

## SPATIAL FLOW VELOCITY DISTRIBUTION AROUND AN INLET PORT/VALVE ANNULUS

by

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*An experimental investigation of the airflow through inlet port of a standard production direct injection diesel engine is presented. The investigation comprises mass flow rate and pressure drop measurements at fixed valve lifts, and spatial distributions of mean and r.m.s. velocity components around the port/valve annulus measured under steady flow conditions by special designed miniature hot-wire anemometer X probe. The results show that the velocity field is distributed non-uniformly across the valve gap and around valve periphery. Nonuniformity is more expressed at higher valve lifts. Flow instability in a jet leaving the port (jet flapping) is also evident since the skewness and kurtosis of the velocity probability distribution function depart from the Gaussian form. The presented experimental method, based on the application of miniature multiple hot-wire probes, makes possible investigation of flow performances of an inlet port and poppet valve assembly of a production engine head without any modification for ensuring an optical access within the port/cylinder.*

Key words: *internal combustion engine flow, inlet port/valve assembly, hot-wire anemometry, spatial flow velocity distribution*

### Introduction

The processes of engine mixture formation and combustion proceed in the turbulent flow ambient created during the intake phase and then intensified by the shape of combustion chamber. Initial structure of in-cylinder turbulent flow field is strongly affected by the configuration of intake system, as well as the geometry of port and valve. Therefore, the investigation and optimization of the intake port and valve design is very important for the achievement of projected engine performances.

The performance of intake system is usually tested under steady flow conditions, at fixed valve lift and constant pressure drop. Neglecting of dynamic aspects of engine operation (the motion of piston and valve, as well as the pressure variation in an intake system) not affect essentially port/valve performance in real engine conditions. This evidence was confirmed by Fukutani and Watanabe [1], Desantes *et al.* [2], and Smith *et al.* [3] for the case of integral flow parameters (mass flow rate and flow coefficients), as well as Bicen *et al.* [4], Khalighi *et al.*, and El Tahry *et al.* [5, 6], Arcoumanis *et al.* [7], and Weclas *et al.* [8] in the case of the distribution of mean and r.m.s. velocities at the valve exit plane. Though the measurement of integral flow parameters at steady flow conditions is not too difficult, the measurement of turbulent flow characteristics in the gap between valve head and seat is much more complex. By application of

non-obtrusive optical measurement methods, a complex geometry leads to the problem of laser beams refraction, which is usually overcome by using the refractive index matching technique. The latter involves replicas of the port and cylinder made from acrylic plastic material, which has the same refractive index as a working fluid (in this case usually water or mixture of oil of turpentine and tetraline). All this means that it is necessary to take into account the geometric, kinematics, and dynamic conditions of flow similarity. Such procedures of measurements are presented by Chen *et al.* [9], Mahmood *et al.* [10], and Nadarajah *et al.* [11], using laser doppler anemometry (LDA) measurements, by Bensler *et al.* [12], using particle image velocimetry (PIV) technique, and by Fan *et al.* [13], using particle tracking velocimetry (PTV) measurement technique.

At the other side, the application of single hot-wire anemometry probe for the measurement of flow field at the valve exit plane is much simpler, but this probe is flow direction insensitive. Wagner and Kent [14] tried to solve this problem by the rotation of probe at many orientations (so-called multiple orientation hot-wire technique). However, whole procedure is very complex, requires significant modification of cylinder head and the validity of results is still very uncertain.

Another more reliable and efficient approach, which uses classical advantages of thermal anemometry with good reproductively of turbulent flow field, is the measurement with modern miniature multiple hot-wire probes [15-17]. The results of such measurement are presented in this paper [18, 19].

## Test procedure

### Flow configuration

The measurement is carried out on the standard production cylinder head of direct injection diesel engine under steady flow conditions. A cylinder head with intake manifold was mounted at the outlet of wind tunnel and fitted with the open-ended cylinder of 90.5 mm bore. At the opposite end of open wind tunnel a high-pressure blower was installed, providing necessary air mass flow rates (up to 165 kg/h). To reduce flow losses, the connecting pipe between the wind tunnel and intake manifold was designed with gradually decrease of inner diameter. The main dimensions of tested tangential type intake port and its position related to cylinder axis are shown in fig. 1.

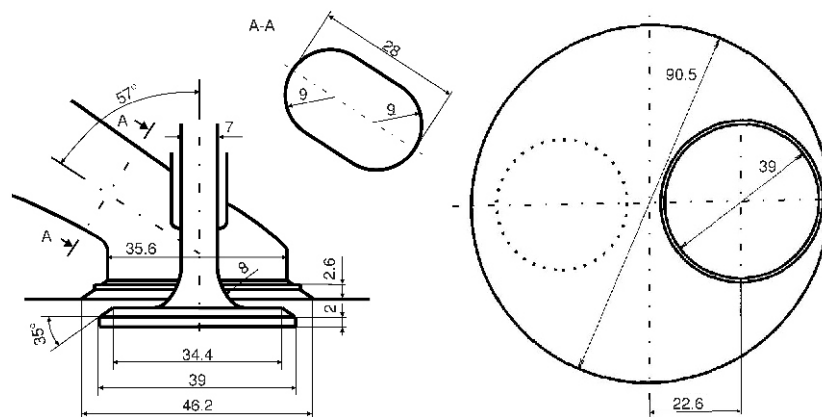


Figure 1. Intake port/valve (left) and cylinder head (right) geometry

### Discharge coefficient measurements

The air mass flow through the intake port/valve assembly,  $\dot{m}$ , is controlled by changing the high-pressure blower rotation rate. The total pressure upstream of the valve,  $P$ , is measured by Pitot tube installed at the outlet of wind tunnel, and static pressure downstream of the valve,  $P_0$ , is assumed to be atmospheric; the pressure drop across the valve is taken as  $\Delta P = P - P_0$ .

The discharge coefficient,  $C_f$ , which is a measure of overall flow losses in port/valve assembly, is calculated using the peripheral lift curtain area,  $\pi d_v h_v$ :

$$C_f = \frac{\dot{m}}{\pi d_v h_v \sqrt{2P\rho \frac{P_0}{P} \frac{2/k}{1} \frac{P_0}{P} \frac{(k-1)/k}{k} \frac{k}{1}}}$$

Values of flow coefficients are calculated in the whole range of valve lift ( $h_{vmax} = 9.2$  mm) at constant pressure drops across the valve of 1, 2, 3, 4, and 5 kPa.

### Velocity measurements at the valve exit plane

The values of mean and rms velocity components at the valve exit plane, in annular area between valve seat and sealing faces (valve curtain area), are measured with specially designed hot-wire X probe. The probe is designed in the Turbulence Flow Laboratory at the University of Montenegro, where also all measurement is carried out. Tungsten wires with  $2.5 \mu\text{m}$  dia and  $0.7$  mm length was used as probe sensors. The wires are attached to the tips of Cr-Ni-Mo steel alloy

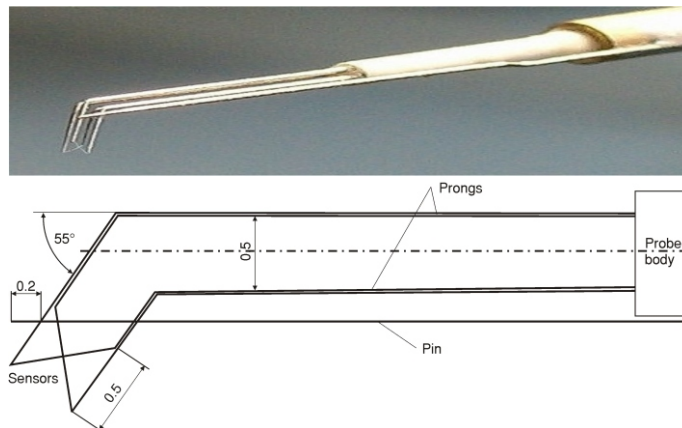


Figure 2. Design and main dimensions of hot-wire X probe

prongs bended at the top at an angle of  $55^\circ$ , which corresponds to the valve seat cone angle. The position of prongs is chosen in such way to achieve minimal scale of measurement volume, and to obtain minimal thermal interference between the sensors (fig. 2).

The probe has been moved in the valve gap from the open end of cylinder. For that the probe should be guided very precisely and closely to the cylinder wall. In this purpose, a special traversing mechanism, enabling controlled translation of the probe in all three orthogonal directions, as well as a rotation in horizontal and vertical plane, was designed. Accuracy of the probe translations with this traversing mechanism was  $10^{-2}$  mm. The exact position of the probe related to cylinder head and valve was realized using pin attached to the probe body side. The pin contact with cylinder head, as well as with valve head, was registered by the change of its electrical parameters. The position of probe related to cylinder head and valve is shown in fig. 3.

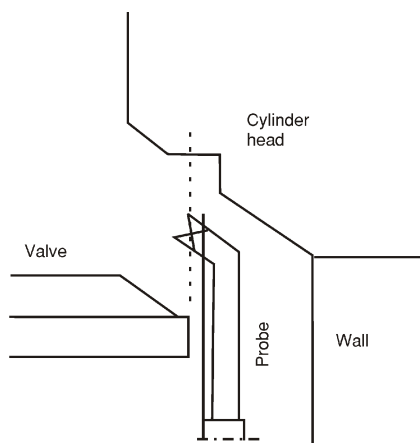


Figure 3. The position of probe in the valve gap

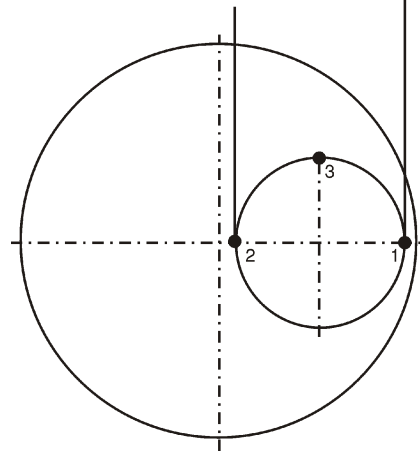


Figure 4. The measurement planes

The probe calibration was done in a potential core of the free round jet of the open wind tunnel, with turbulence level on the centerline below 0.5%. A set of reference calibration data was obtained by “yawing” the probe (probe rotation in the plane of sensors) in the range of  $\pm 30^\circ$ , with the step of  $5^\circ$ , and for each value of yaw angle a velocity calibration was carried out covering a velocity range of 0.5–40 m/s.

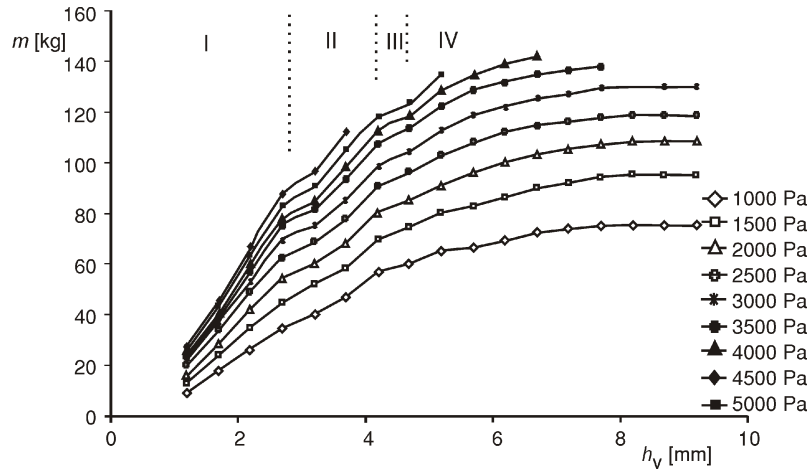
The velocity profiles at the valve exit plane were measured at constant air flow rate of 47 kg/h (which corresponds to the mean flow rate of the unsteady flow for an engine speed of 400 rpm) at three characteristic azimuthal locations around the valve periphery (fig. 4). The mean velocity was obtained by time-averaging the instantaneous velocity values, and turbulent component (the intensity of turbulence) was calculated as root-mean square value of fluctuating velocities.

### Results and comments

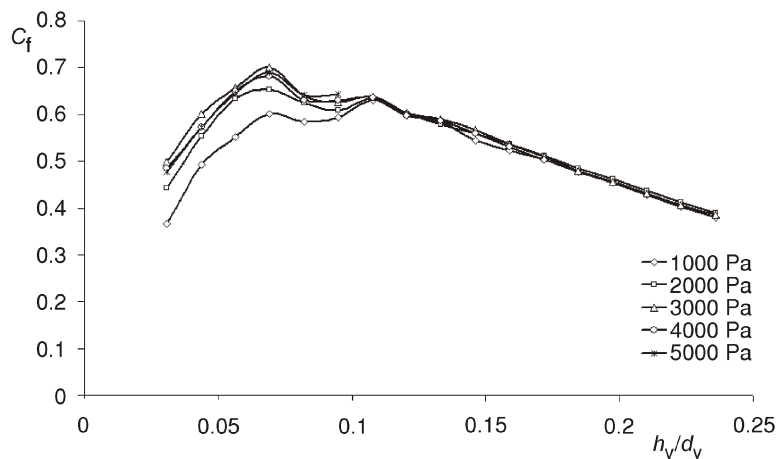
The curves of mass flow rate vs. valve lift, with the pressure drop across the valve as a parameter, are shown in fig. 5. It can be seen that the port/valve flow exhibits four flow regimes indicated by changes in curve slope. The interpretation of these results is similar to that of refs. [4, 8, 20]. At small valve lifts ( $h_v < 2.8$  mm), the flow is initially attached to the walls of the valve passage and corresponds to the flow regime I. For valve lifts greater than 3 mm the flow detaches from the valve sealing face and effectively reduces the actual flow area, corresponding to the flow regime II. The increase in valve lift to values above 4.2 mm results in flow separation not only at the valve but also at the valve seat, and sets on the transition to the flow regime III. With further increase of valve lift ( $h_v > 5$  mm) the flow reattaches on the valve but remains detached at the valve seat. This final state of flow is commonly denoted as flow regime IV.

Aforementioned four flow regimes can be also seen at fig. 6, which shows the change of discharge coefficient in the function of dimensionless valve lift  $h_v/d_v$ . It is evident that discharge coefficient is strongly pressure drop dependent at small valve lifts, much more at lower pressure drop. This is the consequence of pronounced viscous effects at low Reynolds numbers. As the flow velocity increases, and hence the Reynolds number, the flow in the valve passage

**Figure 5. Variation of mass flow rate with valve lift and pressure drop**



**Figure 6. Variation of discharge coefficient with dimensionless valve lift**



becomes highly turbulent and viscous effects less important. Then discharge coefficient starts decrease linearly with increasing valve lift, collapsing into one curve. In final zone discharge into the cylinder is not affected by any reduction in flow area and the only influence on the  $C_f$  is assumed to be surface friction on the valve sealing face.

The analysis of flow patterns at the valve exit is used for the determination of valve positions in which the velocity distribution measurement should be performed. The valve positions of  $h_v = 4, 6,$  and  $8$  mm have been selected as characteristic points (concerning processes of flow separation). The distributions of radial and axial mean and rms velocity components at selected valve lifts, at all three azimuthal locations around the valve periphery (three measurement planes in fig. 4), are shown in figs. 7-9. All the velocity values are normalized by the mean piston speed  $V_k = 1.693$  m/s.

Figure 7 shows the distribution of radial and axial velocity components in the measurement plane 1, which is the closest to the wall. It was expected that the vicinity of the wall will affect considerably the flow field deviation in this plane. However, the comparison with the corresponding velocity profiles in diametrically opposite plane 2, fig. 8, shows that the influence of cylinder wall in this case is relatively small. Nevertheless, some differences can be seen: for ex-

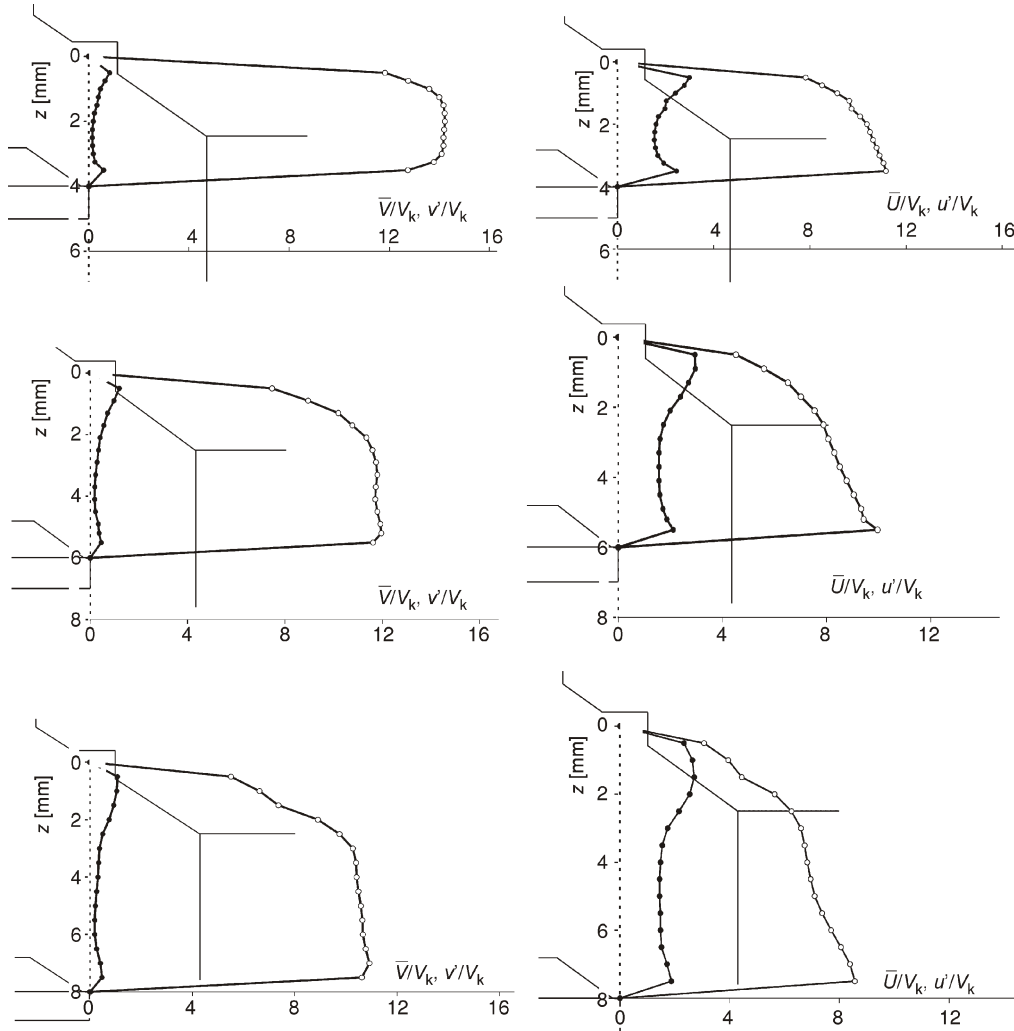
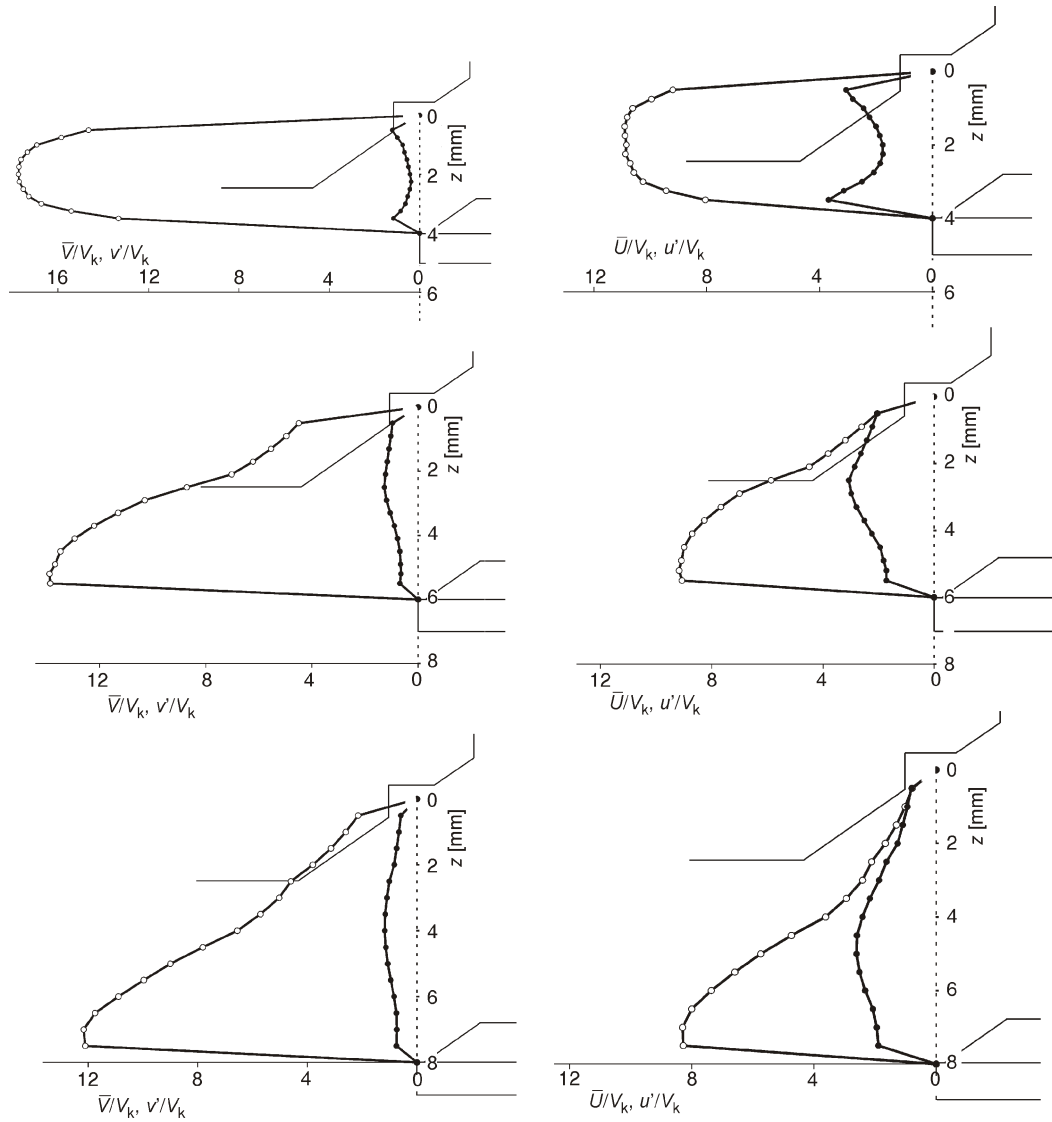


Figure 7. Radial (left) and axial (right) velocity profiles at the valve exit, in the measurement plane 1 (—○— mean velocity, —●— rms velocity)

ample, at  $h_v = 4$  mm, in the measurement plane 1 there is no almost any flow separation, but in the plane 2 it exists at both sides of valve passage, though at valve seat side the flow shows the tendency to reattach to the wall before leaving the valve gap. At higher valve lifts ( $h_v = 6$  mm and  $h_v = 8$  mm), in the plane 2, the bulk flow is directed to the internal side of valve head, with aforementioned tendency of the small part of the flow near the valve seat to reattach to the wall again; in the plane 1, the distribution of fluid flow is much more uniform.

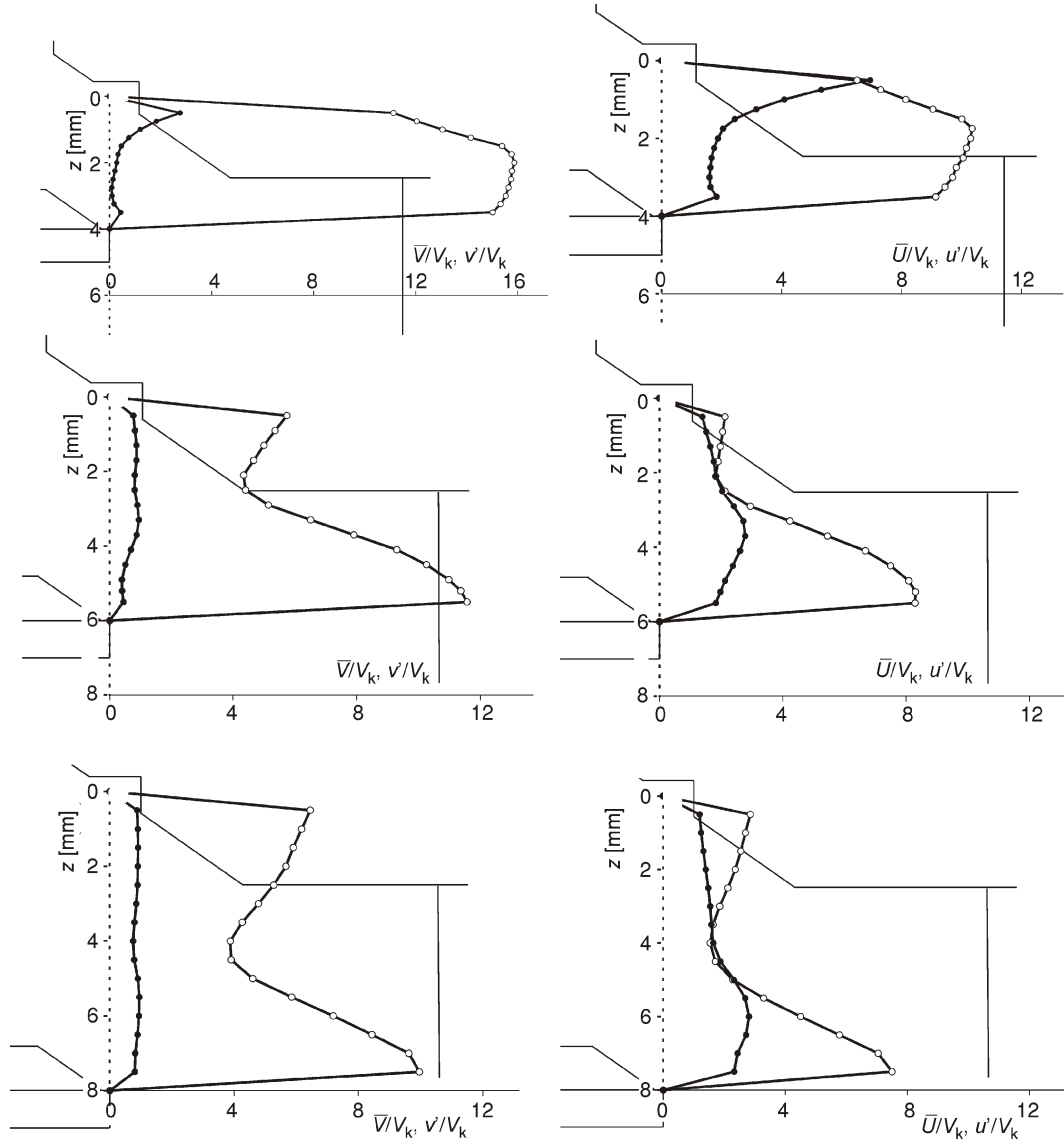
The velocity distribution in the measurement plane 3, fig. 9, is also very interesting. In this plane, at medium and high valve lifts, the profiles of radial and axial mean velocities have the patterns which can not be explained easily. The occurrence of higher mean velocities at the jet edge than in the middle jet region has not been noticed by the other researchers, for example [4-10, 14], in spite of analyzed flow configuration. Therefore, the obtained results need additional explanation. It should be noted here that the validity of obtained mean velocity profiles is



**Figure 8. Radial (left) and axial (right) velocity profiles at the valve exit, in the measurement plane 2**  
 (–○– mean velocity, –●– rms velocity)

checked by the comparison of mass flow rate calculated on the basis of the distribution of radial velocity along the height and circumference of valve curtain area, and the mass flow value measured during the experiment. The good agreement of these two values (difference is less than 2%) justifies the results of measured mean velocity profile.

As concerns the distribution of rms velocity in plane 3, it can be noticed extremely high turbulence intensity at  $h_v = 4$  mm in the boundary layer of jet near the valve seat. At  $h_v = 6$  mm and  $h_v = 8$  mm, the turbulence intensity, similar as in the measurement plane 2, is the highest in the middle jet region, what can be explained by intensive jet flapping again.



**Figure 9. Radial (left) and axial (right) velocity profiles at the valve exit, in the measurement plane 3**  
 (—○— mean velocity, —●— rms velocity)

All these differences in the mean velocity distribution in measurement planes 1 and 2 are much clearer in the case of the presentation of mean velocity flow field in vector form, plots in fig. 10. Also, there are some differences in the distribution of rms velocity components in these planes: in the plane 1, at all observed valve lifts, the high rms levels found, as expected, at the edges of jet, because this is the region of the most intensive turbulence generation; in the plane 2, however, at higher valve lifts ( $h_v = 6$  mm and  $h_v = 8$  mm), the highest turbulence intensity is created near the centre of the jet, which can only be explained by the occurrence of high dynamic flow instability in the jet (jet flapping) in this measurement plane.



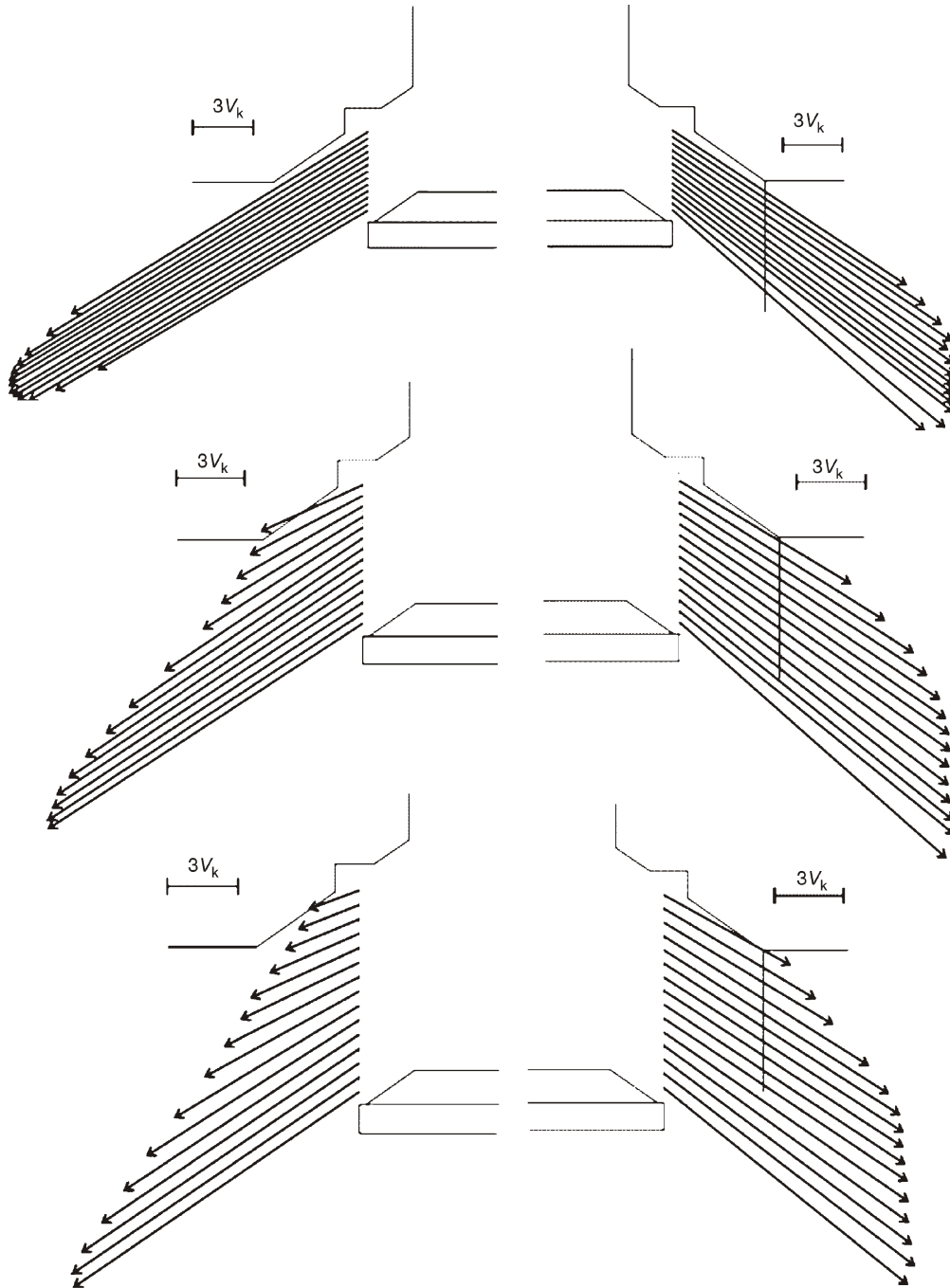


Figure 10. Velocity vectors at the valve exit, in the measurement planes 2 (left) and 1 (right)  
 $h_v = 4$  mm (up),  $h_v = 6$  mm (middle),  $h_v = 8$  mm (down)

Dynamic flow instability of jet (jet flapping) may be one possible source of cycle-by-cycle flow variation and, therefore, it represents very important research problem. Useful

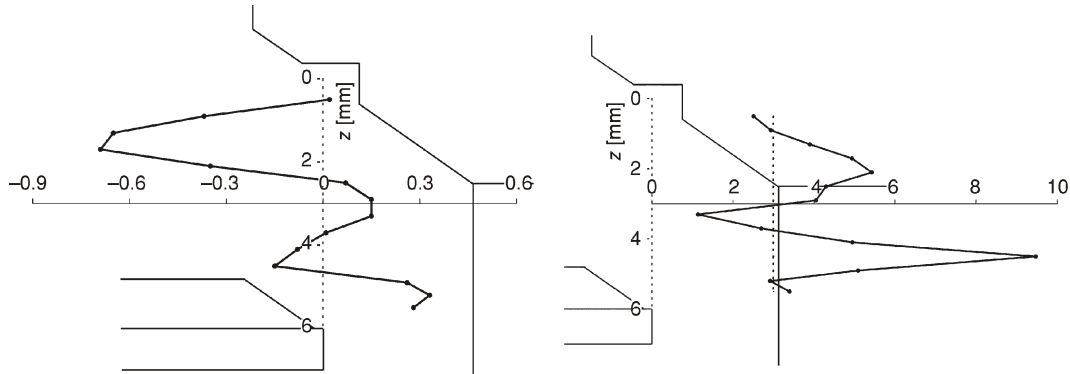


Figure 11. Profiles of skewness (left) and kurtosis (right) at  $h_v = 6$  mm, in the measurement plane 3

indications of possible jet instability are the third (skewness) and the fourth (kurtosis) moment of the velocity probability distribution function, [11]. The deviation of these parameters from their relevant values at Gaussian distribution (0 and 3, for skewness and kurtosis, respectively) may imply jet flapping/instability. Figure 11 shows the changes of skewness and kurtosis factors in the jet in the direction of valve gap centerline (the direction of probe axis) for the measurement plane 3 and  $h_v = 6$  mm.

## Conclusions

The velocity distribution at the exit plane of the intake port/valve, very important for the prediction of in-cylinder flow field, has been investigated using special designed hot-wire X probe. Obtained results enable detailed analysis of flow patterns and dynamic flow instability of the jet at the valve curtain area. The fact that the research has been carried out at standard production engine head, in the conditions where the application of LDA or other laser oriented measurement technique is not possible, opens the perspective for further application of miniature multiple hot-wire probes in the investigation of flow performances of internal combustion engine intake systems.

## Nomenclature

$C_f$ – discharge coefficient, [-]	$\bar{U}, u$ – axial velocity components, mean and rms respectively, [ $\text{ms}^{-1}$ ]
$d_v$ – valve head diameter, [mm]	$\bar{V}, v$ – radial velocity components, mean and rms, respectively, [ $\text{ms}^{-1}$ ]
$h_v$ – valve lift, [mm]	$V_k$ – mean piston speed, [ $\text{ms}^{-1}$ ]
$m$ – mass flow rate, [ $\text{kg h}^{-1}$ ]	$z$ – distance from cylinder head, [mm]
$P$ – total pressure upstream of the valve, [Pa]	
$P_0$ – static pressure downstream of the valve, [Pa]	

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