ENGINE INTAKE AIRBOX CFD OPTIMISATION AND EXPERIMENTAL VALIDATION TESTS

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The effective power of an internal combustion engine is determined by the amount of air that is drawn into the cylinder. One of the basic requirements for the intake is the even filling of all cylinders. This paper deals with the design of an airbox 4-cylinder 2.2 liter naturally aspirated SI engine. The CFD simulation of the air flow through the serial airbox was performed. This showed an uneven filling of the cylinders. With the help of CFD simulations, the shape of the airbox was optimized to improve the uniformity of the cylinders filling. The validation tests of the real airboxes on the flow bench were performed. The standard airbox and the airbox with the optimized shape were compared. The results confirmed the CFD simulations outputs. Furthermore, it has been shown that the air filter chamber can contribute to the uniform filling of the cylinders. The research resulted in the optimization of the engine's intake tract airbox shape.

KEYWORDS

cylinder filling, CFD simulation, flow bench testing, airbox optimization, flow characteristics

1 INTRODUCTION

The power is important parameter of engine. The engine power can be improved, among others, by utilisation of advanced injection systems [Vondracek 2018], or by efficient supercharging [Singh 2011], or for example by better combustion process and diagnostics [Famfulik 2021, Sarkan 2022]. Intake manifold is one of the main part of the engine. The length and diameter of the intake pipes have a major effect on the performance of the internal combustion engine. It must be designed in such a way that the pressure wave caused by the movement of the piston in the cylinder reaches the suction valve just before it closes, thus helping to refill the cylinder. Many studies deal with the parameters of the intake manifold. [Xu 2017, Tyagi 2015, Sedlacek 2016] Variable length piping is often used to improve engine characteristics. [Ceviz 2010] The manifold configuration has a significant effect on the flow characteristics and the quality of the mixture preparation. [Rahiman 2014, Cep 2011] Intake manifold should provide a uniform fresh charge for each cylinder of the engine. This is significantly affected by the geometry of the airbox. [Montenegro 2013, Siano 2014] Not only the airbox volume [Fleck 2008, Brennan 2008], but also its position [Birtok-Baneasa 2017] and shape affect the engine parameters. When designing an airbox, it is necessary to consider the space options, which are usually very limited in the vehicle. For this reason, the shape of the airbox often causes uneven filling of the cylinders, an example being the airbox examined in this paper.

2 CFD SIMULATION

The research was carried out on an airbox from a 2,2 liter Talbot Matra Murena vehicle engine. The air flow through the engine intake airbox was simulated using Ansys Fluent simulation software. Computational Fluid Dynamics (CFD) is a numerical method that deals mainly with fluid flow using the finite volume method (FVM) [Koenig 2019, Richtar 2021]. The standard k-ε turbulence model was chosen to solve the flow simulation in the airbox. This is the most common turbulence model. It solves two separate transport equations for turbulent kinetic energy k and dissipation of kinetic energy ε [Barbouchi 2009] and it models Reynolds stress using turbulent viscosity according to Boussinesqu's hypothesis. [Kozubkova 2008, Warda 2020]

2.1 Boundary conditions

First, the geometric model in Autodesk Inventor software was prepared and imported into Ansys. The model has one inlet and four outlet openings (see Figure 1), boundary conditions were assigned to areas marked in this way. Other areas of the model were defined as wall. For the purposes of this simulation, the numerical mesh was created from tetrahedral volume elements (cells). The basic numerical mesh is further supplemented by a prismatic layer around the walls. This layer is formed by orthogonal rectangular elements and allows to simulate the velocity profile of the flow in the boundary layer more accurately (Figure 2). The numerical mesh was formed by approximately 500,000 cells.

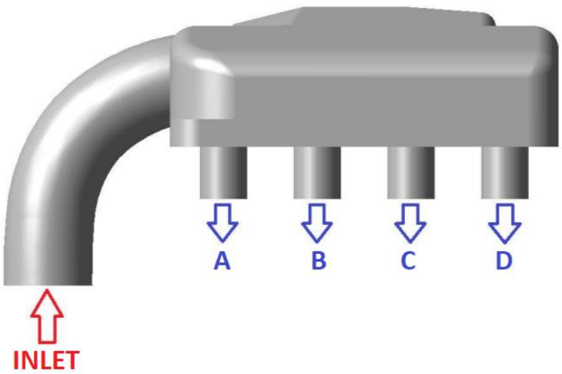

Figure 1. Airbox inlet and outlet openings

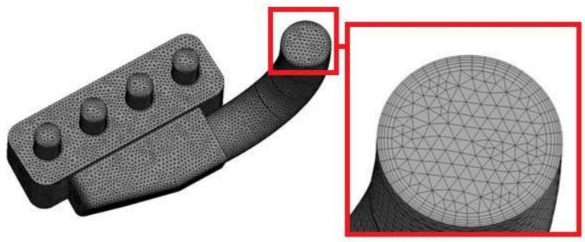

Figure 2. Numerical mesh on a serial airbox with a prismatic layer detail

The airbox inlet is defined as Mass Flow Inlet. The boundary conditions are described here by air temperature (20° C) and constant mass flow, which corresponds to the theoretical cylinder volume filling with air per unit time:

$$\dot{m}_{in} = \rho_{air} \cdot V_D \cdot \frac{n}{60} \cdot \tau \quad (1)$$

$$\dot{m}_{in} = 1{,}205 \cdot 2155 \cdot 10^{-6} \cdot \frac{5000}{60} \cdot 0{,}5 = 0{,}108199\ [kg.s^{-1}]$$

A pressure boundary condition is defined at the airbox outlets. The dynamic flow, i.e. time dependent (Transient), has been considered, because of non-stationary flow in a real engine. The outlet pressure caused by the movement of the piston from TDC to BDC has been obtained from the measurement of the pressures in the intake tract. [Kalabza 2021] The individual waveforms are time-shifted according to the ignition order of the cylinders, ignition sequence 1–3–4–2 corresponds to the established marking D – B – A – C (see Figure 3).

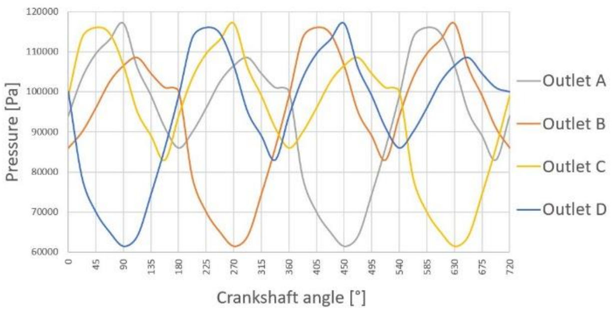

Figure 3. Pressure wave on individual outputs in one cycle

Since it is a naturally aspirated ICE, the flowing medium is ambient air with temperature 20° C, to this corresponds density $1{,}205\ \mathrm{kg.m^{-3}}$ and dynamic viscosity $1{,}7894 \cdot 10^{-5}\mathrm{kg.m^{-1}.s^{-2}}$.

2.2 Numerical flow model setting and calculation

The pressure values at the outlets were measured after 22.5 CA, from this value the length of the time step of the calculation was determined:

$$\Delta t = \frac{22{,}5 \cdot 60}{n \cdot 360} = \frac{22{,}5 \cdot 60}{5000 \cdot 360} = 7{,}5 \cdot 10^{-4}\ [s] \quad (2)$$

A maximum of 30 iterations was set for each time step. The total number of iterations was approximately 2000 for all variants, after which the calculation could be marked as convergent. Residual values fell below the value $1 \cdot 10^{-3}$ at each time step, which was the chosen limit for convergence. The accuracy of the results was checked using the continuity equation for a time interval corresponding to the length of one cycle:

$$\dot{m}_{in} = \dot{m}_A + \dot{m}_B + \dot{m}_C + \dot{m}_D \quad (3)$$

where $\dot{m}_X$ represents mass flow through outlet X.

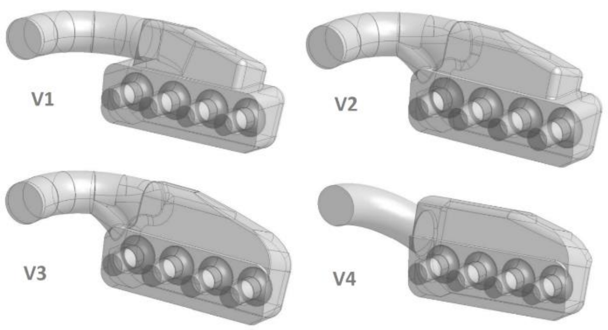

Figure 4. Airbox variants designed for CFD simulation

In total, four model variants were simulated (see Figure 4). The first variant V1 represents the serial airbox. In the second variant V2, the inlet to the airbox was widened and the edges were smoothed. In the third variant V3, compared to V2, the edge at output D was smoothed. In the fourth variant V4, the edge at the outlet D was smoothed, but the inlet remained standard.

2.3 Simulation results

The main evaluation criterion in evaluating the results was the measured mass flow at the outlets. The main goal of the modifications was to balance the mass flows in the individual cylinders. The measured mass flows for all variants are shown in Figure 6. As can be seen from the results, in the third and fourth variants, the cylinders filling was significantly more balanced. Based on the results, a new airbox was produced. Finally, it was manufactured according to variant 3.

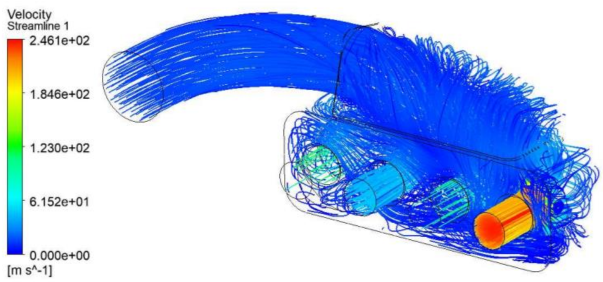

Figure 5. Air flow visualization during the D cylinder filling (airbox V1)

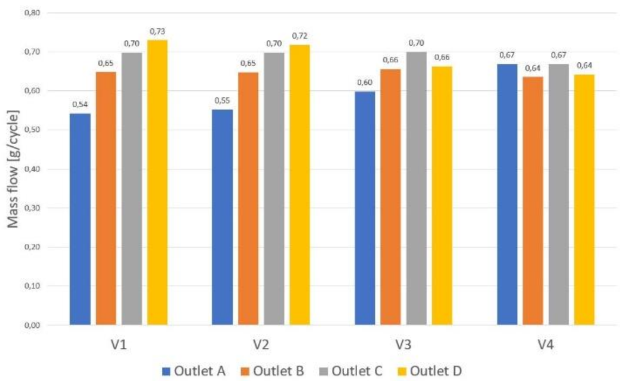

Figure 6. Comparison of mass flows through individual outlets during one suction cycle

3 VALIDATION TESTS

In the second part of the research, the flow properties of the airbox were measured on the air flow bench Superflow SF-260. Flow bench is very popular device used for testing the internal aerodynamic qualities of engine components [Park 2015, Muckova 2021], in this research it was used for validation of CFD simulation results. The measurement was performed at a pressure drop 4-10 mbar which correspond to the average intake manifold pressure values during the real engine operation (3500-6500 $\mathrm{min^{-1}}$).

Flow rates at individual outlets were gradually measured. The measured outlet was opened, and another 3 outlets were blinded (Figure 7). The results of V1 and V3 version measuring are shown in Figure 8. To compare changes in flow characteristics, the individual outlets are compared separately in Figure 9. Finally, the modified version V3 was measured with the air filter (Figure 10). Measurements have shown that the air filter also influences the uniformity of the cylinder filling. When measuring the airbox with the air filter, the filling was more even. In particular, the air flow through outlet A located closest to the inlet was equal to the air flows of the other outlets (especially at a pressure drop corresponding to the part load, which is the most frequently operated engine mode).

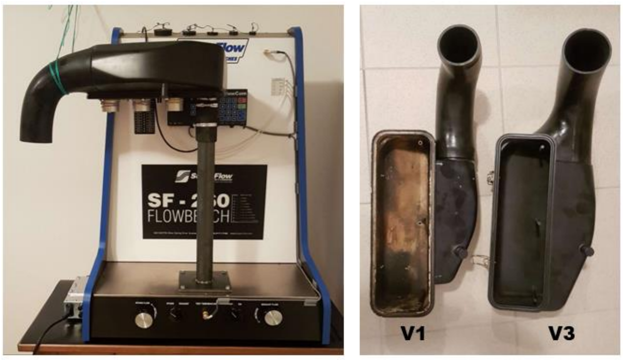

Figure 7. Measuring on the flow bench (left) and tested airbox variants (right)

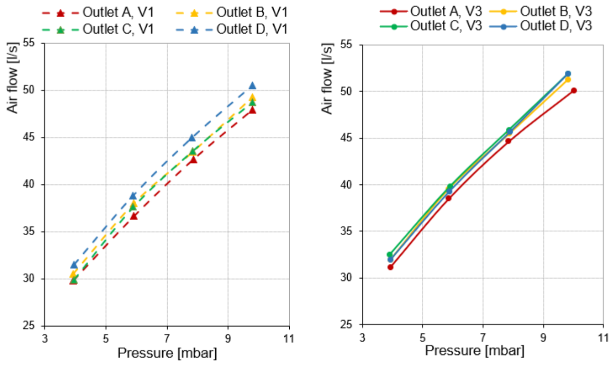

Figure 8. Flow characteristics of serial airbox (V1) and modified airbox (V3)

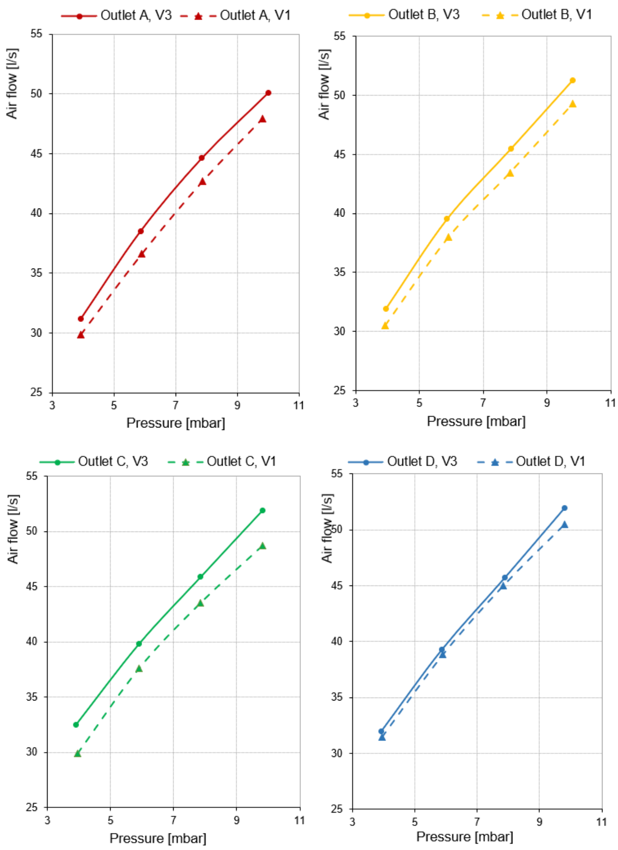

Figure 9. Flow characteristics of serial airbox (V1) and modified airbox (V3) - comparison of individual outputs

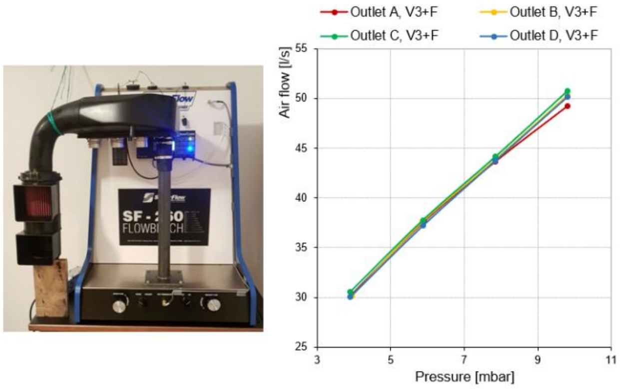

Figure 10. V3 airbox with the air filter measuring (left) and V3 airbox with the air filter flow characteristics (right)

4 CONCLUSIONS

Using CFD simulations, the air flow through the individual airbox outputs was calculated. The simulation showed that the standard airbox doesn´t ensure uniform cylinder filling, which has a negative effect on combustion and on overall engine efficiency. Three new variants of the airbox have been proposed. CFD simulations confirmed that by adjusting the shape of the airbox, a more even filling of the cylinders can be achieved. The best results were obtained with the V3 and V4 variants.

In the next part of the project, validation tests on the flow bench took place. For this measurement, a prototype airbox was manufactured according to the V3 variant and this was compared with a serial airbox. Finally, the modified version V3 was measured with the air filter. In this measurement, the most even filling of the cylinders was measured.

Unlike CFD simulations, flow bench measurements can only simulate stationary flow at a given pressure drop. This fact brings some inaccuracy to the validation tests. Due to the uniform nature of the results from CFD simulations and validation tests, we can assume the correctness of the obtained results

NOMENCLATURE

BDC	Bottom Dead Centre
CA	Crankshaft Angle
CFD	Computational Fluid Dynamics
FVM	Finite Volume Method
ICE	Internal Combustion Engine
SI	Spark Ignition
TDC	Top Dead Centre

$\dot{m}_{in}$	$[kg.s^{-1}]$	mass flow in inlet
$\dot{m}_X$	$[kg.s^{-1}]$	mass flow in outlet X
n	$[min^{-1}]$	engine speed
ρ_{air}	$[kg.m^{-3}]$	air density
Δt	[s]	time step
τ	[–]	2 stroke / 4 stroke engine constant ($\tau = 0{,}5$ for 4stroke ICE)
V_D	$[m^3]$	displacement volume

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