

Semi-Empirical CFD Transient Simulation of Engine Air Filtration Systems

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ABSTRACT

To improve fuel efficiency and facilitate handling of the vehicle in a dense city environment, it should be as small as possible given its intended application. This downsizing trend impacts the size of the engine bay, where the air filter box has to be packed in a reduced space, still without increased pressure drop, reduced load capacity nor lower filtering efficiency. Due to its flexibility and reduced cost, CFD simulations play an important role in the optimization process of the filter design. Even though the air-flow through the filter box changes as the dust load increases, the current modeling framework seldom account for such time dependence. Volvo Car Corporation presents an industrial affordable model to solve the time-dependent dust load on filter elements and calculate the corresponding flow behavior over the life time of the air filter box. The implemented semi-empirical simulation algorithm integrates several sub-models derived from different studies on flows over pleated filters. This work also introduces an experimental method to record the dust pattern on the filter element in order to validate the numerical results. Test results show that the overall dust load as well as its distribution within the filter element can be estimated accurately.

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INTRODUCTION

The air induction system refers to the whole air transportation system including *dirty side duct*, *air cleaner assembly*, *clean side duct*, *resonator* and *charge air duct*. Clean air is inducted from the atmosphere to the engine inlet. This work focuses on the air cleaner assembly upstream of the engine.

The air filter box shown in [Figure 1](#) is the main component of the air cleaner assembly, and its design has to fulfill several requirements. Firstly, the filter efficiency and capacity is restricted by the ISO standard [1]. Secondly, the need for a compact engine bay imposes

some size restrictions. Finally, low pressure losses as well as an air flow at the outlet of the clean side housing as uniform as possible are also desirable.

The literature review shows a lack of numerical studies on the transient behavior of the air filtration system. A method of transient CFD simulation of flows in air cleaners was introduced by Bernard et al. [2]. In this method, a regression model for evaluating permeability and the inertial resistance factor was developed. Additionally, Marco [3] presents a new software tool to analyze pre-development of filter elements with regard to filtration capabilities and pressure drop. The idea of this method is to develop a large database containing tests of

numerous pre-design filter element prototypes in realistic setups and conditions. Such database is then used to predict the performance of a new-design of the air filter geometry.



Figure 1. Test filter box with filter element inside

The objective of this work is to firstly develop a model to account for the dust load in a filter element over time. For this purpose, generic empirical expressions are adopted, hence not needing any specific input from experiments. Secondly, using this model, to solve the transient flow inside the air filter box and calculate the pressure losses between inlet and outlet. Due to the filter element property changes with the increasing dust load during the life time, such transient simulation take into account the history time period of flow inside an air filter box.

To accomplish the objectives, the first step is to model the dust load and identify the corresponding physical quantity to represent it in the mathematical model. The second step is to build the function relating dust load quantity and the pressure loss coefficient that will directly affect the flow field. The implemented algorithm has been tested in a real industrial case. Experimental work has also been conducted to acquire the necessary parameters and also to validate the numerical simulations.

TEST GEOMETRY

The geometry is a FFF (Free Form Fabrication) test filter box manufactured by 3D printing machines in Volvo Car Corporation, solely used for this work. The computational domain corresponding to this filter box is depicted in [Figure 2](#) with the air inlet on the left hand side, connected to the dirty side housing. After the dirty side housing, air flows through the filter region from bottom to top, then the clean side housing and, finally, through the outlet. Both the inlet area and outlet area are 0.0033 m^2 , and the filter element has a thickness of 38mm.

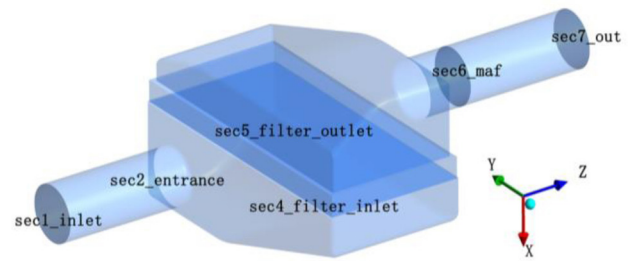


Figure 2. Test filter box geometry

Even though there are different filter structures available on the market, in this work we only consider a rectangular (or nearly rectangular) geometrical structure used in a previous version of the air induction system of Volvo Car Corporation, with triangular (V-shaped) pleats. Filter elements are made from different kinds of filter paper, which is a porous material. [Figure 3](#) shows an example of a typical filter element with a number of pleats. The computational resources needed to completely resolve the pleat structure in the CFD model exceed the scope of this work. Therefore, the filter element has been modeled as an anisotropic porous media. Further details on the filter element are explained in detail in the following section. Only macro-scale properties of the filter, such as porosity and paper permeability, are included in the model.

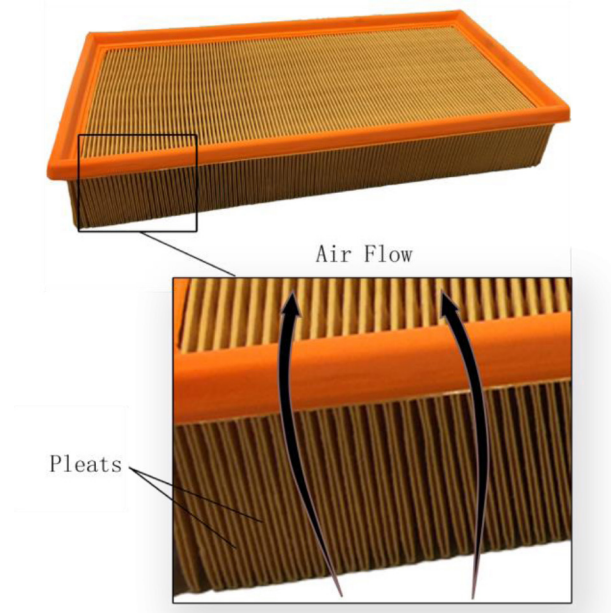


Figure 3. Illustration of flow over a filter element and detail of pleat structure

The distribution of the dust particle size in normal air is different from place to place in the world. In this project, the standard test dust in ISO 5011:2000, ISO fine and ISO coarse is used as dust particles in the simulation (see [Table 1](#)). Even though the volume size distribution of this particular kind of dust is different from the actual dust particles around us, its use minimizes deviations in the experiments due to variation in dust particle properties, and thus lets the work focus on the geometrical comparison.

Table 1. Particle size distribution (Y). Roller analyzer percentage by mass according to ISO 5011:2000 [1].

Size(μm)	Fine grade (%)	Coarse grade (%)
0 to 5	39 $\pm$ 2	12 $\pm$ 2
5 to 10	18 $\pm$ 3	12 $\pm$ 3
10 to 20	16 $\pm$ 3	14 $\pm$ 3
20 to 40	18 $\pm$ 3	23 $\pm$ 3
40 to 80	9 $\pm$ 3	30 $\pm$ 3
80 to 200	-	9 $\pm$ 3
Density(kg/m^3)	900	1200

MATHEMATICAL MODEL

The governing equations used to model the flow of air in a pleated geometry and filter box are the incompressible Navier-Stokes equations:

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

and

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_i \partial x_j} \quad (2)$$

The air flow inside the filter box is assumed to be transitional or turbulent depending on the air flow rate at the inlet of the clean side housing. To solve the effects of turbulence on the mean flow, the Realizable $K - \varepsilon$ eddy-viscosity model has been adopted [4].

Flow through the filter element/filter paper will cause a pressure loss. The filter paper is treated as porous media, in such a way that the pressure loss in the flow is introduced as a momentum source term added to the momentum conservation equation (see equation 3).

$$S_i = -\left(\frac{\mu}{K} u_i + C_2 \frac{1}{2} \rho |u| u_i\right) \quad (3)$$

where K is the permeability and C_2 provides a correction for inertial losses in the porous medium at high flow velocities. In this project the flow through the porous media is assumed to be laminar, and the corresponding pressure drop is given solely by the viscous loss term.

$$S_i = -\frac{\mu}{K} u_i \quad (4)$$

and using pressure loss gradient to replace S_i

$$\nabla p_x = -\frac{\mu}{K} u_i \quad (5)$$

The implementation of UDFs (User Defined Functions) to include these source terms is presented later on in this paper.

Apart from the Eulerian representation of the gas flow, a second discrete phase is also needed to calculate the motion of dust particles in a Lagrangian reference frame.

The force balance on each particle is integrated to obtain its position in time. The dominant forces acting on a particle are the drag force and the Brownian forces [5]. This equation can be written as:

$$\frac{du_p}{dt} = \frac{18\mu}{d_p^2 \rho_p C^c} (u - u_p) + b_i(t) \quad (6)$$

In the above equation, $b_i(t)$ is the Brownian force, defined as

$$b_i(t) = G_i \sqrt{\frac{216\nu\sigma T}{\Delta t \pi \rho_p d_p^5 S^2 C^c}} \quad (7)$$

where G_i is a random number chosen from a normal distribution with a zero mean value and the variance of one.

In the simulation, particles are injected from the inlet surface at the end of each time step of the Eulerian flow field. The interaction between the discrete and the continuous phase is one-way coupling, that is the particles are affected by the continuous phase, but they do not affect each other nor the continuous flow field

The injection batch is divided into a number of parcels, in which all particles have the same diameter. A parcel consists of as many clusters as the number of cells on the injection surface so that one particle cluster is injected from each cell surface.

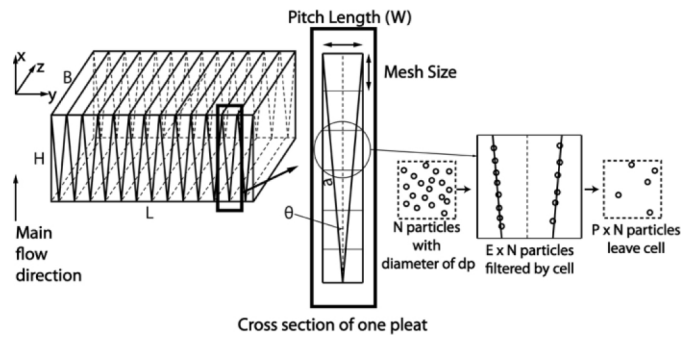


Figure 4. Schematic sketch of filter element, cross section of one pleat and filter motion in one cell.

The mass-flow rate of each dust group in one parcel depends on three parameters: Total air-flow rate ($\dot{m}_{air}$), dust concentration (η), and mass fraction of that particular dust group (according to Table 1. The total air-flow rates are chosen as 360 kg/h and 720 kg/h, whilst dust concentration is always assumed to be 1 g/m³.

$$\dot{m}_{dust} = \frac{\dot{m}_{air}}{\rho_{air}} \cdot \eta \cdot Y \quad (8)$$

Table 2. List of filter element parameters with importance rating. (*)Filter paper material or geometry dependent parameters, fixed for a known filter element. (-)Not a tunable parameter. (1) The most important parameter. (4)The least important parameter.

Parameter name	Symbol	Description	Importance
Permeability	K	The constant in Darcy's law	-
Viscous resistance factor	C	Inverse of K	-
Initial porosity	ε_0	Void volume in a no-load filter element	*
Initial SVF	α_0	SVF for a no-load filter element	*
Main permeability	K_x	Permeability in main flow direction	1
y-dir. Permeability coefficient	β_y	$K_y = \beta_y \cdot K_x$	2
z-dir. Permeability coefficient	β_z	$K_z = \beta_z \cdot K_x$	2
Permeability of particle bed	K_g	Particle bed permeability	3
Penetration rate	P_0	The fraction of particles penetrated	4
Cell SVF	α_c	SVF in a certain cell at current time	*
Fiber diameter	d_f	Fiber diameter of fibrous medium	*

In order to convert the particles injection model to the applicable input parameters, necessary calculations and assumptions are needed. For each dust size group, the input diameter of the particles is assumed to be same value which is the average number of that diameter interval.

Regarding mathematical modeling of the filter element, only its triangular pleated structure (see Figure 4) has been included in the model.

To model the dust load of the filter element, a quantity called solid volume fraction (SVF, defined as equation 9) is introduced. This method has been previously adopted by others [8] [9].

$$SVF = \frac{V_{fibers} + V_{particles}}{V_{cell}} \quad (9)$$

At clean filter element state, that is no dust load, an initial SVF value for each cell is calculated including solely the space occupied by fibrous material (equation 11). By meshing the filter element with quad cells of the same width equal to the pitch length, each cell is given the same fiber volume, total volume and initial SVF. Even though L, H and B in Figure 4 cannot be perfectly divided by the pitch length, the remainder is considered to be insignificant.

Pleat angle θ can be calculated as

$$\theta = \arctan \frac{W}{2H} \quad (10)$$

Then, the no-dust-load fiber media volume for each cell is given by

$$V_{fibers} = \frac{W \cdot thk \cdot W \cdot SVF_{paper}}{\cos \theta} \quad (11)$$

where thk is being the thickness of the porous media.

It should be noted that the SVF_{paper} in equation 11 is different from cell SVF. SVF_{paper} is the volume fraction for fibrous medium itself and depends on fibrous medium property. The value changes only when the fibrous medium is replaced.

When a dust particle is absorbed by a certain cell inside the filter element, the volume of that particle is added to the SVF of that cell. The dust load of each cell is monitored during the whole process.

As the filter element absorbs more and more dust particles and noticeable deposits form, porosity decreases. The SVF of cells collecting particles will eventually reach a maximum value, as described by Kasper et al. [10], which accordingly is the minimum allowable porosity of a granular bed comprised of a given particle size.

Filter porosity, ε , is related to SVF through equation 12:

$$\alpha = 1 - \varepsilon \quad (12)$$

Thus, the minimum porosity, ε_m , has to be included in the model in such a way that, once its value is reached, the cell is treated as blocked and dust particles will leave this cell and continue flowing along their trajectory. In the model, ε_m is set to a constant value.

In reality, when particles go through fibrous medium, not all the particles are absorbed. Collection efficiency, E, is a quantity that shows the percentage of the number of particles that are filtered. The filtration process of suspended particles in the airflow is very complicated because it involves various filtration mechanisms including Brownian diffusion, impaction and interception [13].

A particle is captured purely by interception when it approaches within a particle radius from the fiber surface. Capture by impaction involves deposition due to changes in the direction of the gas flow. In other words, heavy particles that cannot follow the motion of the carrier fluid collide with obstructing surfaces [14]. Lastly, the Brownian diffusion mechanism is due to small size particles colliding with each other. Such collisions may lead to further collisions with either obstacles or