

THE IMPACT OF MASS FLOW AND MASKING ON THE PRESSURE DROP OF AIR FILTER IN HEAVY-DUTY DIESEL ENGINE

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Abstract: *This paper presents a computational fluid dynamics (CFD) calculation approach to predict and evaluate the impact of the mass-flow inlet on the pressure drop of turbocharger's air filter in heavy-duty diesel engine. The numerical computations were carried out using a commercial CFD program whereas the inlet area of the air filter consisted of several holes connected to a channel. After entering through the channel, the air passes among the holes and enters the air filter. The effect of masking holes and hydraulic diameter is studied and investigated on pressure drop. The results indicate that pressure drop increase with decreasing of hydraulic diameter and masking of the holes has considerable effect on the pressure drop.*

Keywords: Air filter, Mass flow, Pressure drop, Heavy-duty diesel engine

1 Introduction

Air cleaning devices for air-borne particles are widely used in various industrial applications such as nuclear, automotive industry, food processing, and etc. Numerous models have been proposed to calculate the efficiency and the pressure drop of filters under steady flow conditions. The majorities of these models are only applicable to flat filters and not pleated filters. Moreover, there are few studies on the variation of these values in dynamic filtration. Kim et al. [1] studied temperature effects on the pressure drop at a ceramic filter. Pressure drop evolution of fibrous filter under continuous aerosol loading has been studied by Bergman et al.[2], Vendel et al.[3], Letourneau et al.[4], Novick et al.[5] and Thomas et al.[6] focusing on high-efficiency particulate air (HEPA) filters. Many authors have considered various aspects of this problem and obtained similar solutions [7-10]. Also Awniet al. [11] predicted efficiency, thickness, porosity and pressure drop at a new model of filter cake. Also several works are fulfilled in CFD field that shows the relation between the velocity and pressure drop. For example Gimbut et al. [12] was studied the influence of the temperature and inlet velocity on the cyclone pressure drop. One application of the air filter is in the heavy-duty diesel engine. Engineers are generally interested in two parameters in order to carry out an assessment of the design and performance of air filters.

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These parameters are the temperature and pressure drop through the air filter. In this work, the effect of mass flow rate inlet on pressure drop was studied. Accurate prediction of air filter pressure drop is very important, because it relates directly to operating costs.

In this work, the air filter in heavy-duty diesel engine that is shown in Figure.1 is studied. This air filter is consisted of nine solid circular plate whereas these plates act as cleaners and also chokers. The inlet area of the air filter consists of many holes. In this air filter, air after crossing a channel enters into the aforementioned holes that creates turbulent flow in the vacant space and then crosses among the plates.

Inlet area of this air filter contains many holes that is connected to a channel. The air, with various mass flow rates, enters the channel and passes through the holes and then enters the filter. In the first section of our study, the effect of the mass flow inlet and percentage of the masking holes on pressure drop are studied. In this section all of the holes are ellipse shaped and in per stage several rows of the holes were closed from the top to bottom.

In the second section of our study, the circles shaped are studied; and it is assumed that all of the holes are opened. The study is performed for three different hydraulic diameters and the results are compared.

In the third step of our work, the pressures drop obtained under different mass flow inlets for the inlet shape studied with different hydraulic diameters are compared.

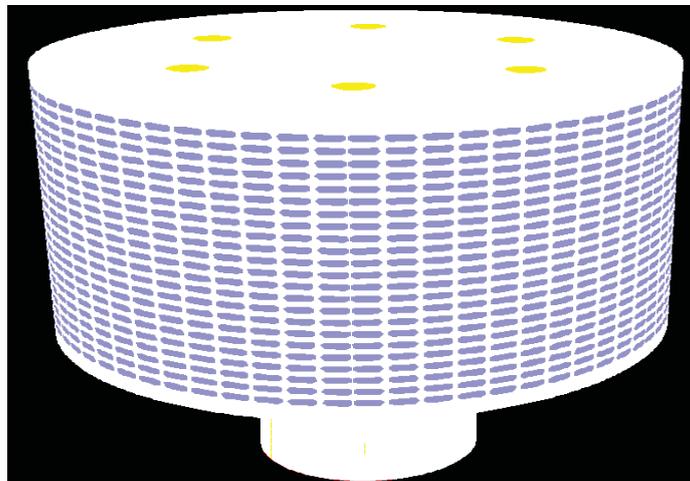


Figure1: The complete shape of the Air filter with ellipse shapes as inlet area

2 NUMERICAL MODEL SETUP

2.1 STUDY MODEL

In this work, the three-dimension geometry of the air filter was generated and the meshing of the volumes was done using Gambit. Only a sector of 60° of this geometry filter was modeled and meshed, due to huge volume of the air filter. Tetrahedron meshes with 1.2, 1.5, 1.8 and 2.1 million elements were generated within the geometry by the CFD software. Preliminary tests showed that the meshing with 1.5 million elements was the one that gave the best compromise between quality of mesh element (in terms of aspect ratio and skewness), CPU time, and numerical dispersion introduced by the spatial discretization method. Eventually, obtained pressure drops were extended to the whole of the air filter and are depicted in charts in the next section. Inlet area in air filter was connected to a channel with a height and radius of 360 and 800 mm, respectively. Meshing for the air filter connected to a channel is shown in Figure.2.

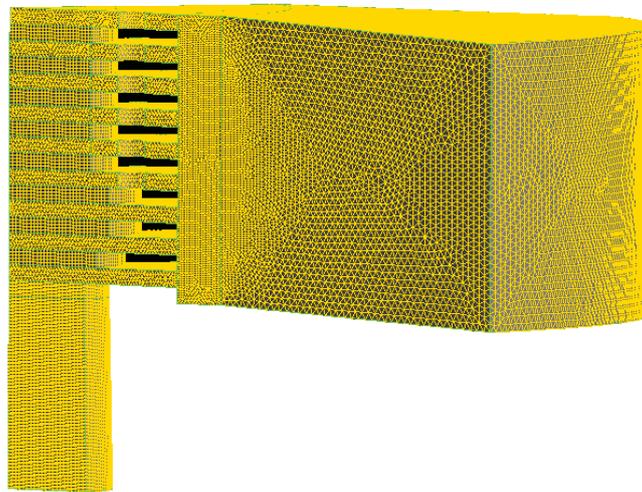


Figure 2: Computational mesh for the air filter with a channel

2.2 BOUNDARY CONDITIONS

The boundary conditions are illustrated in Figure.3, and described below with the following initial conditions;

- The mass flow inlet at the entrance of the channel is defined as turbulent in the normal direction with different mass flow rates.
- The outflow of the air filter was defined as outlet pressure and was assumed to be zero.
- The side of the air filter and channel were defined as periodic.
- Other faces of air filter were defined as wall.
- The fluid was assumed to be incompressible and ideal gas.
- The temperatures at all of the faces were assumed to be constant.

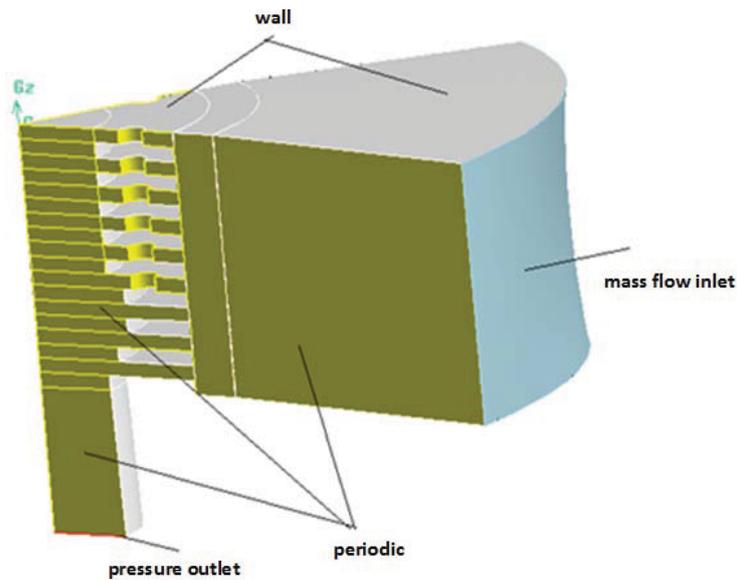


Figure3: Air filter`s boundary conditions for CFD calculations

2. 3 CONSERVATION EQUATIONS

The complicated swirling turbulent flow in the air filter demands on numerical techniques and turbulence models employed in the CFD code when modeling the air filter pressure drop.

In this analysis commercial CFD software package, Fluent v.6.3 ,was used to predict the velocity profile and pressure drop inside the air filter. Under turbulent flow condition, a modification of the realizable K- ϵ model was employed with standard wall function. In all of our simulations the fluid was considered to be Newtonian, incompressible, ideal gas and the properties of the fluid were assumed to be constant .The mass conservation equation, or continuity equation, can be written as flow:

$$\partial\rho/\partial t + \nabla \cdot (\rho\vec{u}) = S_m \quad (1)$$

This is the general form of the mass conservation equation. Here the term S_m ,designates the contribution of mass from another dispersed phase and is equal to zero, ρ is the fluid density and \vec{u} is the velocity vector. For an incompressible fluid the continuity equation simplifies to $\text{div}\vec{u}=0$. The conservation of the momentum in inertial (non-accelerating) reference frame can be written as follow:

$$\partial/\partial t(\rho\vec{u}) + \nabla \cdot (\rho\vec{u}\vec{u}) = -\nabla p + \nabla \cdot (\vec{\bar{\tau}}) + \rho\vec{g} + \vec{F} \quad (2)$$

where p is the static pressure, $\vec{\bar{\tau}}$ is the stress tensor (describes below), and $\rho\vec{g}$ and \vec{F} are the gravitational body force and the external body forces, respectively. For the Newtonian fluid, the stress tensor is given by

$$\vec{\bar{\tau}} = \mu[(\nabla\vec{u} + \nabla\vec{u}^T) - 2/3\nabla \cdot \vec{u}I] \quad (3)$$

where μ is the dynamics viscosity, I is the unit tensor, and the second term in the right side inside the square brackets is the effect of volume dilation and for incompressible fluid it is equal to zero. Turbulence was modeled using the realizable k- ϵ model, since it

has been shown to give accurate results for flows involving rotation, boundary layer under strong adverse pressure gradients, separation and recirculation [13]. In this model the transport equations for k (turbulence kinetic energy) and the ε (turbulence kinetic energy dissipation rate) are as follows;

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_T}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon \quad (4)$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_T}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \rho C_{1\varepsilon} S_\varepsilon - \rho C_{2\varepsilon} \frac{\varepsilon^2}{k + \sqrt{\theta} \varepsilon} + C_{1\varepsilon} \frac{\varepsilon}{k} C_{2\varepsilon} G_b + S_\varepsilon \quad (5)$$

and the adjustable parameters are:

$$\mu_T = \rho C_\mu k^2 / \varepsilon \quad (6)$$

$$C_\mu = \max[0.43, \eta / (\eta + 5)] \quad (7)$$

$$\eta = S K / \varepsilon \quad (8)$$

$$S = \sqrt{2 S_{ij} S_{ij}} \quad (9)$$

In this model G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients, G_b is the generation of turbulence kinetic energy due to buoyancy, σ_k and σ_ε are the turbulent Prandtl numbers for k and ε ; S_{ij} is the mean strain rate tensor and Ω_{ij} is the mean rate of in a rotating reference frame with angular velocity $\overline{\omega}_k$. From these equations one can see that C_μ is not constant, it varies with mean strain and rotation rates. The model constants, $C_{1\varepsilon}$, $C_{2\varepsilon}$, and σ_k and σ_ε are assigned the following values; $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.9$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.2$; these values have been established to ensure that the model performs well for certain canonical flows[14].

3 RESULTS AND DISCUSSION

1. Pressure drop prediction under different mass flow inlet and masking holes

Pressure drop was measured at four mass flow rates and five percentage of masking by the CFD and the results are shown in Figure.7. Mass flow rate ranges from 1 kg/s to 4 kg/s. At mass flow rate of 1 kg/s the pressure drop rises from 0.376KPa at 0% masking to 0.939KPa at 74% masking. At mass flow rate of 2 kg/s the pressure drop varies from 1.486KPa to 3.622KPa at 0% and 74% respectively. Also it can be seen that the same value soars from 3.316KPa to 8.108KPa and 5.789KPa to 13.909KPa at mass flow rate of 3kg/s and 4kg/s for 0% and 74% masking respectively.

As can be seen, the pressure drop increases as mass flow rate rises. It can also be observed that for masking of 50% and higher, pressure drops increase more dramatically than the same value for masking of less than 50% which is not considerable.

The three -dimension contour of static pressure and velocity vectors in two cases were shown in Figures.5 and 6, respectively. As is seen in Figure.6 where no masking is implemented created vortex at mass flow rate of 4 kg/s of more than mass flow rate of 1kg/s. Also when 74% of the holes are masked the same condition can be seen. But when 74% of the holes are closed the created vortex at both mentioned mass flow rates is far more than the 0% masking.

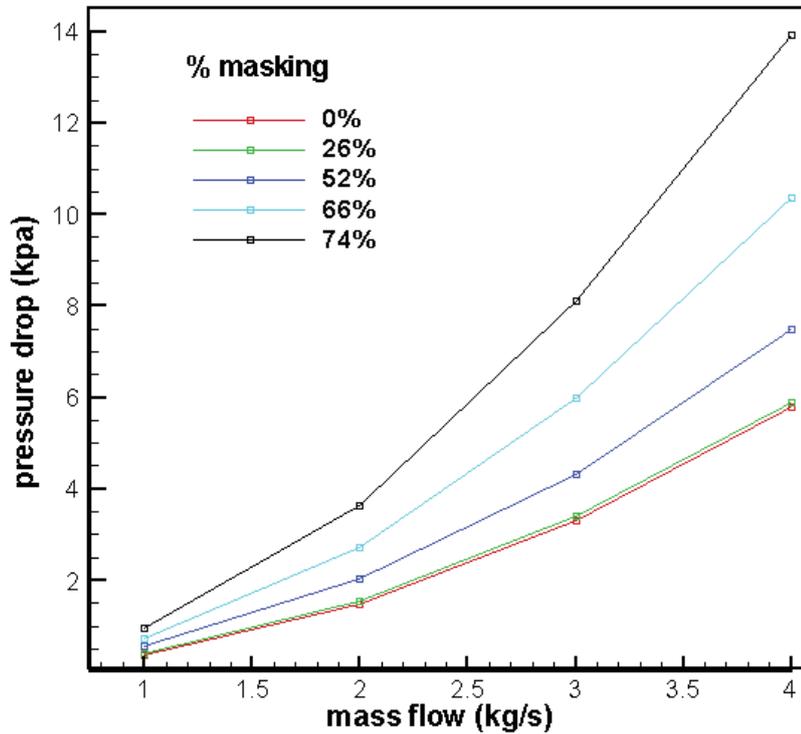


Figure 4: Altering pressure drop with variety of mass flow at different masking holes at air filter

2. Pressure drop prediction under different mass flow inlet and different diameter

This section was predicted the air filter's pressure drop when the shape of the holes alter to circle holes. All of the holes were opened and the air crosses the channel with mass flow inlet ranging from 1 to 4 kg/s. In this section pressure drop in three different diameters were compared and was seen that the decreasing of diameter leads to raising the pressure drop. This rising was seen with high rate when the diameters change from 12.4 to 6.2mm. In Figure.7 the pressure drop at three different diameters were shown.

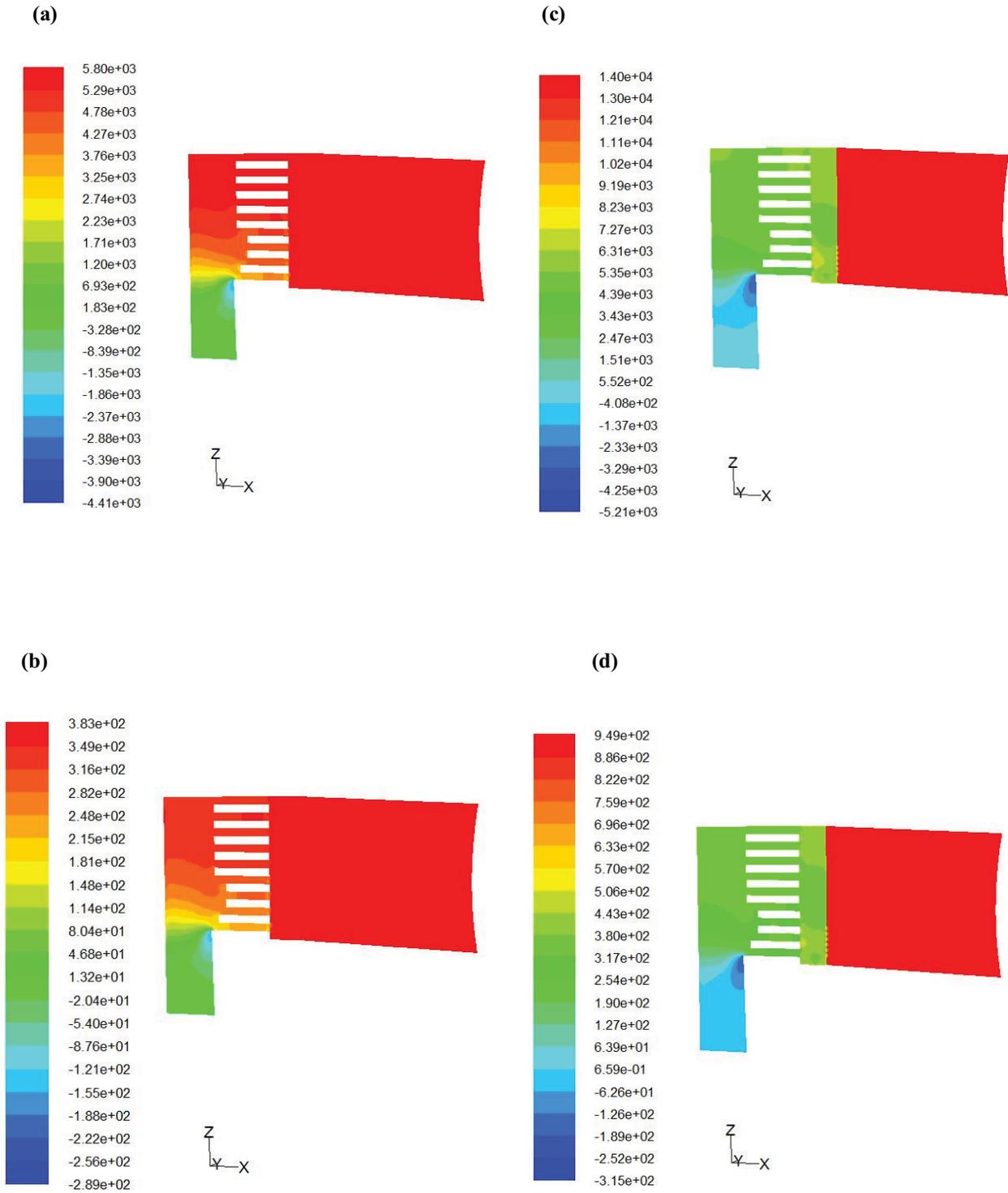


Figure5: Contour of static pressure (Pascal)(a)for mass flow of 4kg/s at 0% masking of holes (b)for mass flow of 1kg/s at 0% masking of holes (c)for mass flow of 4kg/s at 74% masking of holes (d)for mass flow of 1kg/s at 74% masking of holes

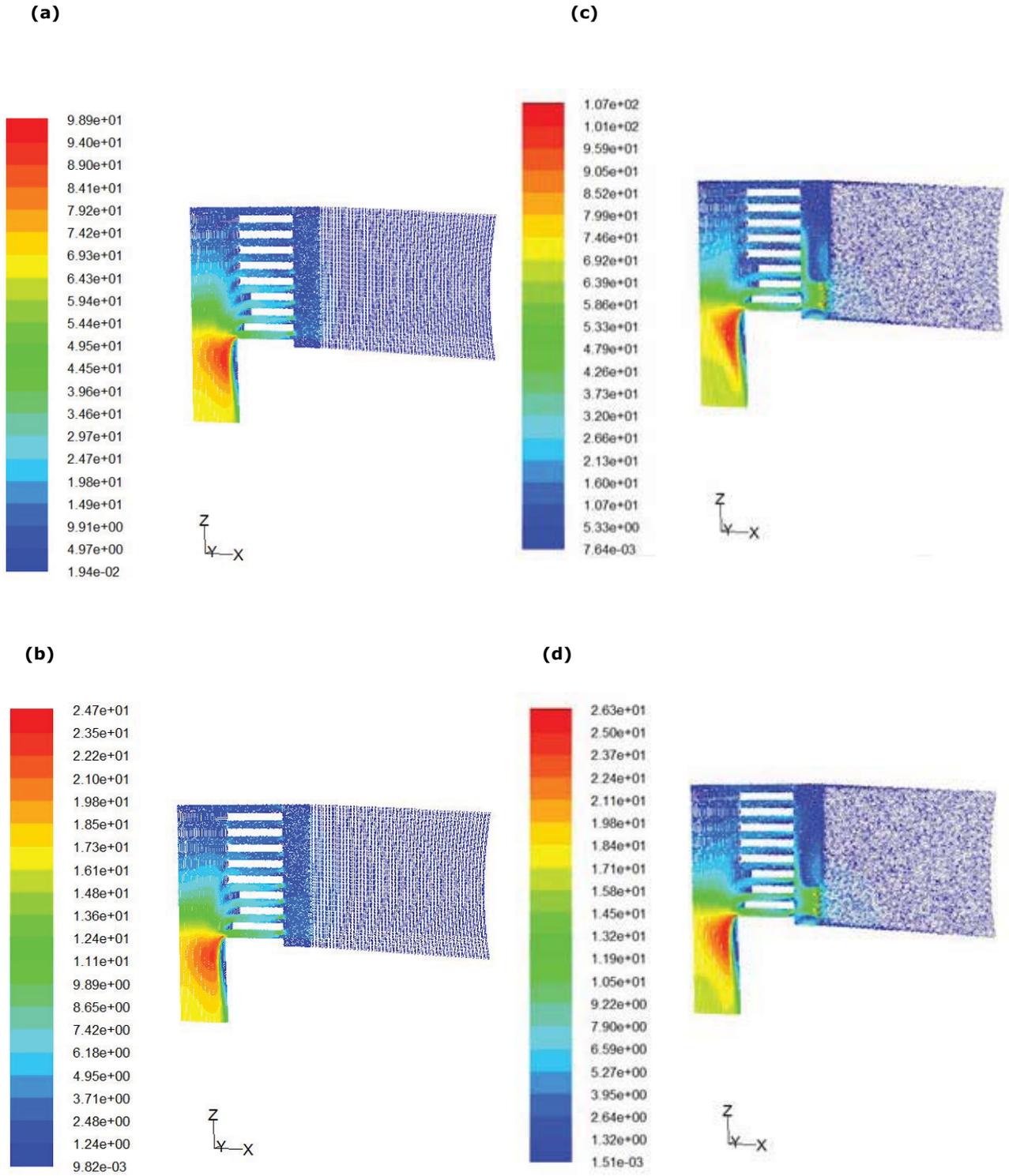


Figure 6: Velocity vector for air filter (a)for mass flow of 4kg/s at 0% masking of holes (b)for mass flow of 1kg/s at 0% masking of holes (c)for mass flow of 4kg/s at 74% masking of holes (d)for mass flow of 1kg/s at 74% masking of holes

3. Pressure drop prediction under different mass flow inlet for two inlet shapes with different hydraulic diameters

In the third section the effect of the mass flow inlet on the pressure drop at the air filter between two different inlet shapes (ellipse and circle) was investigated. In both cases, all of the holes are open. In this state the hydraulic diameter for ellipse is 10.6mm and for circle is 24.8 mm, but the numbers of the ellipse approximately are more than doubled of the number of circles. In Figure.8 it is resulted that the pressure drop resulting the variety of mass flow inlet in both cases are equal. It was shown that if the total hydraulic diameters at air filter in both cases be considered, the pressure drop is independent of the shape of the inlet holes.

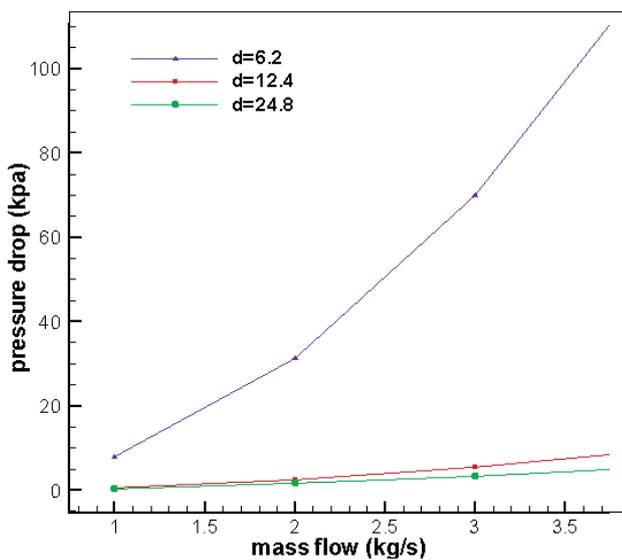


Figure7: Altering pressure drop for different two kind of diameters

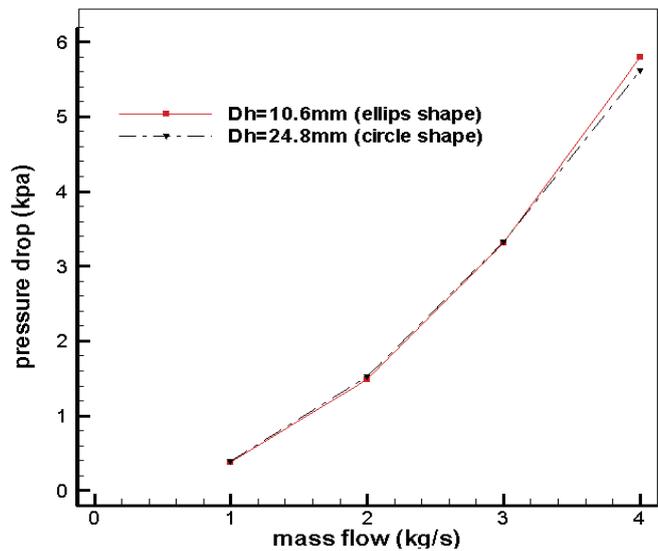


Figure8: Altering pressure drop with shape as an inlet area

4 Conclusions

In this paper a computational fluid dynamics (CFD) calculation approach to predict and evaluate the impact of the mass-flow inlet on the pressure drop of turbocharger's air filter in heavy-duty diesel engine was investigated. The CFD code with the realizable $k-\epsilon$ turbulence model, predict the pressure drop in air filter with variety shapes with different hydraulic diameter as an inlet area. It can clearly be seen that pressure drops depends on mass flow and hydraulic diameter. And it can also be concluded that the pressure drop independent of the shape of the holes in air filter.

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