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CHARACTERISTICS OF THE FLOW FIELD IN THE COMBUSTION CHAMBER OF THE INTERNAL COMBUSTION TEST ENGINE

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Results of a research study into the velocity field in combustion chamber of internal combustion engine are presented in the paper. Measurements of fresh charge flow velocity in the cylinder axis and near the cylinder squeezing surface were performed. The hot-wire anemometer was used. The measurement results were used for analysis of turbulence field in the examined combustion chamber. It turned out that in the axis of cylinder the maximum of velocity occurs 30 deg before TDC and achieves 6 m/s. In the studied combustion chamber, the maximum value of turbulence intensity was close to 0.2 and it was achieved 35 deg BTDC. Additionally, the maximal velocity dispersion in the following cycles of the researched engine was at the level of 2 m/s, which is 35% of the maximum value of flow velocity. At a point located near the squeezing surface of the piston, a similar level of turbulence, but a the smaller value of the average velocity was achieved. The turbulence field turned out to be inhomogeneous in the combustion chamber.

Keywords: engine, measurement, flow field, turbulence

1. INTRODUCTION

Determining the influence of engine working space geometry on flow field turbulence in piston engine cylinder had significant impact on developing new combustion conceptions: lean mixture combustion, heterogeneous mixture combustion and on high-speed, high-pressure engine design. An increase in turbulence intensity entails an increase in combustion speed. Lower non-repeatability of speed in successive cycles is observed in engines with charge in cylinder swirl (Horvatin and Hussman, 1969; Wigley and Hawkins, 1978). In consequence, it leads to lower engine thermal cycle non-repeatability. One of the fundamental problems in combustion engines domain, which has been researched from many years, is non-repeatability of work cycles (Urushihara et al., 1996). In 1966 Patterson (Paterson, 1966) observed non-repeatability of cycles on the basis of pressure variation. Many researchers have studied the unrepeatability of engine cycles based on the analysis of combustion pressure (Wagner et al., 2000). One of the factors influencing this unrepeatability is the unrepeatability of the flow field around the spark plug, which significantly affects the ignition kernel formation (Cupiał et al., 2007). Whitelaw and Xu (Whitelaw and Xu, 1995) researched the influence of charge swirl on non-repeatability of engine work cycles. Velocity fluctuation was found to influence engine work cycles non-repeatability. Charge swirl contributes to an increase of flame kernel shape repeatability. Introducing charge swirl has caused an increase in cylinder pressure and combustion speed increase of 10-16%. For engines without charge swirl the turbulence has been described as isotropic and homogeneous (Das and Chmiel, 1994; Mirkowski, 1995). For engines with charge swirl strong anisotropic and non-homogenous turbulence has been observed. Heywood (1986; 1988), and

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Pischinger have affirmed that the optimal charge swirl velocity near the spark plug should be in the range of 3-5 m/s because of heat loss and flame kernel development. Higher charge flow velocities make the glow phase of discharge on spark plug break off. Erdil and co-workers (Erdil et al., 2002) presented results of their investigation of experimentally measured turbulent velocity field in an SI engine. They found that the velocity field in the cylinder of IC engine is unrepeatable in the following cycles. Akkerman and co-workers (Akkerman et al., 2009) found that the rms-turbulent velocity is smaller than the piston speed. In the case of zero initial turbulence, the flow at the top-dead-center may be described as a combination of two large-scale vortex rings of a size determined by the engine geometry. When the initial turbulence is strong, then the integral turbulent length demonstrates similar properties in a large range of crank angles (Akkerman et al., 2009). Huang and co-workers (Huang et al., 2009) have studied spatial evolution processes of flows in the cylinder of a four-valve, four-stroke, single cylinder, reciprocating motorcycle engine installed with elliptic and circular intake ports. They found that the cycle-averaged turbulence intensity in the symmetry plane of the engine with the elliptic intake port is larger than that of the engine with the circular intake port. Physically, a larger tumble ratio and turbulence intensity imply larger rotation rate and diffusivity, and therefore could promote mixing and flame propagation properties in the flow field (Huang et al., 2009). Research on engineless test bed is one of ways of flow processes in engine cylinder analysis (El Khafaji et al., 1972). This test bed is a physical model of engine intake process. Numerical research into engineless test bed allows to investigate inlet manifold properties and the influence of inlet manifold shape on charge swirl rate at the end of compression stroke (Sak et al., 2007; Wigley and Hawkins, 1978). This is a typical method, which is commonly used to comparative investigations (Breuer et al., 2005). A suitable level of charge turbulence in the combustion chamber of the IC engine is one of the methods of improving the combustion process. A suitable turbulence level of the charge is obtained by the initial swirl and squish. The initial swirl in the cylinder is made by the intake system (Paul and Ganesan, 2010). The flow of charge in the radius direction inward the chamber is forced by squeezing the surface of the piston. Obtaining the proper velocity of charge near spark plug is an essential problem.

Research studies using hot-wire anemometer (CTA) are very often used in investigation of flow processes of combustion chamber of internal combustion engines. This method is relatively cheap as it allows to mount probes instead of a spark plug or injector (Catania and Mittica, 1985; 1989; Hassan and Dent, 1971; Mirkowski, 1995). Laser method requires a proper adapting of the engine. In combustion chamber special glass windows in the destination of implementing laser rays should be mounted (El Khafaji et al., 1972; Hascheret al., 1997). This method was applied for studying the flow field in the combustion chamber of IC engine. Based on measurements with LDA the method showed that the maximum of swirl velocity of fresh charge was appearing a few degrees before TDC (Hascheret al., 1997). The authors proved that the intensity of turbulence was increasing linearly with the growth of the rotation speed of the engine (Dimopoulos and Boulouchos, 1997).

The best thing of the CTA method is that it makes it possible to investigate flow velocity inside the bowl of a piston (Catania and Mittica, 1985; 1989). Using CTA method both an average speed and parameters determining the turbulence of charge were determined (Dimopoulos and Boulouchos, 1997; Heywood, 1986; Horvatin and Hussman, 1969). Intensity and kinetic energy of the turbulence were calculated on the basis of the obtained data. This method was used to point out to swirl process in the cylinder of IC engine (Urushihara, 1996).

The value of the signal depends not only on the fluid flow velocity but also on the pressure of the fluid. The impact of this factor should be taken into account at calculating flow parameters based on CTA signals (Mirkowski, 1995).

The present study into charge flow field in combustion chamber of piston engine can be a source of valuable information for better knowledge concerning phenomena taking place in the piston engine. It has been proved many years ago that the swirl of fresh charge in the cylinder of piston engine has a direct impact on charge preparation to combustion and significantly influences the initial geometric shape of flame kernel in spark ignited engines. Better repeatability of flame front propagation in combustion chamber occurs in engines with adequate charge turbulence level before the initiation of combustion. In consequence it leads to lower non-repeatability of following engine cycles which is most important in engines combusting lean mixture. The combustion process in such engines is characterized by low flame front propagation velocity and the great non-repeatability of following engine cycles.

2. THE TEST STAND

The study was conducted on a single-cylinder S320 test engine working at 1000 rev/min. The compression ratio of the engine is 8.5. The head is designed in a four-valve system that allows to install up to 9 spark plugs. Two of the spark plug seats are used as pick-up seats. One of them was located in the axis of cylinder (Point A) of the cylinder and the other near piston squish surface (Point B). The measurements were conducted with a fully open throttling valve. The combustion engine was equipped with electric engine working as a prime mover. The measurements were conducted on the engine driven without supplying fuel.

The test stand (Fig. 1) consisted of:

- Single cylinder S320 test engine,
- Electric engine working as a prime mover,
- Air flow through engine measurement system consisting of Roots flowmeter and equalizing tank of volume equal to 1.5 m2,
- Digital data acquisition system for fast-changing pressure in engine cylinder recording,
- Kistler CAM 2611 digital crank angle transducer,
- FMC 921 hot wire anemometer extension card,
- Hot-wire anemometer pick-ups for in-cylinder flow velocity measurements equipped with adaptors designed to mount the pick-ups in spark plug seats.

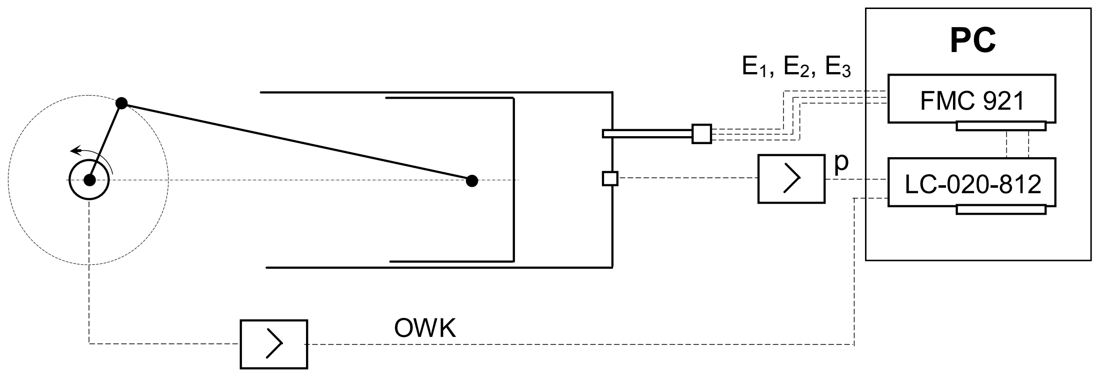

Fig. 1. Measurement system diagram

Pressure recording system:

- Piezoelectric pressure pick-up - Kistler SN 6061,
- Charge amplifier - Kistler 5011,
- Digital crank angle transducer - Kistler CAM 2611
- Oscilloscope - HAMEG HM 2037,
- 12-bit, eight-channel analogue-digital converter extension card - AMBEX LC020812,
- IBM PC/AT computer,
- "LCTXR" software designed for data digital recording

The software designed for data digital recording and the necessity of registering five channels simultaneously allowed to register up to 80 cycles. The hot-wire anemometer pick-up in X configuration with perpendicular sensors was used in order to measure the charge flow velocity. The hot-wire anemometer and measurement probe was an original solution of the authors. That construction of the probe allows to place the measurement part of the probe inside combustion chamber in many points. Additionally, that construction makes it possible to rotate the measurement probe around its axis which allows to select accurate direction of measurement. The anemometer extension card FMC 921 adapted to the pick-ups was used in the measurement system. Using such measurement system allowed to record and store measurement data directly in the PC computer. The software used the calculation algorithm on the basis of registered signals. The measurement extension card is equipped with two hot-wire anemometer sets.

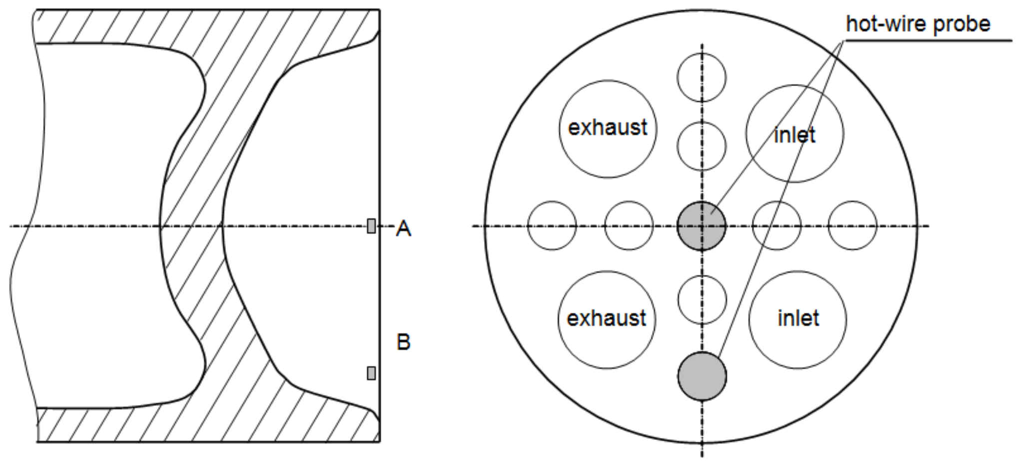

Fig. 2. Configuration of measurement points in combustion chamber of test engine

Figure 2 presents a configuration of measurement points in combustion chamber of the test engine. The measurement probe could be placed in two points: A and B. One was in the axis of the engine cylinder and the second was located near the squish surface of the piston. Both points were located in spark occurrence of normally working engine.

3. MEASUREMENT METHOD

The hot-wire anemometer method is one of the few methods which is possible to use in research studies of flow field of fresh charge inside cylinder of internal combustion engine. This method allows to use some technological holes which have already been done in the head of engine to mount a probe. The hot-wire sensor is constructed from supports and a wire is spread between them. The sensor is connected to one of the branches of Wheatstone bridge which is supplied with output voltage from servo-amplifier. A hot wire anemometer makes use of the principle of heat transfer from a heated surface being dependent upon the flow conditions passing over it. The main principle of a constant temperature hot-wire anemometer (CTA) is that mean temperature of wire must have a constant temperature A supply voltage of the bridge can be increased to maintain a constant temperature.

At the first stage of anemometer’s work there is an increase of voltage that powers the Wheatstone bridge which lasts until the resistance of the sensor achieves the intended value. In steady conditions of flow, the electric power P supplied to the wire, due to electro-thermal transformation of energy, turns into the heat stream $\dot{Q}$:

$$P = \dot{Q} = I_w \cdot U_w = I_w^2 \cdot R_w = \frac{U_w^2}{R_w} \tag{1}$$

A drop of the voltage on the wire is part of the voltage supplying the measuring bridge:

$$U_w = \frac{R_w}{R_1 + R_w} \cdot U \tag{2}$$

In consequence the electric power can be described by:

$$P = \frac{R_w \cdot U}{\left(R_1 + R_w\right)^2} \tag{3}$$

The heat stream carried away by convection from the hot wire is described by:

$$\dot{Q} = \alpha \cdot S \cdot \left(\theta_w - \theta_0\right) = \alpha \cdot \pi \cdot d \cdot l \cdot \left(\theta_w - \theta_0\right) \tag{4}$$

or:

$$\frac{R_w}{\left(R_1 + R_w\right)^2} U^2 = \alpha \cdot \pi \cdot d \cdot l \cdot \left(\theta_w - \theta_0\right) \tag{5}$$

A proper description of heat exchange coefficient α presents the greatest difficulty. This coefficient is in the form of the dimensionless numbers: Nusselt, Reynolds and Prandtl numer. The dimensionless equations are given in the form as Kramers, Collis or Arques equation (Elsner and Drobniak, 1995). On the basis of studies conducted by Prof. J. Mirkowski in Institute of Internal Combustion Engines and Control Engineering, for probe made from PtRh 10, diameter 10 μm, the following equation is obtained (Mirkowski, 1995):

$$Nu = 9.00327 \cdot 10^{-2} + 0.954164 \cdot Re^{0.327} \quad \text{for} \quad 0.1 \le Re \le 7 \tag{6}$$

The wire of the probe can be warmed up to temperatures not higher than 1200K. For this reason this method can be used only for driven engine without combustion process. In normal working engine temperature would be higher than the temperature of wire. In driven engine, temperature of air, during compression stroke, achieves the value of approximately 700K. In order to obtain correct results the correction of measurement signal is necessary for the sake of pressure and temperature changes.

Pressure and temperature changes occur at the same time in the cylinder. During calculating flow velocity on the basis of stored data from measurement bridge compensation of influence of the above mentioned parameters should be done. To this end pressure in the cylinder of IC engine should be measured at the same time with signals from CTA unit. In this case piezoelectric sensor was used. Pressure signal was used to calculate temporary air density in the cylinder. On the basis of pressure, air temperature in the cylinder of engine was calculated. In order to determine kinetic viscosity in following crank angles, equations describing changes of this parameter in temperature function $\eta = \eta(T)$ were written. Nusselt number is function of surface film conductance coefficient and thermal conductivity coefficient of fluid. Values of the above mentioned parameters depend on fluid temperature. For that reason any changes of these parameters should be taken into consideration. Special equations were determined on the basis of literature (Dimopoulos and Boulouchos, 1997), which defined the dependence of thermal conductivity as a function of temperature. Parameters which describe fluid properties were determined for layer temperatures around hot wire (Elsner and Drobniak, 1995). An increase of fluid pressure causes an increase of signal value from the measurement system. Instantaneous temperature measurement system was calibrated in thermal chamber. Voltage signal from temperature measurement system is linearly dependent on temperature. An amplification factor k_θ [V/k] is determined as a result of calibration. Measurement system is treated as proportional with amplification k_θ. Time constant is calculated and corrected on the basis of voltage signal, which is treated as an inertial system. Detailed equations describing the used measurement method can be found in the literature (Elsner and Drobniak, 1995).

4. MEASUREMENT RESULTS INTERPRETATION

The flow field in the engine cylinder and of course in the combustion chamber is turbulent. Turbulent local fluctuations lead to an improvement in the mixing rate. It is essential to proper working of spark ignition engine. Turbulent flows are dissipative. In order to keep up turbulent processes is necessary to supply some energy. The mean source of turbulent velocity fluctuation is shear in the mean flow. Flow processes in the combustion chamber of internal combustion engine are turbulent and unrepeatable in the following cycles.

Statistical methods are used to define such a flow field. The instantaneous flow velocity of a specific cycle can be set as a sum of mean velocities of all cycles, mean velocity fluctuation and random fluctuation of component velocity.

$$U(\varphi,i) = \overline{U}(\varphi) + \widetilde{U}(\varphi,i) + u(\varphi,i) \tag{7}$$

In order to analyse the relation set, the flow velocity is given as a sum of mean velocity obtained by averaging the relation set regarding crank angle, value of mean velocity fluctuations and value of random velocity fluctuations.

The mean velocity value for all the analysed cycles:

$$\overline{U}(\varphi) = \frac{1}{N}\sum_{i=1}^{N} U(\varphi,i) \tag{8}$$

The mean velocity for the individual cycle $\overline{U}(\varphi,i)$ is determined by filtering voltage signal obtained from the measurement system. The filtering was conducted with a low-pass filter of experimentally selected limit frequency.

Fluctuation of mean velocity:

$$\widetilde{U}(\varphi) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\overline{U}(\varphi,i) - \overline{U}(\varphi)\right]^2} \tag{9}$$

Velocity fluctuation:

$$u(\varphi) = \sqrt{\frac{1}{N}\sum\left[U(\varphi,i) - \overline{U}(\varphi,i)\right]^2} \tag{10}$$

Turbulence intensity:

$$u' = \frac{u(\varphi)}{c_m} \tag{11}$$

Turbulent kinetic energy:

$$k = \frac{1}{2}\rho(u_i)^2 \tag{12}$$

The mean velocity $\overline{U}(\varphi,i)$ in the analysed cycle can be presented as a sum of mean velocity of all cycles $\overline{U}(\varphi)$ and mean velocity fluctuation $\widetilde{U}(\varphi,i)$:

$$\overline{U}(\varphi,i)=\overline{U}(\varphi)+\widetilde{U}(\varphi,i) \tag{13}$$

Such presentation of charge flow velocity in piston engine cylinder gives the value, which is most consistent with variations of velocity in real conditions. It gives information concerning mean velocity of all cycles, mean velocity fluctuations and fluctuation of velocity responsible for turbulence generation inside the engine cylinder.

5. RESULTS

The presented results were obtained on the basis of measurements using a single pick-up in the combustion chamber. The measurements were performed three times using the same pick-up. This made it possible to minimise any possible influence of measurement properties of the pick-ups in their first use on later obtained results.

Before the first use of the pick-up it was held at the temperature of 750K in the stream of air according to the manufacturer's recommendations. The measurements were also performed with the use of other pick-ups of the same type.

The flow field measurements were done at the ignition points (A) and (B) placed in the combustion chamber (Fig. 2). The test engine normally works as a multi spark ignition engine. Results in both points A and B (Fig. 3) for ignition points are presented below.

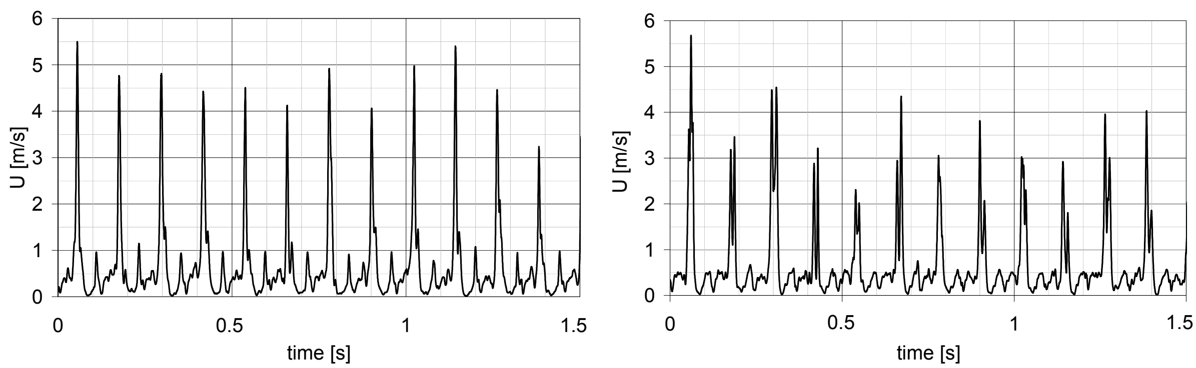

Fig. 3. Charge instantaneous velocity variation curves at the ignition points of the investigated combustion chamber, (left- in point A, right – in point B)

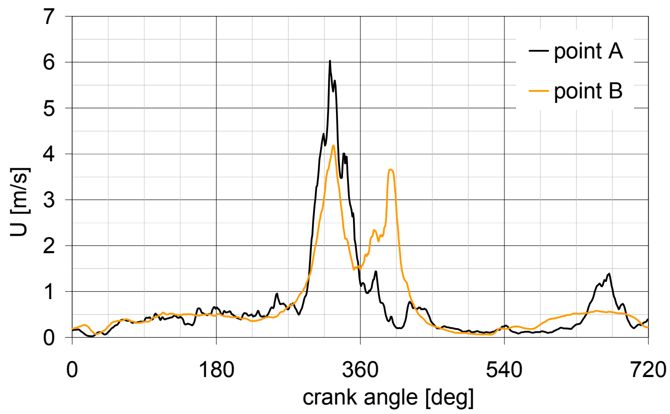

Fig. 4. Instantaneous velocity for single cycle of engine

Fig. 3 depicts the instantaneous velocities in the following engine cycles. High non-repeatability can be observed in the cylinder axis as well as near the squish surface of the piston. Velocities measured in the cylinder axis (point A) are shown on the left and velocities measured near the squish surface (point B) are shown on the right.

Figure 4 depicts instantaneous velocities obtained from one cycle of engine. The type of measured velocity variations near the piston squish surface reveals a direct influence of piston squish. The charge flow in the direction of the centre of combustion chamber occurs in the initial phase before 330° crank angle. After that there is retention of charge flow and then the charge begins to flow from the centre of the combustion chamber to the direction of cylinder walls. In the axis of cylinder the maximum of velocity occurs 30 deg before TDC and achieves 6 m/s. In the right picture two maximums of velocity are shown. One of them occurs 25 deg before TDC and the other occurs 35 deg after TDC. The former maximum was caused by squish effect which occurs at the end of compression stroke of the piston and the latter is caused by an opposite effect of piston movement. The so-called squish process, which proceeds at the end of the compression phase in the combustion chamber is important for the intensification of turbulence process. The hot-wire anemometer measurement method allows to obtain the absolute values of flow velocity. That is why two maximums can be seen in the flow velocity graphs. The change in the velocity sense occurs later in the measurement points located further from the head surface because the squish process starts later there. The flow field in the cylinder and consequently in the combustion chamber of IC engine is unrepeatable in the following cycles that cause difficulty in determining the mean velocity of a single cycle. On the basis of scientific literature (Catania and Mittica,1985), (Catania and Mittica,1989) and our own experience a range of frequency was determined which allowed to find the mean velocity by using digital filtrating of signals. Digital filtering of recorded signals determines the mean velocity of an individual cycle. The low-pass filter and LCT program were used to do so. Normalized limit frequency in the range of 18÷21 was determined. The harmonic of 18÷21 rank determine the mean velocity as the higher harmonics determine the velocity fluctuation.

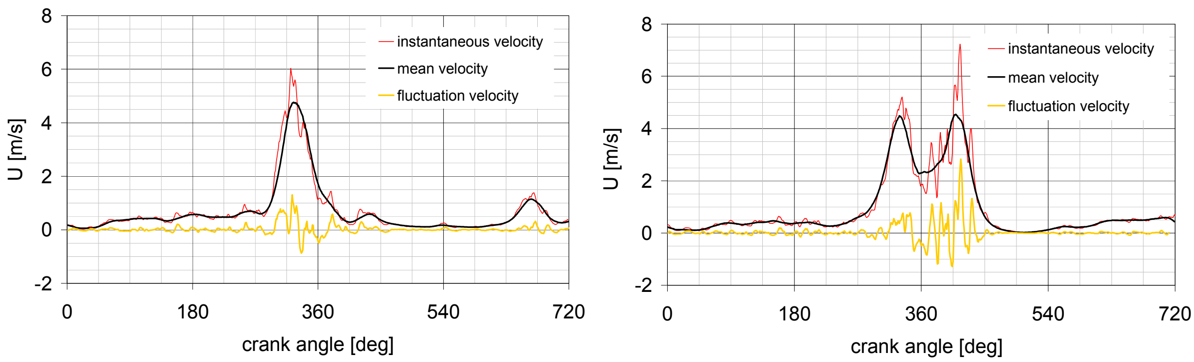

Fig. 5. Example of instantaneous velocity, mean velocity obtained by filtration and velocity random component variation in chosen cycle, (left- in cylinder axis, right – near to squish surface)

Figure 5 depicts decomposition of instantaneous velocity. As an effect of this decomposition two components of velocity are obtained: the mean velocity of a single cycle and random component of this velocity. Mean velocity is responsible for generating large scale eddies and swirl process which occurs in the cylinder of IC engine. The random component has an effect on production of small eddies and turbulence in the cylinder.

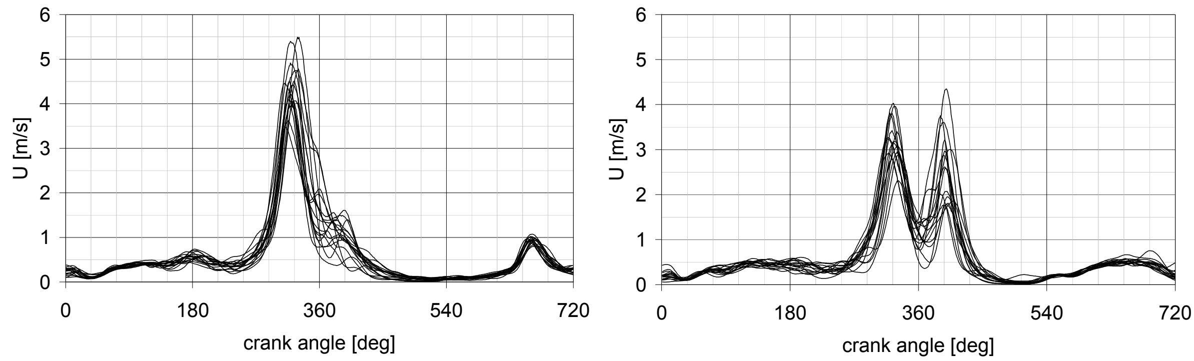

Fig. 6. Set of the mean velocities obtained by filtrating signals, (left- in cylinder axis, right – near to squish surface)

Figure 6 depicts the mean velocities received by digital filtrating of signal for following cycles. In both cases a significant spread of maximum of velocities as to value and crank angle was observed. This unrepeatability of mean velocity has an impact on unrepeatability of thermal cycle of IC engine. In normally working spark ignited engine for quality of thermal cycle an initial size and shape of ignition kernel has an essential impact. This shape and size is to a large degree depended on flow processes that occur in the vicinity of a spark plug. Too high flow speed or too high level of turbulence can disturb proper ignition process.

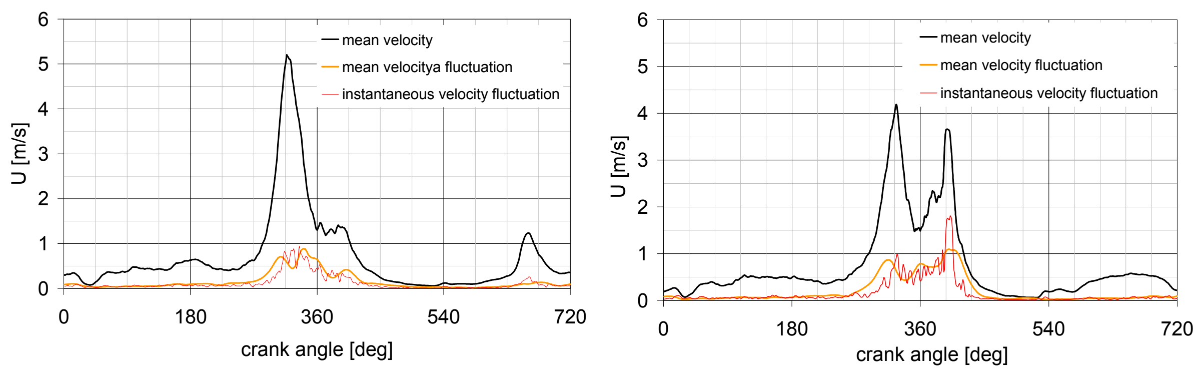

Fig. 7. Example of mean velocity, mean velocity fluctuations and velocity random component variation for data set, (left- in cylinder axis, right – near to squish surface)

Fig. 7 shows the mean velocity obtained as a result of averaging the mean velocity fluctuation and value of velocity random component for 80 following cycles regarding the crank angle. The mean velocity fluctuation informs about the variations of mean velocity in the following cycles of engine work. It can have significant influence on engine work non-repeatability as different flow conditions in following cycles occur in the ignition region. Instantaneous velocity fluctuation gives information on turbulence level in the combustion chamber.

Measurement data allow to calculate turbulence field parameters such as turbulence intensity u’ and turbulent kinetic energy k. Results of turbulent flow field measurements in the test engine are presented below. Figure 8 shows turbulence intensity in both ignition points of the engine. These two points are very important for working engine because ignition process occurs there. The turbulence intensity gains its maximum 35°CA before TDC. Two local maximums occur near the piston squish surface. It is caused by the charge return flow resulting from the piston movement in the direction of BDC.

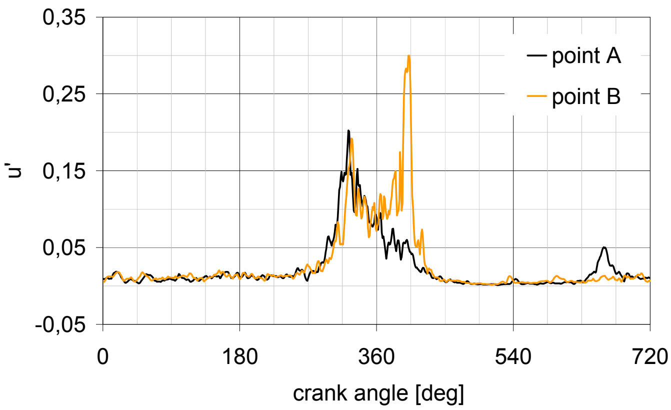

Fig. 8. Turbulence intensity variation curves at ignitron points

Figure 9 depicts turbulence kinetic energy determined on the basis of stored data. This data is connected with density of charge. It is known that charge in cylinder of IC engine has variable density. The maximum value of the turbulence kinetic energy in the axis of the cylinder before TDC was 5 J/m^3. In the axis located near the squeezing surface it was nearly 4 J/m^3.

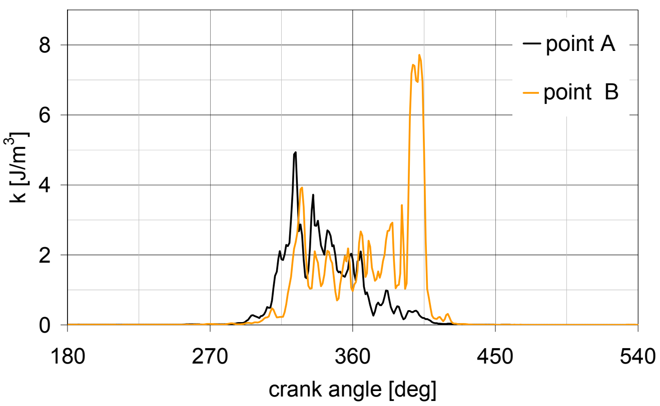

Fig. 9. Turbulent kinetic energy

Turbulence kinetic energy such as intensity has similar shapes of course. It can be produced by fluid shear or through external forcing at low-frequency eddies. Turbulence kinetic energy is dissipated by viscous forces at the Kolmogorov scale.

For working engine flow processes which occur before TDC is essential because these are responsible for turbulence effects. After intake valves closure there is an increase of charge turbulence caused by the generated macro-swirl and the charge flow from the area of piston squish surface to the cylinder centre. A high turbulence value in the region of ignition a few CA degrees before TDC is important regarding the engine work quality (Cupiał et al., 2007).

The presented measurement results show that the flow processes in the researched combustion chamber occur in the most intensive way near the engine head. Both the flow velocity and the charge turbulence parameters begin to increase after 270°CA and gain the maximum near 35°CA before TDC. It can be stated on the basis of analysis of turbulence intensity obtained at the successive measurement points that the highest turbulence occurs in the combustion chamber axis in ignition points.

6. CONCLUSIONS

The paper presents results of experimental research study of the flow field in the combustion chamber of internal combustion test engine. The hot-wire measurement method was used. The results showed that there is significant inhomogeneity of turbulent flow field in the engine combustion chamber. The main conclusions are:

- The measurements of velocity variations of charge inside the engine combustion chamber revealed high non-repeatability of these variations in the following cycles. The non-repeatability occurred in the aspect of the velocity values as well as the aspect of crank angle corresponding with the maximal value.
- The maximal velocity dispersion in the researched engine was in the following cycles at the level of 2 m/s, which is 35% of the velocity maximum value.
- It turned out that in the axis of cylinder the maximum of velocity occurs 30 deg before TDC and achieves the value equal to 6 m/s. In the combustion chamber of the investigated engine, the maximum value of turbulence intensity was close to 0.2 and it was achieved 35 deg BTDC.
- The maximum value of turbulence kinetic energy was 5 J/m3.
- Areas of considerably diversified turbulence are to found in the engine cylinder. Values of turbulence parameters in the area located near the squish surface of the piston are a little smaller than those in the axis of the cylinder, obtained before TDC . However, the maximum values were obtained during the expansion stroke (Point B), when combustion process dominated. Values of turbulence obtained before initiation of the combustion process are important for engines.
- The charge turbulence, which is generated during the intake stroke in the test engine, is also important regarding the engine work. The mixing of fuel and air occurs at that time, i.e. when the charge is prepared to be combusted. Homogeneity of air-fuel mixture leads to better combustion and as a consequence to a decrease in toxic components concentration in exhaust gases and an increase in engine work parameters.

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