Koc. J. Sci. Eng., 5(1): (2022) 22-30 https://doi.org/10.34088/kojose.789291

Kocaeli University

Kocaeli Journal of Science and Engineering

http://dergipark.org.tr/kojose

Two Dimensional and Stereo PIV Comparison for Port Applications

Burak YELKEN [1,*], İsmail Hakkı SAVCI [2], Zafer DÜLGER [3]

[1] *Department of Mechanical Engineering, Kocaeli University, Kocaeli, 41310, Turkey,* ***ORCID:*** *0000-0001-6902-8528*
[2] *Ford Otosan R&D Center, İstanbul, 34885, Turkey,* ***ORCID:*** *0000-0002-7923-6061*
[3] *Department of Mechanical Engineering, Kocaeli University, Kocaeli, 41310, Turkey,* ***ORCID:*** *0000-0002-5043-788X*

Article Info

Research paper

Received : September 02, 2021
Accepted : November 03, 2021

Keywords

Swirl
2D PIV
Stereo PIV
Uncertainty Analyze

Abstract

Fuel-air movements in-cylinder are one of the most critical diesel engine parameters to determine engine performance and emission. Swirling movement in the engine combustion chamber is investigated advanced experimental techniques to improve the air intake design.
Honeycomb measurement method and PIV (particle image velocimetry) method are used to measure the swirling airflow. The honeycomb measurement method can directly measure the swirl. However, it does not give detail information about the flow field. On the other hand, the PIV technique is one of the non-invasive measurement methods for swirl measurement. PIV can directly measure the velocity vector of the cylinder section.
In this study, the honeycomb measurement method was performed to measure the swirl ratio of 13L and 9L engines. The uncertainty analysis was determined for the reliability ratio of the measurement. In addition, PIV measurements are performed to understand the velocity field of the cylinder section. This velocity field gives detailed information about the center of the swirl and the velocity index of the velocity field.

1. Introduction

The most important fundamental parameters affecting engine performance are air intake quality, fuel injection values and air-fuel mixture. Therefore, the diesel engine's power, torque, and emissions are specified depending on these three basic parameters.

It is challenging to optimize the combustion phenomenon in the cylinder due to the fuel's high number of combustion parameters and the physics complexity. [1]. Some of these parameters, fuel pressure and droplet size, play a critical role in combustion efficiency. Another factor affecting the combustion quality is the flow structure inside the cylinder at the end of the compression process. The characteristics of flow start from the inlet of the intake port and develop during the combustion process.

When air enters the cylinder, two types of flow motion occur. The first is a swirl motion for a diesel engine and the other is a tumble motion for a gasoline engine. In Figure 1, the left flow represents swirl motion and the right one represents tumble motion [2].

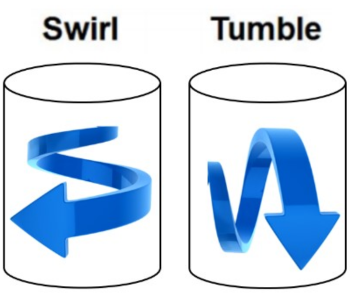

Figure 1. Swirl and Tumble notation [2]

Studies on the vortex motion properties in the cylinder and its effects on the combustion performance are still published. Different test rigs are used for design optimization to obtain the desired swirl pattern in the cylinder.

One of the critical parameters affecting the vortex motion is the engine's air intake duct design. The angular position of the air inlet duct is examined with particle

* Corresponding Author: yelkenburak@yahoo.com

imaging velocity measurement. With this method, the effects of various air intake geometries at different angular positions on the engine performance were analyzed on a test engine. It was found that the swirl and tumble properties were similar between other ports. However, they differ according to angular positions [3]. In terms of the valve's openings in the cylinder head, it has been observed that while the fully open valve gives the most vital large-scale structures, more significant amounts of kinetic energy are converted into small-scale turbulence with smaller openings [4].

One of the biggest challenges of the particle imaging velocity measurement technique is that the swirl motion occurs inside the cylinder. Tests were carried out using a particle imaging velocity measurement technique on a transparent diesel engine to overcome this challenge. The obtained measurement results were analyzed statistically, and the movements between motorcycles were determined by grouping. It has been determined that the swirling motion of the flow, especially between cycles, changes from a vortex to circular type [5]. When using the particle imaging velocity measurement method, the selection of the surface being measured is essential. The swirl mechanism's behavior against time has been studied by taking measurements from different characters and making 2-dimensional and 3-dimensional measurements in the steady-flow state [6]. Similar inspections and tests have been carried out on various engines, such as heavy diesel engines. In the tests performed on the engine, swirl was measured by both torque meter and particle imaging velocity measurement methods. With these measurements, the tangential velocity profile was determined, the measurement results obtained by theoretical calculations were compared, and the turbulence characteristic of the flow was determined [7].

With all these studies, the particle imaging velocimetry measurement technique contains errors and uncertainties as in every measurement. In some studies, velocity measurement with particle imaging has focused on error sources. Mainly, particle density, particle diameter, velocity gradient and particle displacement parameters were studied. A four-dimensional uncertainty surface was created; a methodology was developed by creating a particle imaging measurement method algorithm [8]. Simultaneously, two-dimensional and 3-dimensional measurements were performed using particle imaging velocimetry to minimize the uncertainties in size and reduce the error rate. The error rate was focused on improvements that have been made by making calibration changes [9]. The particle imaging velocimetry measurement method is a technique used by researchers but is still under development. A correlation was obtained in a study between particle image density, particle properties, and how the peak sizes in the system change for particle imaging velocimetry measurement. As a continuation of this study, interrogation region size, illumination intensity, image size parameters and effects were investigated [10].

Using CFD tools, developing a computational fluid dynamics method for flow factor and swirl ratio is also efficient for studies. It is possible to generate different velocity vectors for various valve openings and compare them with analysis results. It was found that a difference between 5 and 25 percent was observed in the swirl ratio values. However, the analysis could only estimate flow factor values with a difference of 5 percent. [11].

In the literature review studies, it was seen that the particle imaging velocimetry measurement method is still being developed. There are different uncertainty calculation approaches, and it is used by various researchers in other applications and studies. Besides, studies in the literature are carried out with simple test setups [5-7,12]. Therefore, different particle imaging velocimetry measurement methodologies in complex applications such as engine in-cylinder flow are discussed in the completed task.

This study aims to examine different swirl ratio measurement methods and other approaches. Within the study's scope, torque bench measurements at steady flow condition, 2D and 3D particle imaging velocimetry measurements were made on both the 13L engine cylinder head and the prototype part simulating the 9L engine. Swirl rates and swirl properties were investigated. Uncertainty analysis of the measurement results has been completed. The most accurate swirl measurement approach for an engine port in the automotive industry will be examined in detail by comparing different measurement methods.

2. Materials and Methods

Many experimental techniques can be used for performance reviews of internal combustion engines. However, the results for performance review and verification purposes must be collected accurately and in detail. Firstly, the test device's calibration, the test method's repeatability, and the measurement's quality should be assured.

There are different experimental techniques to measure the swirl in diesel engines. These techniques are Laser Doppler Velocitymeter, Anemometer with Hotwire and Particle Image Velocimeter (PIV). Due to the technical imaging used for Laser Doppler Velocitymeter and Particle Imaging Velocitymeter methods, test engines must be designed and manufactured with transparent, optically accessible materials. For this reason, their application is costly. This reality has led to the creation and development of different swirl ratio measurement methods over time. Engineering firms such as FEV, AVL, and Ricardo have developed their techniques and designed test setups to measure the vortex ratio precisely in a continuous flow state.

In this study, the port swirl ratio measurements were made with the test setup developed by FEV.

2.1 Swirl Ratio Measuring Device – Steady Flow Test Bench

In this study, a steady flow test bench is used to measure the swirl ratio. This method does not include the effect of valve and piston movements. Measurement is performed with constant valve openings and under steady flow conditions.

A steady flow testing mechanism enables air movement measurement, depending on the air suction channel geometry in the engine cylinder. Thus, the performance of the air intake duct to produce swirl and tumble movements can be examined.

In this study, since the vortex movement of the air inside the cylinder in diesel combustion engines is examined, the vortex ratio measurement mechanism will be explained in this section. The steady flow test device, which is used during the tests, is shown in Figure 2. This system determines the swirl ratio for diesel engines and has a module for particle imaging velocity measurement.

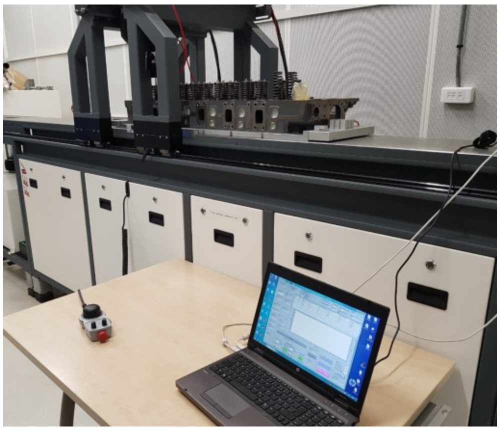

Figure 2. The steady flow test device

In this study, steady-state swirl ratio measurement results will be used as baseline reference measurements. Steady-state swirl ratio measurement with honeycomb is the state-of-the-art method. The honeycomb swirl anemometer's working principle measures the torque value from the honeycomb mounted in the cylinder at the test bench. A blower obtains airflow with constant pressure. The mounted honeycomb does not have any motion. The tangential component of the airflow creates momentum on the honeycomb geometry in the test bench. The force on the honeycomb is measured with a torque meter. By using this angular momentum value, the swirl ratio is calculated by using the swirl ratio equation. This measurement is repeating for each valve lift starting from 1mm up to maximum valve lift values.

3. Uncertainty Analysis

Test results as a result of each measurement contain uncertainty. Therefore, the first step, PIV testing, should be focused on repeatability. The measured and calculated value's uncertainty should always be determined, expressed numerically. Besides, minimizing these errors will increase the reliability of the study.

It is essential to have a process that characterizes the measurement's quality, is immediately applicable, easily understandable, and generally accepted. This is to calculate and express the uncertainty of the value obtained as a result of the measurement.

The error in the data obtained at the end of the experimental studies can emerge in two different ways. One may be due to the experiment set's structure and measuring devices; the other may be caused by the person experimenting. It is possible to correct such errors with a skilled or trained meter or experimenter. However, it may not always be possible to identify the mistakes caused by test equipment [13].

Many methods can be applied to determine the error rate of the test results values calculated with the data collected from the measuring instruments used in the experiments. One of these is the error analysis of the experimental findings with the uncertainty analysis method developed by Kline and McClintock [14].

Let the magnitude be "R," which is the result function desired to be obtained or determined due to an experimental study if this magnitude is expressed by a function in the format R = R (v1, v2, ...,vn) depending on the measurement sizes v1, v2, ... vn. And, the uncertainty values of these variables are w1, w2, ... wn if the measurement uncertainty of the R-result function is found by the RSS (root sum square) method [13] [15].

Uncertainty w of a variable v is found with the expression;

$$\pm w = k\sqrt{(A_1)^2 + (A_2)^2 + .. + (B_1)^2 + (B_1)^2 + ..} \quad (1)$$

Here A1, A2, ... show random errors and B1, B2, ... show systematic errors. After the uncertainties resulting from these two types of errors are converted to the same reliability level, they are collected in a vector. The "k" value here is the "coverage factor" defined above. This method is applied to all measurement variables to find w_1, w_2, ... w_n.

In the Kline and McClintock uncertainty analysis method, if the error rates for each independent variable x_1, x_2, x_3 ..... x_n are w_1, w_2, w_3, ... wn and the error rate of R size is shown with w_R, Kline and McClintock uncertainty analysis equation is shown as below;

$$w_R = \pm\left[\left(\frac{\partial R}{\partial x_1}w_1\right)^2 + \left(\frac{\partial R}{\partial x_2}w_2\right)^2 + \left(\frac{\partial R}{\partial x_3}w_3\right)^2 + \ldots + \left(\frac{\partial R}{\partial x_n}w_n\right)^2\right]^{\frac{1}{2}} \quad (2)$$

or

$$\frac{w_R}{R} = \left[\left(\frac{w_{x1}}{x_1}\right)^2 + \left(\frac{w_{x2}}{x_2}\right)^2 + \left(\frac{w_{x3}}{x_3}\right)^2 + \ldots + \left(\frac{w_{xn}}{x_n}\right)^2\right]^{\frac{1}{2}} \quad (3)$$

The most significant advantage of uncertainty analysis is that the variable causing the most significant error can be detected immediately.

The swirl coefficient value is a dimensionless flow value, and the swirl coefficient formula is given below;

$$D = \frac{M*R_{cyl}}{\rho_{cyl}*\dot{V}_{cyl}^{2}} = \frac{M*R_{cyl}*\rho_{cyl}}{\dot{m}^2} \quad (4)$$

Here;

D = Swirl coefficient
V_{cyl} = Air flow rate (m^3/s)
M = Moment on honeycomb (Nm)
R_{cyl} = Cylindrical tube radius (m)
ρ_{cyl} = Air density before honeycomb (kg/m^3)

Parameters measured during the experiments are; airflow, temperature, pressure and torque. The error rates given by the test device manufacturer for these parameter measurements are as follows;

Pressure sensor error value;	+/- 0.05 %
Temperature sensor error value;	+/- 0.5 ^{0}C
Flowmeter error value;	+/- 2 %
Torquemeter sensor error value;	+/- 0.1 %

If the formula for value D is remembered to find the uncertainty value of the swirl coefficient,

$$D = \frac{M*R_{cyl}}{\rho_{cyl}*\dot{V}_{cyl}^{2}} \quad (5)$$

Here;

$$\rho_s = \frac{p_1}{R*T} * \left(\frac{p_2}{p_1}\right)^{\frac{1}{K}} \quad (6)$$

If it is substituted in equation number 5;

$$D = \frac{M*R_{cyl}}{\frac{P_1}{R*T}*\left(\frac{P_2}{P_1}\right)^{\frac{1}{K}}*\dot{V}_{cyl}^{2}} \quad (7)$$

The uncertainty formula is expressed in the following ways.

$$w_D = \pm\left[\left(\frac{\partial D}{\partial M}w_M\right)^2 + \left(\frac{\partial D}{\partial T}w_T\right)^2 + \left(\frac{\partial D}{\partial P}w_P\right)^2 + \left(\frac{\partial D}{\partial \dot{V}}w_V\right)^2\right]^{\frac{1}{2}} \quad (8)$$

or

$$\frac{w_D}{D} = \pm\left[\left(\frac{w_M}{M}\right)^2 + \left(\frac{w_T}{T}\right)^2 + \left(\frac{w_P}{P}\right)^2 + \left(\frac{w_V}{V}\right)^2\right]^{\frac{1}{2}} \quad (9)$$

Similarly, formulas calculated for uncertainty analysis within the mass flow and flow coefficient are given as below.

Mass flow uncertainty analysis;

$$\frac{w_{\dot{m}}}{\dot{m}} = \pm\left[\left(\frac{w_T}{T}\right)^2 + \left(\frac{w_P}{P}\right)^2 + \left(\frac{w_V}{V}\right)^2\right]^{\frac{1}{2}} \quad (10)$$

Flow coefficient uncertainty analysis;

$$\frac{w_D}{D} = \pm\left[\left(\frac{w_M}{M}\right)^2 + \left(\frac{w_T}{T}\right)^2 + \left(\frac{w_P}{P}\right)^2 + \left(\frac{w_V}{V}\right)^2\right]^{\frac{1}{2}} \quad (11)$$

If the uncertainty analysis numerical calculation is made for the swirl ratio;

For 13L engine measurements for;

$$\frac{w_D}{D} = \pm\left[\left(\frac{0.1}{70.36}\right)^2 + \left(\frac{0.5}{26.64}\right)^2 + \left(\frac{0.0005}{679,19}\right)^2 + \left(\frac{0.02}{514,67}\right)^2\right]^{\frac{1}{2}} \quad (12)$$

Uncertainty is calculated as 0,019.

For prototype part measurements that simulate 9L engine;

$$\frac{w_D}{D} = \pm\left[\left(\frac{0.1}{90.44}\right)^2 + \left(\frac{0.5}{27.92}\right)^2 + \left(\frac{0.0005}{610{,}39}\right)^2 + \left(\frac{0.02}{396{,}07}\right)^2\right]^{\frac{1}{2}} \tag{13}$$

Uncertainty is calculated as 0,018.

Uncertainty value has been calculated for all valve openings. It is seen that the uncertainty value of each valve opening is the same when the initial valve openings are ignored. The uncertainty graph for the 9L engine is shown as follows (Figure3).

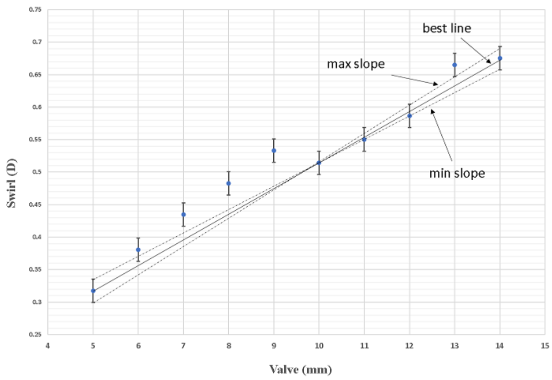

Figure 3. Uncertainty graph of swirl measurement

If numerical calculation is made for uncertainty analysis for mass flow and flow coefficient;

The uncertainty value for mass flow is calculated as 0,019. The uncertainty value for the flow coefficient was calculated as 0,019.

4. Particle Imaging Velocitymeter

A particle imaging velocimeter (PIV) measurement system has a technique that can generate experimental data without interfering with the flow field. Imaging the flow field and obtaining velocity vectors are the outputs of this measurement technique. The PIV system examines the flow field in many branches and verifies the results obtained using the developed computational fluid dynamics methods.

The PIV systems, main elements are double-pulsed laser, high-resolution speed camera, particle generation system, data acquisition system, and computer (Figure 4). The particles whose size and density are determined depending on the fluid type and flow conditions of interest are illuminated on a laser plane. The light scattered from the particles is recorded one after another by the high-resolution speed camera. Velocity vectors are obtained using the particles displacement measurements in a specific time interval by examining two consecutive images.

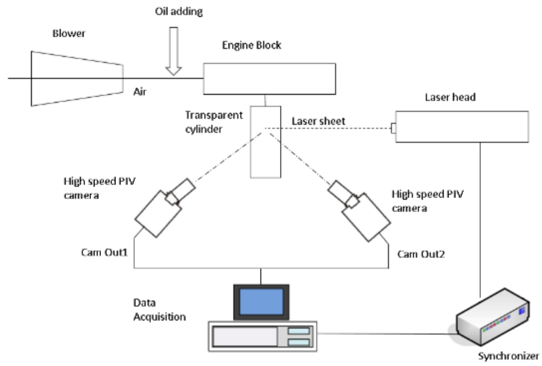

Figure 4. PIV working principle

Depending on the number of high-speed cameras, the test setup is called 2D PIV or 2d/2c if only a single camera is used. A single camera is used to record images and, in turn, measure two velocity components. If two high-speed cameras are used, it is called Stereo PIV or 2d/3c. In this case, two cameras are using different observation angles. So that information on the third (out-of-plane) velocity component can be retrieved (Figure 5).

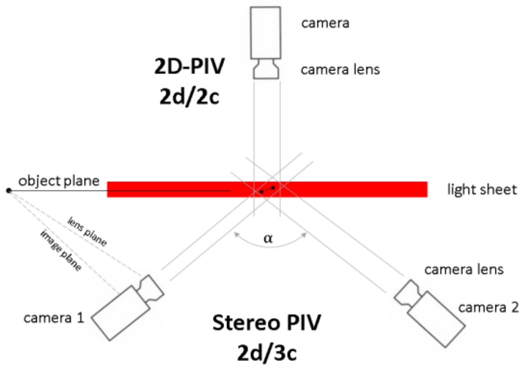

Figure 5. 2d/2c vs 2d/3c PIV measurement system

To perform measurements, the cylinder wall is produced with a transparent material, as shown in Figure 6. In this way, with the two air intake valves opening in the figure, the cylinder's air movements can be displayed by the PIV system. During the transparent cylinder measurement, it is fixed to the cylinder head with the help of a lower piston, and it is ensured that no leakage occurs.

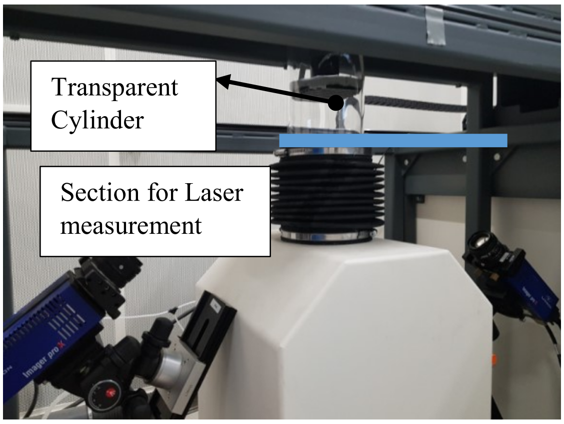

Figure 6. PIV measuring system transparent cylinder wall

4.1. 2D and 3D Particle Imaging Velocitymeter

The particulate air flow sent into the cylinder will be displayed with a CCD camera's help on the created laser plane, as shown in the figure below. (Figure 7)

Before starting the measurement process, calibration of the high-resolution speed camera and the laser plane to be created is required. The calibration plane shown in Figure 8 is used for this calibration process.

After the calibration plane is placed in the transparent cylinder wall for calibration, as in Figure 9, it is determined that the laser beam plane and the calibration plane are matched, and these points appear with the high-resolution speed camera.

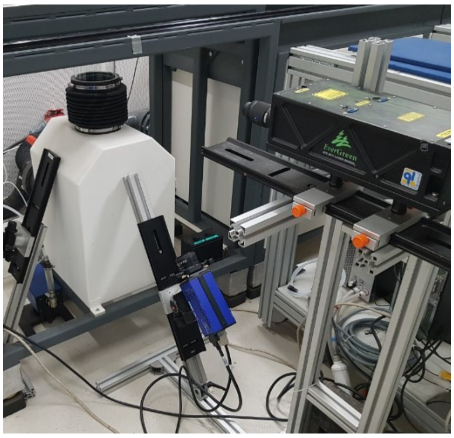

Figure 7. 2D PIV test setup PIV

Figure 8. Calibration plane

Figure 9. Calibration plane assembled

Each point on the calibration plane must be seen and marked before testing by the high-resolution speed camera. In the test setup, the high-resolution speed camera angle was measured as 47.6°. As seen in Figure 10, points at this angle were determined, marked and corrected to the computer screen's x-y plane.

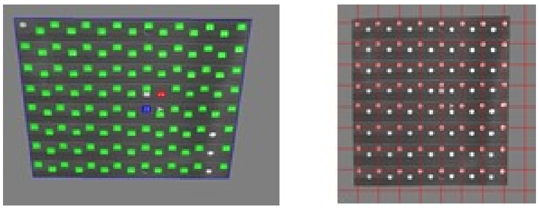

Figure 10. Calibration plane point scan and correction images

Two high-speed cameras (CCD) are used in the 3D PIV measurement system (Figure 11).

Figure 11. 3D PIV test setup

After the calibration processes are completed, the calibration plane is taken from the transparent cylinder, and the tests are carried out.

5. Steady Flow Test Bench (Honeycomb) and Particle Imaging Velocitymeter Measurement Results

The results are obtained for the steady flow bench for two different engine configurations, as shown in figure 12.

The details of the engine configurations are shown in Table 1

Table 1. Engine Dimensions

	A	B
Cylinder Diameter (mm)	115	130
Number of Cylinder	6	6
Number of Valves	4	4

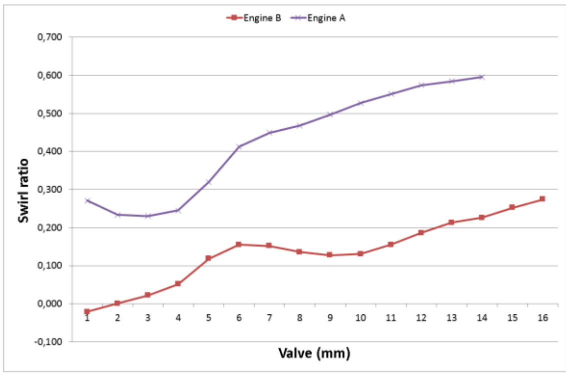

Figure 12. Comparison of the swirl level of two engines

Figure 12 shows the results of the swirl measurement of two engines with different port designs. Engine B has a swirl rate of at least 4-5 times higher than the honeycomb technique measured in engine A. All results at this figure. However, measuring the air distribution from the ports in the cylinder is critical to understand the swirl rates. For this, the PIV method can be used to measure the airflow in the cylinder. When measuring at different valve heights, it is sufficient to measure with a single camera when using the 2d PIV method, while two cameras should be used for 2d / 3c PIV. However, in 2d PIV, fast but low-accuracy measurements are made by a single camera, while the 2d / 3c PIV method enables complex but highly accurate measurements. With this study, the measurement approaches will be discussed for the engine port application.

For the 2d / 2c setup, measurements are made on a slice parallel to the y-z plane along the piston bowl's axis. The laser plate illuminates the plane in the negative z-direction, and the camera focuses the aircraft from a 45-degree perspective. The spatial resolution is about 2mm. The data were averaged from 100 snapshots. The left side of the plane becomes a distorted image due to its angular appearance. Velocity information cannot be captured accurately at the edges. The 2d / 3c PIV experiments use the setup shown in figure 4. The two cameras are mounted between 45 degrees in the opposite direction. Calibration adjustments are made with the images obtained from two cameras.

Figure 13 shows the 2d flow distribution of Engine A for an 11mm valve lift. Test results are shown that the swirl value of the honeycomb measurement and 2d PIV measurement is slightly different. The swirl ratio of the honeycomb measurement is 0.55, but the 2d PIV measurement is 0.68. So, PIV measurement techniques should be improved.

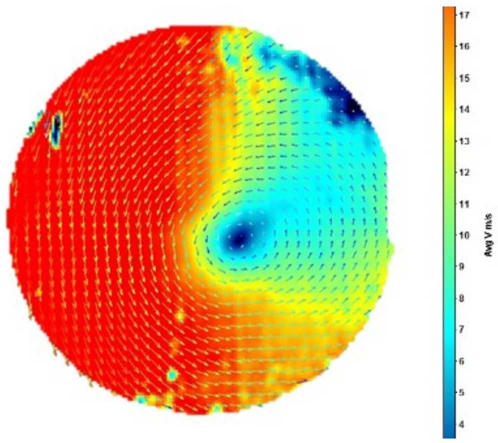

Figure 13. 2d PIV Measurement

Figure 14 shows the 2d/3c flow distribution of Engine A for an 11mm valve lift. The center of the velocity is close to the center of the circle. Velocity index is typically used to define the location of the high-velocity flow. [16] The swirl ratio of the 2d/3c measurement results is 0.58.

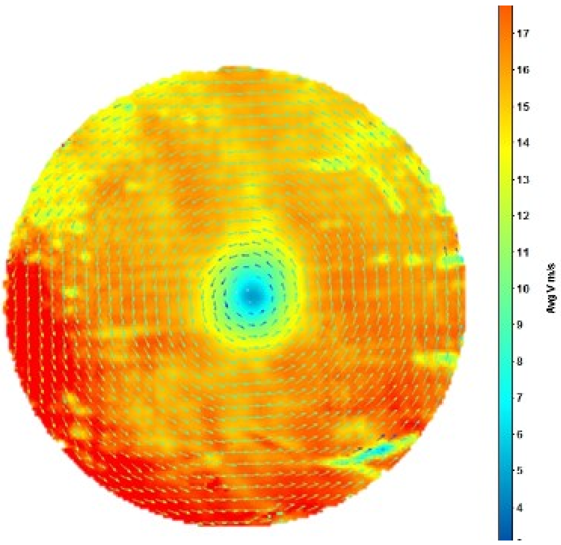

Figure 14. 2d/3c PIV Measurement

Figure 15 shows Engine A's 2d and 2d / 3c flow distributions for an 11 mm valve lift. The 2d and 2d / 3c measurement techniques were compared in terms of velocity index and swirl ratio. The velocity index of 2d PIV is 0.45, and the 2d / 3c PIV speed index is 0.51. The differences are 11.8%. As a result of the measurement made with these two methods, the swirl ratio difference is 12 percent. Besides, making the comparison with the reference measurement shows that the 2d / 3c method gives a closer result.

2d/2c and 2d/3c methods were compared with Engine B, lower swirl ratio. Figure 16 shows the 2d and 2d/3c flow distributions of Engine B for an 11 mm valve lift. Velocity distributions of the two methods for Engine B have similar results to Engine A.

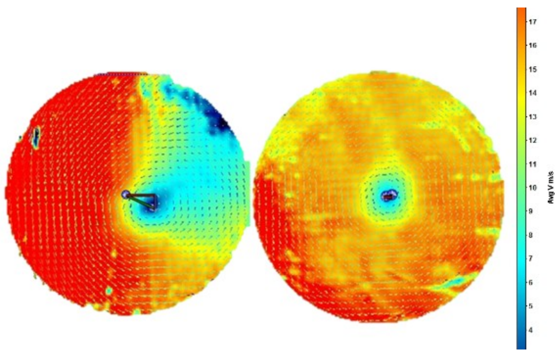

Figure 15. 2d-2d/3c PIV measurement results for a high swirl case (Engine A)

Figure 16 shows the 2d and 2d / 3c flow distributions of Engine B for an 11mm valve lift. Again, the results of the 2d and 2d / 3c measurement techniques are comparable for Engine B in terms of the velocity index and swirl ratio.

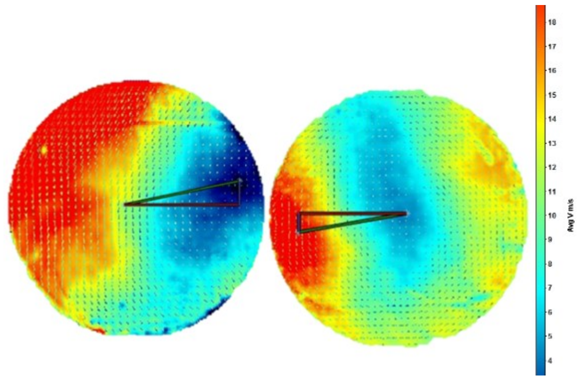

Figure 16. 2d-2d/3c PIV measurement results for low swirl case (Engine B)

When compared to the measurement results in figure 15 and figure 16, it is seen that while a swirl center of Engine B is formed slightly in the cylinder, the speed distribution has accumulated on one side of the cylinder. On the contrary, in Engine A, the flow rate is spread more homogeneously around the swirl center.

6. Conclusions

In this work, port performance is investigated experimentally by honeycomb torque measurement and PIV methods. Nevertheless, the PIV measurements are provided by insightful information on port measurement's velocity structure in terms of the velocity magnitude and velocity structure. MATLAB tool is developed based on the PIV results. This tool generates the velocity index, flow distributions and distance of the velocity index from the center.

An objective of the study was the investigation of the suitability of the PIV techniques for port measurement. PIV measurements can be performed by either 2d PIV or 2d/3c PIV. The advantage of the 2d PIV is being easy to setup and measure.

Furthermore, the experimental measurements demonstrate that 2d PIV cannot measure velocity distribution and velocity index for high swirl ratio case well, but 2d/3c measurement is comparable with the honeycomb measurement method. Besides, 2d PIV and 2d/3c PIV measurements show a similar velocity index but a different velocity distribution for the low swirl ratio case.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Heywood, J., 1988. Internal Combustion Engine Fundamentals, McGraw-Hill, New York, USA.

[2] Yelken, B., Savcı, İ.H., Dülger, Z., 2021. Investigation of air movement in cylinder in diesel internal combustion engines and comparison of measurement methods. Engineers and Machinery, **62**(703), pp.221-244.

[3] Bottom, K.E., 2003. PIV measurements of in-cylinder flow and correlation with engine performance, Ph.D. thesis, University of Wisconsin – Madison, Wisconsin.

[4] Vester, A.K., Nishio, Y., Alfredsson, P.H., 2019. Investigating swirl and tumble using two prototype inlet port designs by means of multiplanar PIV. International Journal of Heat and Fluid Flow, **75**, pp.61-76.

[5] Cosadia, I., Bore´e, J., Charnay, G., Dumont, P., 2006. Cyclic variations of the swirling flow in a diesel transparent engine. Experiments in Fluids, **41**, pp.115–134.

[6] Rabault, Jean, Vernet, Julie, Alfredson, Per-Henrik, 2016. A study using PIV of the intake flow in a diesel engine cylinder. International Journal of Heat and Fluid Flow, **62**, pp.56-67.

[7] Doosje, E., Bastiaans R.J.M., Baert, R.S.G., 2004. Application of PIV to characterize the Flow-Phenomena of a Heavy-Duty Cylinder Head on a Stationary Flow-Bench. In Particle Image Velocimetry: Recent Improvements, pp. 301-313.

[8] Timmins, Benjamin H, 2011. Automatic particle image velocimetry uncertainty quantification, Utah State University Ms.C. thesis, pp. 67-68.

[9] Abe, M., Longmire, E. K., Hishida, K. and Maeda, M., 2000. A Comparison of 2D and 3D PIV Measurements in an Oblique Jet. Journal of Visualization, **3** (2), pp.165-173.

[10] Warner, Scott O., 2012. Autocorrelation-based estimate of particle image density in particle image velocimetry, Utah State University Ms.C. thesis, pp. 49-51.

[11] Dwarshala, S., Vandana, S., and Rambhaji, G., 2016. Computation and validation of in-cylinder flow field, swirl and flow coefficients for a naturally aspirated single-cylinder diesel engine. SAE Technical Paper, 2016-28-0018.

[12] Özgün, Ö., Kumlutaş, D., Yücekaya, U. A., 2017. Investigation of flow structures with three dimensional background positioned density difference (schlieren) method and verification with particle imaging velocity measurement. Engineers and Machinery, **58**(687), pp.29-40.

[13] Onan, Cenk, 2013. Investigation of heat and mass transfer from moving liquid film at the exterior surface of pipes, Ph.D. Thesis, pp.104-111.

[14] Kline, S.J. ve McClintock, F.A., 1953. Describing uncertainties in single-sample experiments. Mechanical Engineering, **75,** pp.3–8.

[15] Sadıkov E., Kangı R., Uğur S, 1995. Measurement uncertainty, TÜBİTAK Marmara Research Center National Metrology Institute, pp.55-61.

[16] Leong W.A., Eroglu S and Guryuva S.,2012. Using STAR-CCM+ for Catalyst Utilization Analysis. Paper presented at Star Global Conference, Amsterdam, 19-21 March.