Spatial Evaluation of In-Cylinder Turbulence Flow Using High-Resolution PIV

by

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ABSTRACT

Two-color dual sweep PIV has been developed and examined to measure quasi-instantaneous two-dimensional velocity data in a practical engine. The particle-seeded flow field was illuminated by scanning laser beams(blue and green) of Ar laser. Direct picture was taken at TDC compression with 1.7 magnifications, resulting in paired particle images distinguished by color. The results indicate that this type of PIV could provide useful information of complex turbulence flow as well as counter like tumbling flow, and also the spatial resolution achieved was adequateto resolve the few mm turbulence integral length scales.

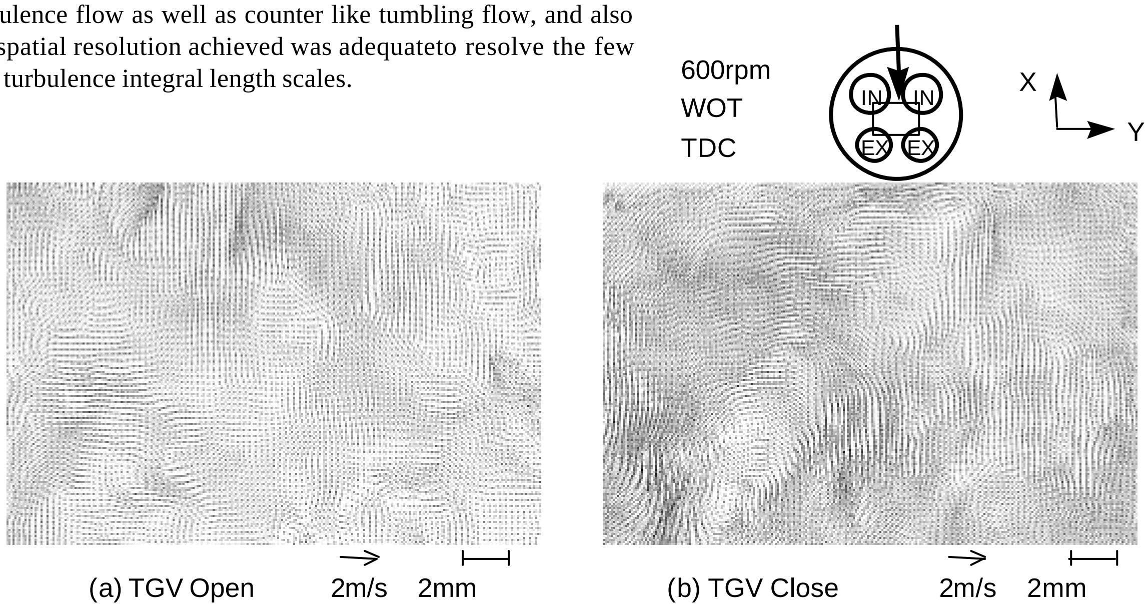
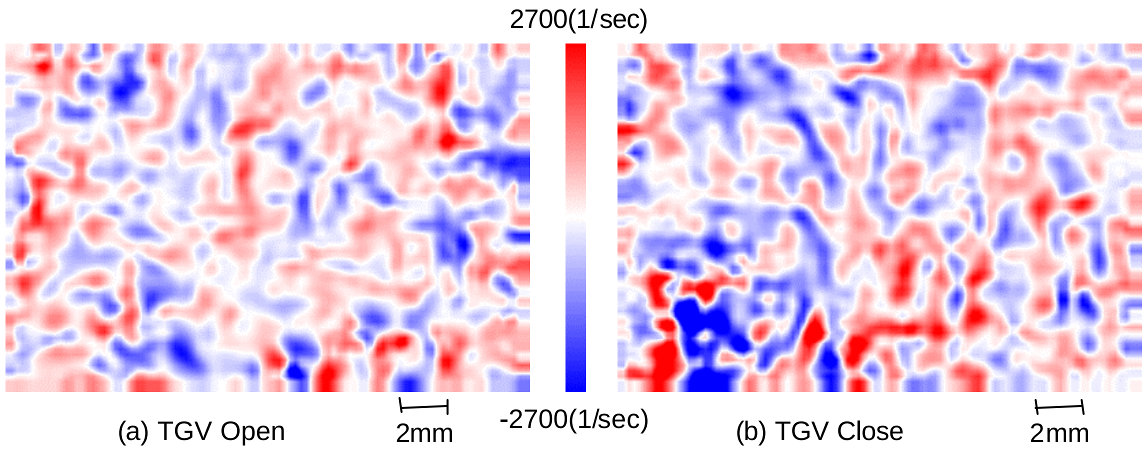


Fig.1 Quasi-intantaneous velocity distributions.



1.

Fig.2 Large-scale vorticity

INTRODUCTION

In-cylinder flow diagnostics have been well established for these decades, which could provide very useful information of flow and its turbulence characteristics. The measurement results allow us to improve combustion performance and help to understand what in engine development. It is well know that the turbulence intensity makes significant influence on combustion, so that accurate turbulence measurement is an important task. The desirable turbulent intensity can increase flame propagation speed so as to control combustion in engine. LDV has been a powerful tool to measure turbulent characteristic at a certain location with high data rate, which allows us to analyze data in statistic fashion. But, LDV is a point measurement, could not provide whole flow field information. This is a trade off relationship. Time series analysis of LDV data and its ensemble averaged spatial map differs from the actual flow due to no-spatial correlation. It is needed to measure spatial flow structure at the same time in order to discuss the correlation of turbulence to combustion in engine.

PIV is attractive in terms of spatial measurement method. Super-resolved PIV has been developed and examined to in-cylinder gas flow [1,2]. Despite of that all of these methods use double pulse YAG laser, the direction of flow cannot be identified and the range of application is currently limited. In this research, a PIV that uses a two-color dual sweep as the light source and 6cm x 7cm format color film as the recording method was developed to identify the direction of flow and obtain a high-resolution whole velocity. This paper describes the development of the PIV and its demonstration in measuring the in-cylinder gas flow in a 4-stroke gasoline engine with a tumble generator valve (TGV). Special affeusion was considered in order to have fine measurement grid of 250μm in space.

2. NECESSITY OF SPATIAL TURBULENCE MEASUREMENT

As shown in Fig. 3, various measuring methods are available to evaluate in-cylinder gas flow. It is not so easy to measure whole flow field. Understanding of flow should be 3-D and time-dependant, that is, four coordinates should be considered. Turbulence value is not steady, varying in time and space, it may be produced, generated by bulk flow and piston motion. Then, high temporal and spatial resolved measurement is essential to analyze turbulence. The turbulence measurement should be done with very high data rate. Regarding the time direction, the LDV has satisfied with these requirements and therefore provided valuable information on turbulence. Ensemble averaged LDV velocity maps were demonstrated to show the spatial correlation, but the uncertainty and applicability has been never examined. Fraser et al. used a 2-point LDV to obtain the spatial scale directly [3]. Glover et al. used a scanning LDV to make time-wise evaluation of turbulence regarding one space dimension, assuming that a sufficiently fast scanning speed establishes Tailor's vortex-freeze hypothesis and the time is almost the same [4,5].

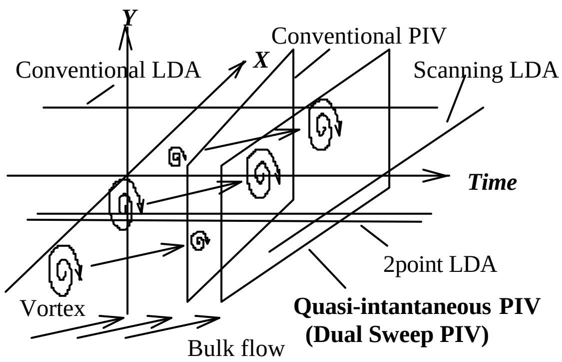


Fig. 3 Illustration of varied turbulence measurements.

Spatially resolved PIV can provide much valuable data in space than LDV-based method. In this research, a two-color dual sweep PIV will be investigated and examined to measure turbulent intensity with/without tumble generating valve in a practical transparent engine.

3. TWO-COLOR DUAL SWEEP PIV MEASUREING SYSTEM

3.1 Visualization and Image Recording

As shown in Fig. 4, the beam from an Ar laser (4W) was splitted into two colors, 514.5nm and 488nm by a color filter and reflected with a rotating mirror, which makes a laser sheet in a measurement region. This mirror rotates at half engine speed, and the scanning laser sheet is produced in each cycle at the same phase. In the measurement, the mirror rotation speed was set up to 300 rpm at 600 rpm engine rotation speed. The scanning speed of the laser beam was 28.3 m/s. The velocity near the compressing stroke TDC was about 2 m/s, and the tracer particles almost freeze within the radiation time (about 8μsec) of the laser beam.

The time interval of the two laser beams was adjusted so that the tracer particles in the scanned area move at an appropriate distance. This can be easily adjusted by the relative angle of the green and blue beams. The scattered light from the particles was green and blue in turn. In the measurement, a conventional color film was used, in which a double-exposed image of green and blue particles was obtained.

This laser beam scanning has very high light intensity so as to detect small seeding particles. Here, TiO2 was used as seeding particles.

To visualize in-cylinder flow, a transparent single-cylinder engine with quartz piston was used, which enables us to see the flow from the bottom side of the extended piston. The laser beam was radiated from an 8mm spacer with a quartz window inserted into the cylinder gasket. The compression ratio in the experiment is low, 5.4 in comparison of the actual one of 9.5. The test engine can implement a tumble generator valve (TGV) attached to the inlet port to vary the gas flow characteristics. The experimental conditions and engine specification used in the test was shown in Table 1.

Table 1 Engine specification and experimental operating conditions

Bore	97mm
Stroke	74mm
Displacement	547cc
Compression Ratio	5.4
Engine Speed(motored)	600rpm
TGV	OPEN/CLOSE

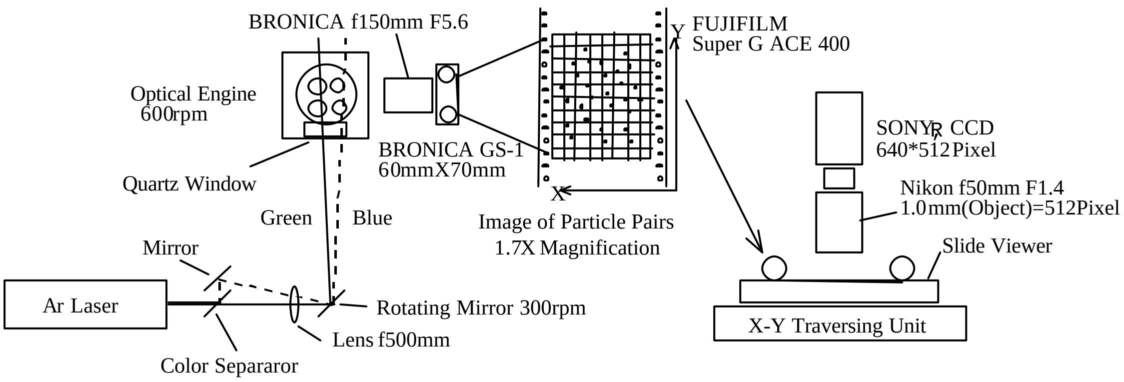


Fig. 4 Schematic diagram of engine, optics and interrogation system used for dual sweep PIV.

3.2 Image Processing

The measured images are recorded in the film. The images were read by 3CCD camera, in which blue and green images are separated by color filter. These two color images can not separated perfectly so that there are several uncertainty. By averaging 10 images, the peaks location in blue and green were determined by software developed. The 3CCD has 8bit resolution in intensity, but the measured resolution is lower than this. The interrogation area was determined by scanning laser beam area in a certain speed. The interrogation area should be small enough to have high spatial resolution. On the other hand, particle in the interrogation area should be enough to be detected as images, that is, at least several particles in each inter-area. This is another factor to determine the final measurement accuracy. An optimization process should be carried out to have reasonable interrogation size and enough particle number. As shown in Fig. 5, the ambiguity of cross-correlated PIV is small, the interrogation spot can set smaller than auto-correlation PIV. In this test, the interrogation spot size was set to 850μm on the film. Because the photographic magnification is 1.7, the interrogation spot size is 500μm in the actual flow field. The velocity vector was obtained at 250μm intervals, and an XY traversing unit was used to half-lap of the interrogation spot size at a time. The velocity vector is obtained from cross-correlation between the green and blue images in the interrogation spot. The FFT method is used for calculating the cross-correlation to increase the processing speed. But the FFT method is affected by the cyclic function. The direct method is used to recalculate the difference between the picture elements of five pixels before and after the peak of the cross-correlation obtained by the FFT method. The secondary minimum square method is also used to interpolate the sub-pixel peak and enhance the resolution.

As the final operation, the effect of the scanning beam speed at a different time is modified as shown in Fig. 6. Because the time interval of these two colors laser beam passing, velocity in X-axis is shifted by Tm, this shift is corrected to obtain the velocity in the X and Y directions. Tm is obtained from the X amount of particles that move in the X direction and the beam scan speed V.

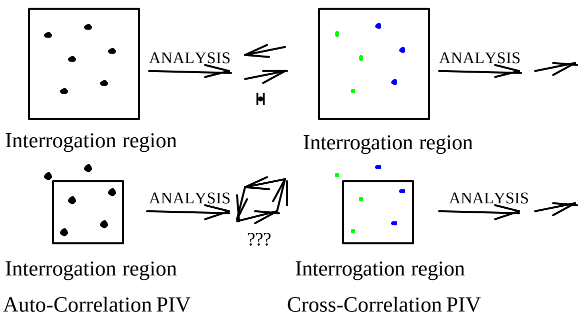


Fig. 5 Advantages of cross-correlation PIV against auto-correlation PIV.

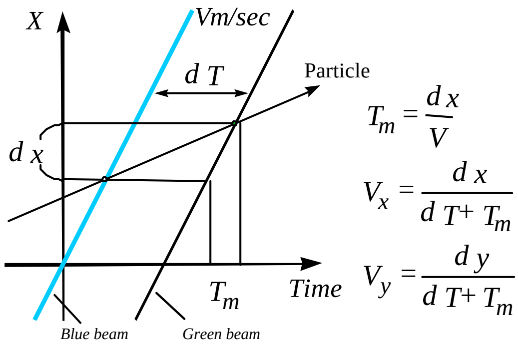


Fig. 6 Correlation of dT affected by sweep beams.

4. RESULT AND DISCUSSION

The PIV measurements were curried out in an engine. The results are compared with / without TGV. The measuring plane is near the ignition plug, which is 5 mm below from the cylinder head.

Fig. 1 shows the "quasi-instantaneous velocity map " at TDC and the engine speed was. Although the scan time in the horizontal direction stays the same, the scan time in the vertical direction shifts by 0.7 ms (a crank angle of about 2.5deg).

When the TGV is open and closed, the complex flow field was produced and reverse flow was observed. When the TGV was open, no remarkable bulk flow was found and turbulence generated in the intake process. When the TGV was closed, about 20 mm class vortex was observed. This is not described here, but a comparison with other cycles indicated that the scale, intensity, and generation location of this vortex significantly depend on the cycle.

This PIV has a disadvantage of laser beam scanning, but the advantage is this very high spatial resolution (500µm) in whole engine flow field. The conventional PIV cannot provide this kind of high resolution. This is because of sheet the light scattering intensity from the particle is strong and the sensitivity of the film is high.

Fig. 1 vector map was progressed through high frequency filter and the result is shown in Fig. 7, the filter is correspond to 6 mm size. This operation is performed for the spatial domain, and the spatial turbulence component can also be extracted from the "quasi-instantaneous velocity." When the TGV was open and when it was closed, many vortexes that are isotropic and distributed relatively uniformly in the space appeared. The generation location and intensity of individual vortex are completely random for each cycle.

Fig. 2 shows the result of vortices of Fig. 1. The vortex portion and dark portion shown in Fig. 7 closely correspond to each other. Judging from the darkness, when the TGV is closed, the turbulence is stronger. Fig. 8 show the results of quantitatively comparing the intensity of turbulence and the integral space scale. The turbulence intensity in the X and Y directions was obtained from the RMS value of velocity shown in Fig. 7. The integral length scales in the X and Y directions were obtained from the distance at which the auto-correlation function of the vorticity shown in Fig. 2 becomes 1/e. As a result, the turbulence intensity is 20 to 30% greater when the TGV is closed, but the integral length scale when the TGV is open was the same as that is closed. This indicates that the vortex structure remains unchanged and only the turbulence intensity becomes 20 to 30 % greater when the TGV is closed.

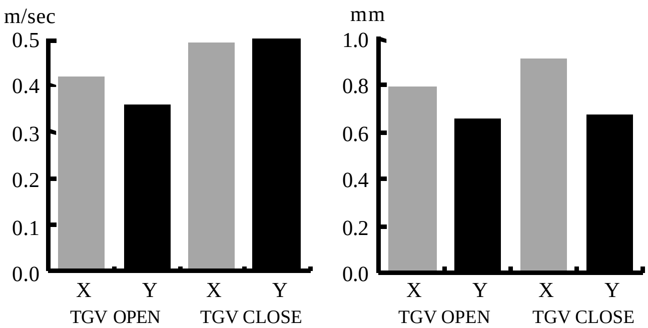


Fig. 8 Turbulence intensity & length scale

5. CONCLUSION

The two-color dual sweep PIV was developed and applied for in-cylinder turbulence measurement in an engine. The measurement results could provide very fine vortex structure in a flow. This high spatial resolution of 250 μm is one of the advantages of this developed PIV. The comparison of turbulent characteristics with and without TGV were due, the results show TGV can produced much higher turbulence (20-30%) in the flow, while the bulk flow was less influenced.

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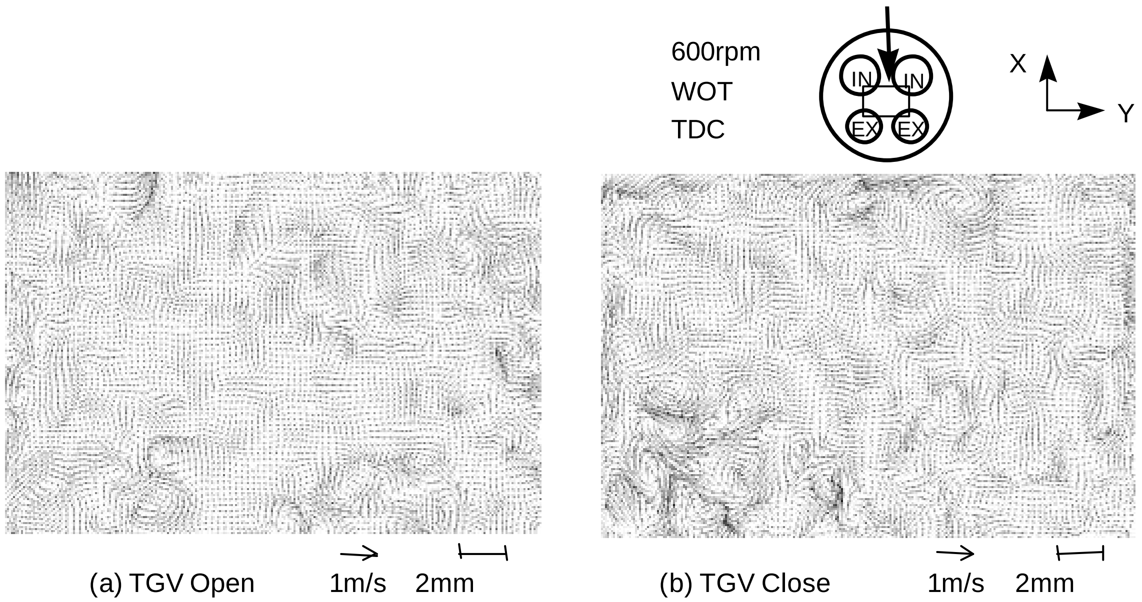

Fig. 7 High-pass spatially filtered velocity distributions of the spatial-frequency corresponding to cutoff 6mm.