600	15	0.531	0.4700
D8	600	20	0.531	0.4700
D9	800	05	0.531	0.4700
D10	800	10	0.531	0.4700
D11	800	15	1.000	0.5545
D12	800	20	1.000	0.5545
D13	1000	05	0.531	0.5545
D14	1000	10	0.531	0.5545
D15	1000	15	1.000	0.4700
D16	1000	20	1.000	0.4700

Table 2. Designed Pressure Drop Values

No	Pressure Drop (Pascal)	No	Pressure Drop (Pascal)
D1	4985.389	D9	1357.231
D2	9970.777	D10	2714.463
D3	4268.732	D11	3803.730
D4	5691.643	D12	6772.534
D5	1693.133	D13	549.347
D6	3386.267	D14	1089.694
D7	5492.897	D15	5943.506
D8	7323.863	D16	7924.674

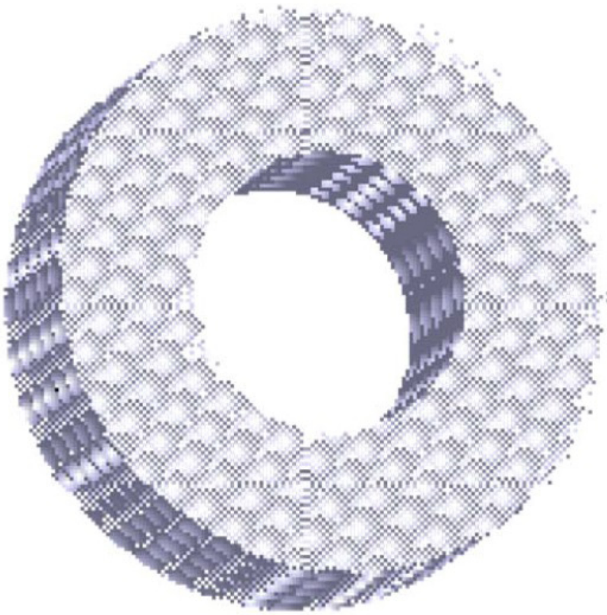

Figure 2. Proposed Ceramic Air filter Model.

The geometry of the filter was built using CATIA V5R16 and imported to the FLUENT software for analysis of the flow behaviour. The mesh creation was done using ANSYS mesh package, with an automatic meshing schemes. Here the domain was meshed with tetrahedron cells but includes few other types of cells where necessary as shown in Figure 3. The domain was split into cells containing 352855 faces and 115976 nodes.

The other mesh details are; max cell volume - 4.420044e-13, min cell volume -2.241704e-07, max face area - 9.606133e-09. min face area- 7.421689e-05, mesh volume -8.196584e-04.

Considering the inlet as the starting of the pipe which contains the filter and exit as the end of the pipe as shown in Figure 1, the simulation is initialized using the inlet pressure and flow iteration is continued until it reached the convergence. During the simulation, the meshed model is considered as a pressure based system, initialized with 20m/sec inlet velocity and 101325 Pascal pressure and with superficial velocity at the exit. A k-∈ viscous model is applied to study the mean flow characteristics because this model is capable of describing both laminar and turbulent flow characteristics. Other boundary conditions of the filter like the details of the substrate and the wall are specified. Out of these, Substrate is the air filter. Cell Zone condition of the substrate is considered as porous zone with laminar flow. The analytical expressions for the

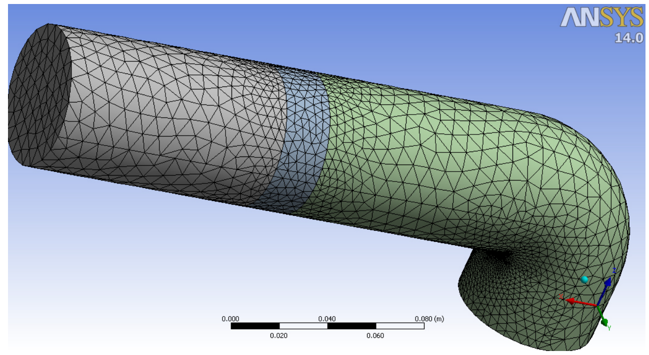

Figure 3. Proposed Ceramic Air filter Meshed Model.

properties of the porous zone such as inertial resistance and viscous resistance are given below.

$$\text{Inertial Resistance} = \frac{2 \times 1.75 \times (1 - \in)}{\in \times \theta \times d_p} \tag{7}$$

$$\text{Viscous Resistance} = \frac{150 \times (1 - \in)^2}{\theta^2 \times {d_p}^2 \times \in^3} \tag{8}$$

The inertial resistance and viscous resistance which are used as cell zone conditions of the substrate in this simulation work for various porosities, sphericities and particle diameters are obtained based on the above correlations for the sixteen different designs. The flow characteristics through the filter were studied and the pressure drop values for the sixteen different designs were established which are presented below in Table 3.

5. Results and Discussion

A comparative analysis of the pressure drop values for the sixteen different designs obtained through design and simulation is presented below in Table 5. It is observed that the correlation factor between the design procedure and simulation is 0.99489.

The existing air-filters required pressure drop as obtained from filter manufacturers is 1592 Pa. It is observed from Table 4 & 5, the design numbers D5, D9, D13, D14 will have a pressure drop value below the current requirement of the air-filter. The graphical representation of pressure drop for these Designs as obtained through the simulation is presented below from Figure 4 to Figure 7.

It is observed that increasing the particle diameter and reducing the filter thickness will result in pressure

Table 3. Simulated Pressure Drop Values

No	Pressure Drop (Pascal)	No	Pressure Drop (Pascal)
D1	4950.76	D9	1250.76
D2	9911.62	D10	2207.04
D3	4207.04	D11	3797.96
D4	5311.02	D12	6207.04
D5	1158.46	D13	490.76
D6	3158.46	D14	937.96
D7	5010.57	D15	5011.02
D8	7295.62	D16	7895.62

Table 4. Designed and Simulated Pressure Drop Values

No	Pressure Drop (Pa)		No	Pressure Drop (Pa)	
	Designed	Simulated		Designed	Simulated
D1	4985.389	4950.76	D9	1357.231	1250.76
D2	9970.777	9911.62	D10	2714.463	2207.04
D3	4268.732	4207.04	D11	3803.730	3797.96
D4	5691.643	5311.02	D12	6772.534	6207.04
D5	1693.133	1158.46	D13	549.347	490.76
D6	3386.267	3158.46	D14	1089.694	937.96
D7	5492.897	5010.57	D15	5943.506	5011.02
D8	7323.863	7295.62	D16	7924.674	7895.62

Table 5. Recommended Designs

No	Control Factors			
	Particle Diameter (d_p)	Filter Thickness (L)	Sphericity (Ø)	Porosity (∊)
D5	600	05	1.000	0.5545
D9	800	05	0.531	0.4700
D13	1000	05	0.531	0.5545
D14	1000	10	0.531	0.5545

drop. It is inferred that higher porosity will lead to lesser pressure drop. The pressure drop is directly proportional to thickness. Lesser the Sphericity the higher will be pressure drop. Higher the particle diameter with lesser filter thickness will yield better pressure drop.

The simulation and designed data show a strong correlation with a correlation factor of 0.9948, with the designed data little over predicting the drop in pressure. This minor discrepancy between the results of design and simulation value is because, in theoretical design, exact values of pressure are considered at the inlet and the exit of the filer; whereas in simulation, pressure varies from inlet to the outlet over the complete volume.

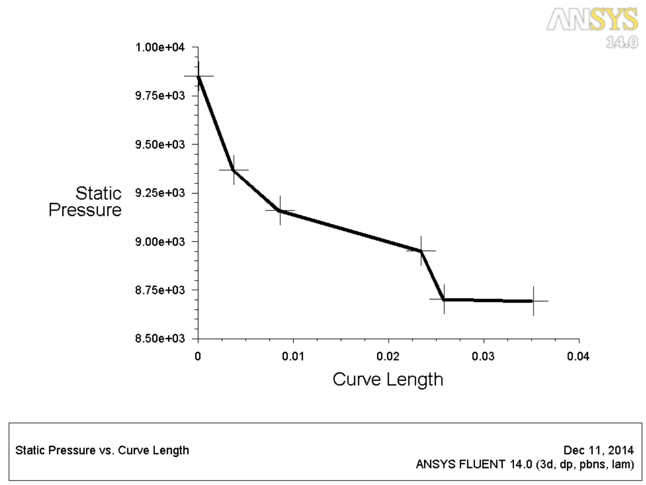

Figure 4. Pressure Drop for Design 5. (Filter Thickness 5 mm, Particle Diameter 600 μm, Sphericity 1, and Porosity 0.5545)

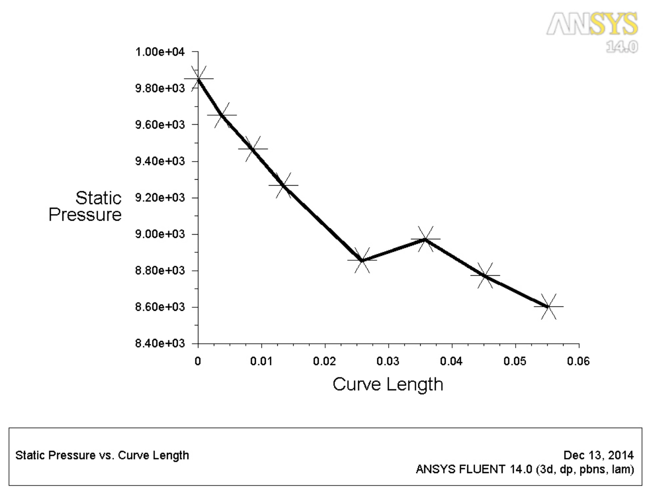

Figure 5. Pressure Drop for Design 9. (Filter Thickness 5 mm, Particle Diameter 800 μm, Sphericity 0.531, and Porosity 0.47)

6. Conclusion

- Ceramic air-filters can replace the existing air-filters made out of cotton gauge, paper, fibrous materials, foam, etc. with even better pressure drop.
- The thickens of these filters are in the range of 5 mm to 10 mm which will result in huge savings compared to the existing vary large filters in terms of space required.

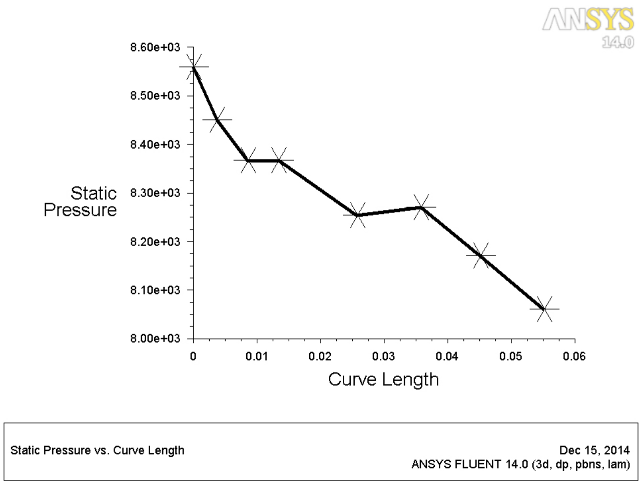

Figure 6. Pressure Drop for Design 13. (Filter Thickness 5 mm, Particle Diameter 1000 µm, Sphericity 0.531, and Porosity 0.5545)

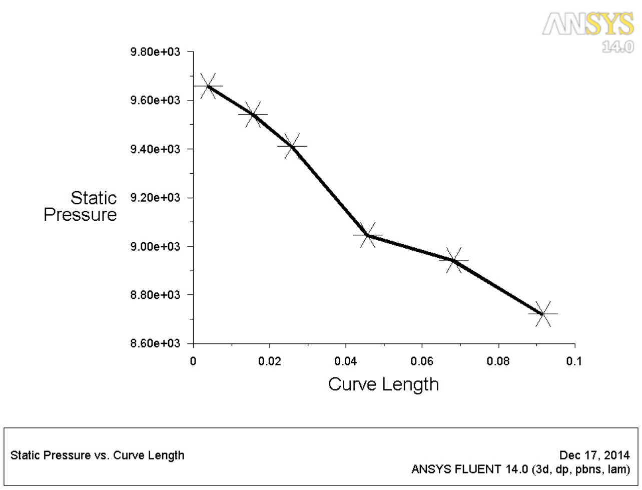

Figure 7. Pressure Drop for Design 14. (Filter Thickness 10 mm, Particle Diameter 1000 µm, Sphericity 0.531, and Porosity 0.5545)

- A stack of this hollow air filters can also be effectively used for superior dirt protection.
- However using these filters with thickness more than 20mm will have higher pressure drop and hence it is not recommended to go beyond this thickness.
- As the filters are made out of ceramics the life span of the filter will be very high.
- Damage of the filter due to either the harder and sharp particles or due to cleaning process is avoided.
- Based on the design and simulation work carried out, the designs; D5, D9, D13, D14 are recommended for further experimental work and validation of results.
- Out of the above four recommended filters, the filters which have the particle size of 600 µm and 800 µm with 5 mm thickness will have better air-purification because of lower pore size.

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