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Visual study of capabilities of managing IC engine filling degree vs engine ecological indicators

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Abstract. The operation of an internal combustion engine in a transient state is related to constant changes in cylinder filling degree. Managing a steady course of engine torque demands constant corrections in the volume of air delivered to the engine. In this work, different engine throttle management strategies were analyzed. The effect of throttle velocity on emissions was depicted. The research has shown that the greatest value of work density is reached by the IC engine for relatively low values of throttle angle. For shown values, disturbances in air flow in engine intake which may adversely affect emissions due to uneven cylinder filling were researched with the use of Digital Particle Image Velocimetry. The conducted research has shown significant unevennes in air supply to individual cylinders in the engine. This effect may cause discrepancies in air excess ratio for each cylinder, and result in heightened harmful substance emission.

1 Introduction

The way in which IC engine cylinders are filled with fresh air-fuel mixture load not only determines its power, allowing to control its value, but also significantly affects the course of the combustion process. Combustion of the air-fuel mixture in wrong proportions results in obtaining a wrong value of the air/fuel equivalence ratio “λ”, thusly increasing harmful substance emission into the environment. Management of quantity and flow of the air in the engine intake system is the subject of interest in research centers across the world. One of the effects of conducted research that can be observed is the electronic throttle, which is widely utilized nowadays. Forming and managing a correct correlation between the throttle and acceleration pedal is remarkably important for obtaining proper dynamic and ecological parameters. An abrupt change of throttle position by the driver with the desire to suddenly accelerate can result in fuel starvation, significantly worsening engine operation quality. The electronic throttle executed commands from the ECU, which correct engine operation parameters on the basis of information supplied by a range of sensors.

The significant majority of vehicles used nowadays is power by four-cylinder engines. An ideal state for such an engine is a situation in which all four cylinders are supplied with the same amount of air-fuel mixture, allowing each of them to reach identical operating parameters. However, in a practical situation, an unevenness in supply of fresh air into the cylinders can occur. In modern engines, the utilization of combustion sensors based on wideband lambda sensors (two for each cylinder pairs in a 4-2-1 exhaust system) partially solves this problem. However, the correction occurs after the combustion process has already taken place. Moreover, most engines utilize a narrow-band lambda sensor. The main source of information about the quality of the combustion process is the amount of free oxygen present in exhaust gasses. Fuel dosage is selected in a way that allows to obtain the stoichiometric composition of the air-fuel mixture ($\lambda=1$). Because of this, the value computed by the ECU is an averaged value for all cylinders. Despite the correct value of the average air-fuel ratio, a situation in which some of the cylinders operate on a lean air-fuel mixture, while the other ones operate on a rich air-fuel mixture, can occur. Such a situation negatively affects engine operation and its substance emissions.

One of the basic solutions of this problem is a correct design of the intake manifold, in a way which assures that the following conditions are observed:

1. The cylinder filling ratios are even for all cylinders.
2. The mass of air sucked into each of the cylinders is measured.
3. In the future, the design has to allow the utilization of separate pressure sensor for each cylinder, which will allow to introduce absolute correction in fuel dosage.

2 Throttle impact

Engine operation in transient states causes bigger difficulties in supplying the correct amount of air to the engine than operation with constant parameter values. In older vehicles, the throttle was fully connected with the acceleration pedal, meaning the driver had full control of the throttle opening angle. It is common to press the

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acceleration pedal fully to gain maximum vehicle acceleration. However, such behavior adversely affects the amount of air-fuel mixture delivered to the cylinders. Limiting the possible throttle opening angle to a degree, especially at lower engine speeds, to ensure better engine performance is a more beneficial solution. This is due to the fact that most drivers do not pay attention to adverse effect of fully opening the throttle, while the electronically controlled systems choose the cylinder filling ratio more precisely and depending on the engine need for its current operating state. In Table 1, experimental data from measurements of maximum engine torque as a function of engine rotational speed and throttle opening angle was presented.

Table 1. Maximum engine torque as a function of engine rotational speed and throttle opening angle [3].

Maximum engine torque	
Engine speed [rpm]	Optimum opening of the throttle [%]
1000-1500	35
1500-1600	50
1600-2000	60
2000-2750	70
2750-6000	100

Throttle opening values in respect to engine speed presented in Table 1 were chosen with the intent of obtaining maximum engine torque in its whole range of operation. Presented data depicts the parameters of acceleration process for a popular, naturally aspirated IC engine of 1.6 liter displacement. It is apparent that at lower engine rotational speeds, maximum throttle opening angle does not affect the generated torque in a positive way. It is advisable to initially open the throttle valve only partially (as little as 35% for low engine rpm's), reaching full throttle opening as late as at 2750 rpm.

During torque measurements, specific fuel consumption was also registered. Measurement results were presented in Table 2.

Table 2. Specific fuel consumption in respect to engine rotational speed and throttle opening [3].

Minimum fuel consumption	
Engine speed [rpm]	Optimum opening of the throttle [%]
1000-2700	35
2700-2900	45
2900-3750	50
3750-4500	60
4500-6000	100

Data contained in Table 2 presents the minimum specific fuel consumption in respect to engine rpm and throttle opening. Same as for torque-related data from Table 1, full opening of the throttle at lower engine speeds does not positively affect fuel consumption.

During ecodriving the driver possesses greater consciousness about the need to correctly operate the throttle. On the other hand, when the driver desires to achieve maximum driving dynamics, it is practically impossible for him to operate the throttle in an optimum way. Too abruptly opening of the throttle at the lower range of engine rpm's results in hampering of engine dynamics, higher fuel consumption and higher CO_2 emissions.

An electronically controlled throttle provides a more advantageous way of controlling the throttle opening angle, by opening the throttle only in a certain range during full acceleration at lower engine rpms. The ECU computes the optimum throttle opening angle basing on all the operating parameters and driver input and sends the information to the throttle, where it is realized either by a stepper motor or a DC electric engine with a mechanical gear.

An excess of the driving power is needed to the correct operation of the throttle, allowing to overcome the resistances of the return spring, aerodynamic resistances associated with the air flow through the partially opened throttle plate while ensuring sufficient acceleration and deceleration in throttle movement. To examine the effect of throttle plate movement speed on engine operation indicators, a range of simulations were conducted with the use of Vehicle Road Load Simulator and a virtual engine saved in it. The vehicle acceleration phase was the subject of research, as it is in principle the most energy consuming and most substantially emissions-affecting phase of vehicle movement. Research results were presented in Figs. 1÷4.

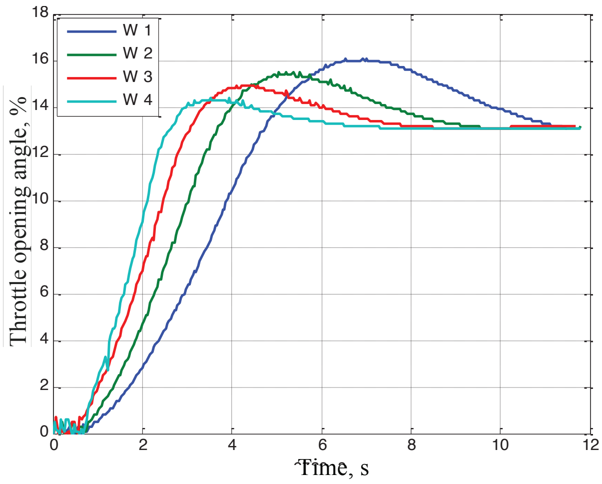

Fig. 1. Throttle opening angle vs throttle movement speed management strategy.

Throttle operation for four different variants of throttle velocity control was shown in Figs. 1 ÷ 4. The first variant depicts the slowest control variant, whereas the fourth variant (W4) is the fastest one.

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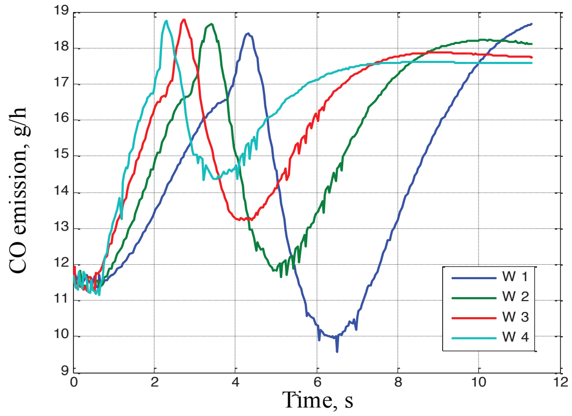

Fig. 2. Carbon monoxide emissions vs throttle opening velocity.

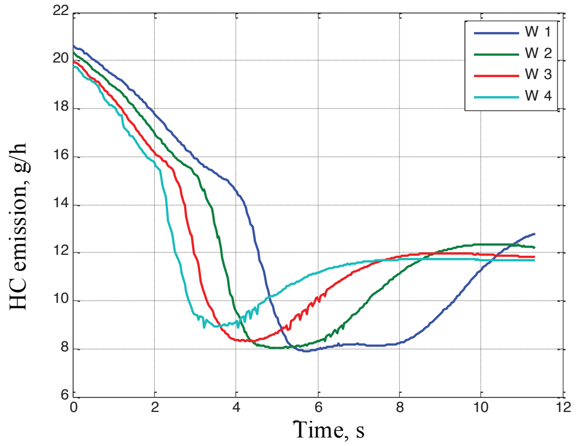

Fig. 3. Hydrocarbon emissions vs throttle opening velocity.

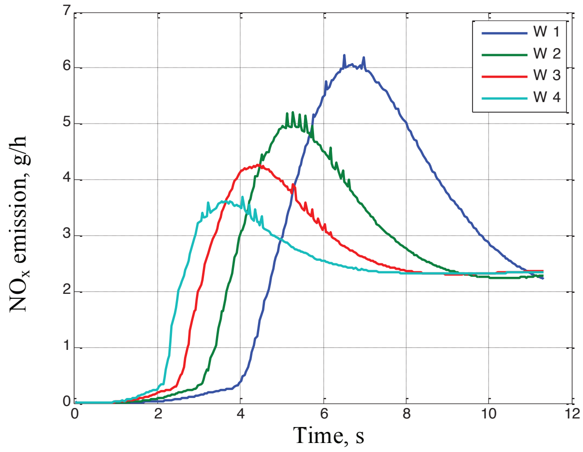

Fig. 4. $\mathrm{NO_x}$ emissions vs throttle opening velocity.

To showcase the differences between different throttle control variants for the chosen acceleration profile, work cycles for each researched variant were shown in fig 1. It can be seen that for the faster throttle control variant, signal overlaps faster with the velocity profile, and signal overdrive is not as significant as it is for lower throttle control speeds.

Next graphs show the results of measurements of the amount of toxic exhaust gas components (carbon monoxide, hydrocarbons and nitric oxides) for engine operation at throttle velocities depicted in Fig. 1.

The amount of carbon monoxide, which is the product of incomplete combustion at the beginning stage of the acceleration phase increases, and the intensity of said increase is dependent on the throttle velocity. In the later part of the acceleration phase the amount of emitted CO drops, its level reaching the lowest value for the slowest throttle velocity control strategy. The last phase of vehicle acceleration is related with an increase in CO emission and its stabilization for each shown case. The variant for which emissions are lowest can be determined by computing the field under each curve. For carbon monoxide, emissions are lowest in variant 3.

Hydrocarbons, which are unburned or partially burned fuel particles, are toxic substances. In Fig. 3 it was shown that HC emissions are also dependent on throttle operation velocity. The lowest HC emissions were obtained for variant 1, which is the slowest.

Nitric oxides are particularly toxic. They form as a result of reaction of the fuel with oxygen, depending on combustion pressures and peak temperatures. Nitric oxide emission shown in Fig. 4 clearly shows a lower value for higher throttle velocity. This is confirmed by calculating the field under the graph.

Only a short fragment of the acceleration was shown in Figs. 2, 3 and 4. Research for the same modifications was also conducted for a full city driving cycle, and the summary amount of emissions of mentioned exhaust gas components was the same as for presented short fragments. This confirms a previous statement that the acceleration phase is the most significant in the ecological aspect.

3 Air distribution in the intake manifold

An even cylinder filling in a multi-cylinder engine severely affects the quality of the air-fuel mixture, due to the utilization of aggregated control devices.

The literature study in the field of intake manifold research shows, that most studies rely on computer simulations [1,4]. Basing on the analysis of methods used for research of multi-phase flow phenomena, it was deduced that it is possible to experimentally investigate the flow in the intake manifold with the use of the Digital Particle Image Velocimetry (DPIV) method (Fig. 5) [2, 5].

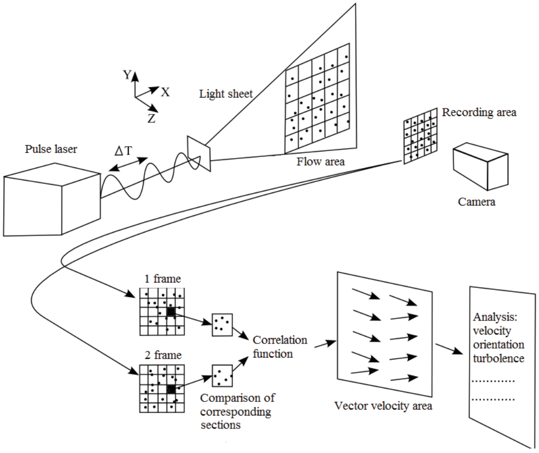

Fig. 5. Idea of DPIV measurement technique [10].

DPIV is a noninvasive method of researching the flow phenomena with the use of a light sheet generated by laser in the inert seeding particles mixed with the medium flowing through the manifold and registered by a video camera placed perpendicularly to the light sheet. To use the described procedure, the investigated element has to have at least two transparent walls which are perpendicular to each other. Images are registered in a strictly determined time gap and analyzed in respect to changes in concentration of seeding particles suspended in the flowing gas. Consequently, placement of seeding particles from the previous picture is searched in the next one. To determine the averaged seeding particles movement a Cross Correlation Function (CCF) is used [6]. Before captured images can be subject to verification by the DPIV algorithms mentioned above, it is recommended to carry out a series of image processing with the use of graphics software. Every pair of recorded images is subject to geometrical analysis, which searched for areas of pixel concentration that are constant in position (creation of background image). The generated background image is subtracted from all raw images of the recording session. The effect of this subtraction is a new series of images which show only seeding particles flowing in interest area. Measurements, which are prepared in such a way lower the risk of occurrence of noise caused by uneven lighting etc.

Generation of image depicting the flow of seeding particles, which is free of interruptions, requires capturing a series of images, conducting full calculations for each image, and then averaging of obtained results [9].

To investigate and understand real phenomena occurring in the intake system, a Volkswagen 9A engine intake manifold was chosen as a research object. Measurements of velocity fields distribution for flow velocities corresponding to 1500 rpm and 2000 rpm and 10, 20, 30° throttle angles were conducted. The choice of parameters was backed by previously conducted simulations, which have shown that they correspond to velocity fields most often utilized in city driving. Results were shown in form of colored vectors in figures 6(a)÷12(a), whereas essential markings corresponding to those figures were applied to figure 6(a)

An initial analysis of obtained results has shown significant disproportions and unevenness in air flow through the manifold for all chosen parameter. A vortex forming above the inlet to the third cylinder may be the effect of the ejector-like operation of the air stream just above the throttle body. Its presence significantly lowers the velocity before the inlet to the fourth cylinder, thusly lowering its filling ratio. A characteristic vortex can also be seen above the inlet to the first cylinder, which is caused by the influence of manifold walls. A significant reduction in air flow velocity can be observed in this area. To eliminate the resulting effect of air particles moving against the assumed air flow direction, a transparent plastic baffle was used to reduce the manifold volume in this section. Research was repeated after modifying the manifold in such way, with results shown in Figs. 6(b)÷11(b).

The analysis of vector velocity fields presented in Fig. 6 shows significant in cylinder filling for the manifold with modified geometry.

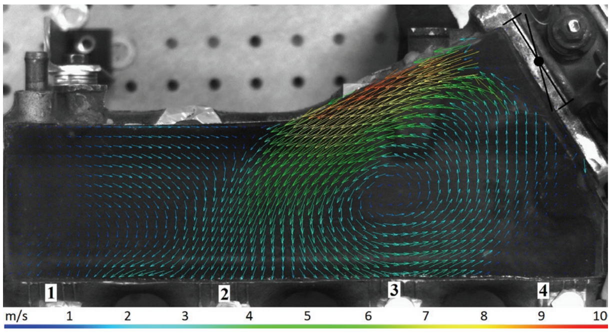

Fig. 6(a). Velocity vector distribution and air flow direction in the intake manifold for 1500 rpm and 10° throttle position angle.

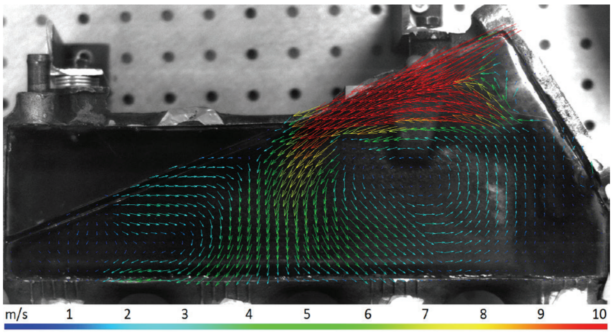

Fig. 6(b). Velocity vector distribution and air flow direction in the intake manifold for 1500 rpm and 10° throttle position angle.

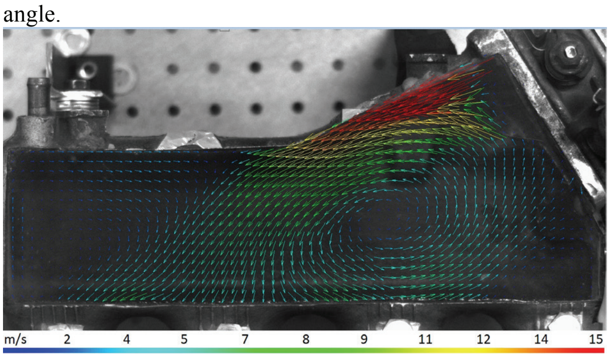

Fig. 7(a). Velocity vector distribution and air flow direction in the intake manifold for 1500 rpm and 20° throttle position angle.

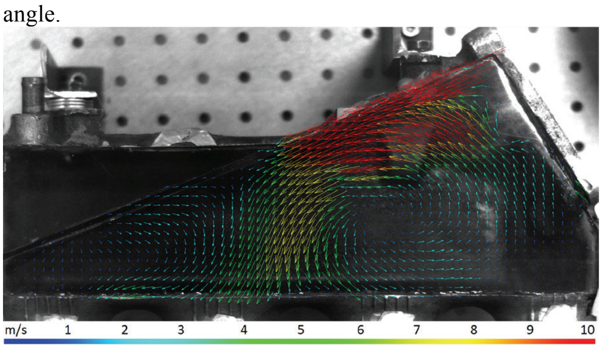

Fig. 7(b). Velocity vector distribution and air flow direction in the intake manifold for 1500 rpm and 20° throttle position angle.

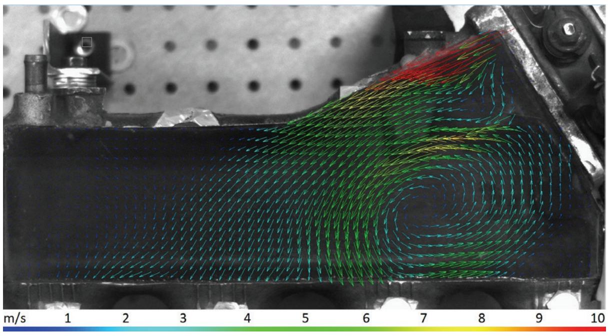

Fig. 8(a). Velocity vector distribution and air flow direction in the intake manifold for 1500 rpm and 30° throttle position angle.

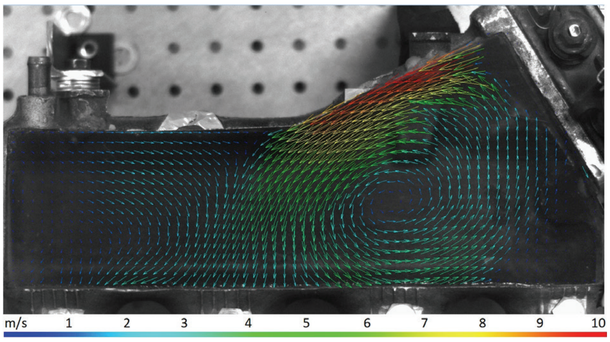

Fig. 9(a). Velocity vector distribution and air flow direction in the intake manifold for 2000 rpm and 10° throttle position angle.

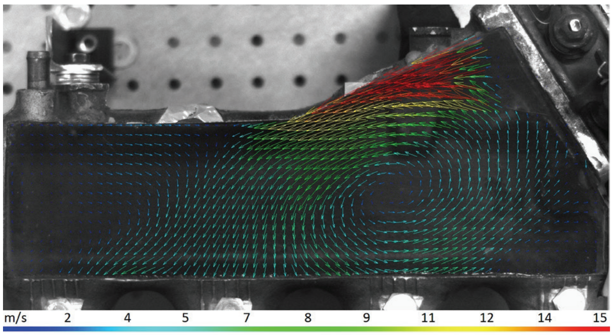

Fig. 10(a). Velocity vector distribution and air flow direction in the intake manifold for 2000 rpm and 20° throttle position angle.

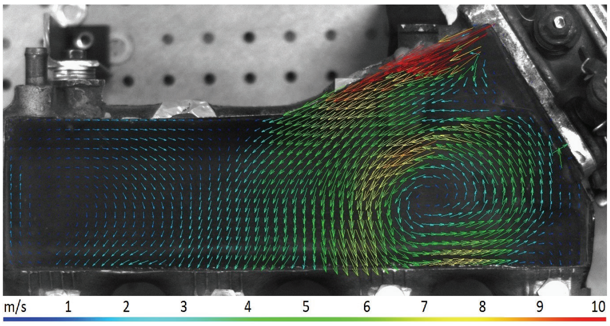

Fig.11(a). Velocity vector distribution and air flow direction in the intake manifold for 2000 rpm and 30° throttle position angle.

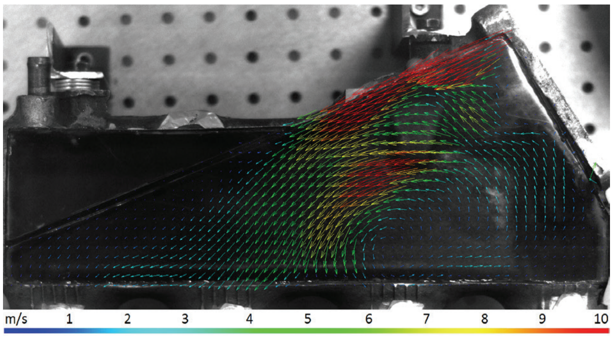

Fig. 8(b). Velocity vector distribution and air flow direction in the intake manifold for 1500 rpm and 30° throttle position angle.

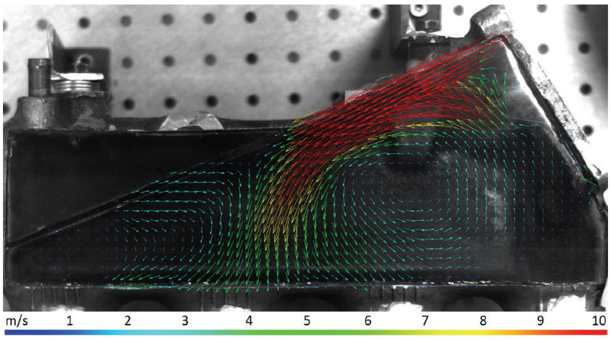

Fig. 9(b). Velocity vector distribution and air flow direction in the intake manifold for 2000 rpm and 10° throttle position angle.

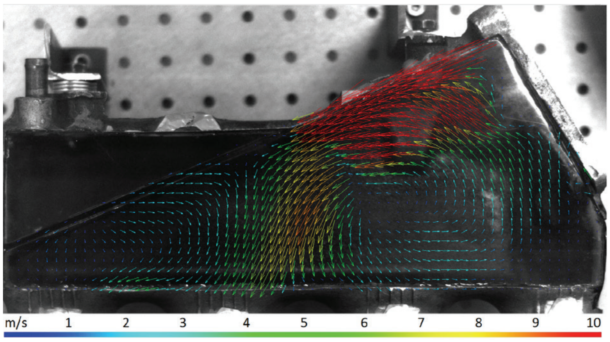

Fig. 10(b). Velocity vector distribution and air flow direction in the intake manifold for 2000 rpm and 20° throttle position angle.

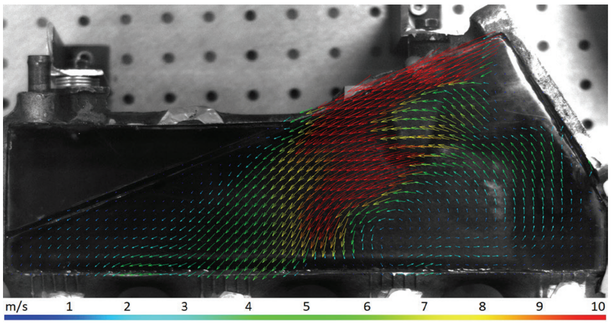

Fig. 11(b). Velocity vector distribution and air flow direction in the intake manifold for 2000 rpm and 30° throttle position angle.

Despite lack of vortex formation above cylinder 1, for each research case significantly higher flow velocities in the area of the second cylinder were noted. To precisely depict the differences in cylinder filling, a velocity profile was made along the cylinder inlet line. Results were shown in Figs. 12÷13. Position of inlet canals was schematically shown by a black line.

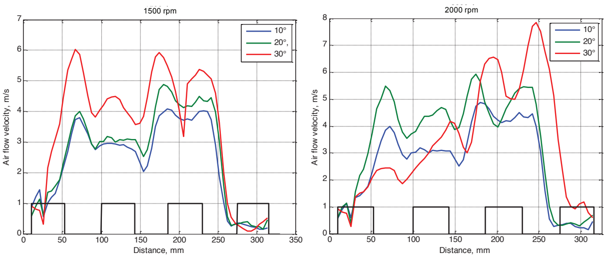

Fig. 12. Velocity profile distribution in the plane of stock manifold outlet for different throttle position angles.

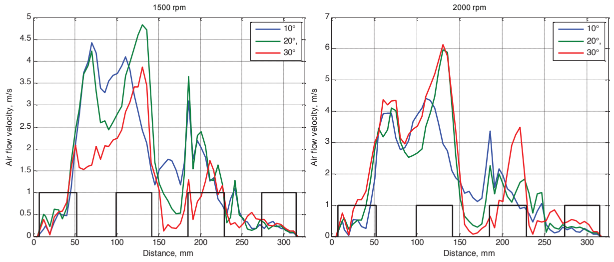

Fig. 13. Velocity profile distribution in the plane of modified manifold outlet for different throttle position angles.

A clearly visible difference in cylinder filling (Fg. 12÷13) can denote different values of the lambda parameter for each cylinder and increased harmful substance emissions. A modified manifold geometry, whose velocity profile was depicted in Fig. 13 exacerbates the disproportion in filling ratio.

4 Conclusions

Improper control of cylinder filling in an IC engine can adversely affect harmful substance emissions, as simulations have shown. The utilization of electronic throttle control systems solves this problem to a significant degree. It is vital to maintain the throttle in a good technical condition. Its contamination or wear of its components may result in an improper operation.

Unevenness of filling in a multi-cylinder engine can result in different excess air coefficient for each of the cylinders. Conducted experimental researches have shown uneven velocity field distribution at cylinder inlets of the exemplary manifold during even air extraction from every canal. Such state does not occur during engine operation - in real-life conditions, the air is being sucked out of each cylinder alternately. However, it can be assumed that the conducted research gives an outlook on flow resistances for each cylinder inlet. Discrepancies occurring during a real work cycle will affect cylinder filling to a smaller degree, however the differences in cylinder filling shown in the course of this research will occur during engine operation, albeit to a smaller degree. The research has also shown that a larger capacitive part of the manifold is essential. It not only positively affects the uniformness of the velocity field distribution, but also reduces the unwanted wave effect occurring due to the pulsating nature of valvetrain operation.

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