A Discussion of Research into Cyclic Flow Variations in Internal Combustion Engines

Introduction

Cycle-to-cycle flow variations in engines can cause cyclic combustion variations, decreasing combustion efficiency and increasing the likelihood of misfires. A study by H. Shen, P.C. Hinze, and J.B. Heywood discussed below determined that flow variations have a greater effect on cyclic combustion variation than shifting of the flame center and variations in the residual gas fraction, showing that cyclic flow variations in engines merit further study. However, quantifying cyclic flow variations, and distinguishing macro-scale cyclic flow variations from small-scale turbulence can be difficult. Ensemble-based Reynolds decomposition is a traditional method by which turbulence is quantified, but it does not account for cyclic flow variations. Proper Orthogonal Decomposition (POD), Gaussian filtering or filtration following Fast Fourier Transform (FFT) is used by some of the studies discussed below for the separation of turbulence, cyclic flow variations and the mean flow. Others use flow characteristics other than velocity, such as swirl ratio or circulation, to measure cyclic flow variations. These studies aim to create methods by which various data sets from different operating conditions may be compared, and, ultimately, minimize cyclic variations in engines.

Overview of Current Literature

Cycle-to-cycle variations in combustion are influenced by a variety of factors, such as variations in turbulence intensity, flame center shift due to convection, and variations in residual gas fraction. In a study by H. Shen, P.C. Hinze, and J.B. Heywood, these factors were taken into account in order to create a computer code that predicted the extent of cyclic variability in combustion. This model was compared with experimentally obtained results, and was used to determine the extent to which each of the factors mentioned above affected cycle-to-cycle variation. The study found that variations in turbulent intensity have the greatest effect on combustion variations, and that this effect decreases as the flame size increases. This is because the growing flame is influenced by a larger portion of the in-cylinder flow field, leading statistically to a decrease in the variation of the turbulent intensity affecting the flame. It was also found that flame center shift only influences the later stages of the combustion process, and cyclic variations in residual gas fraction have almost no effect on cycle-to-cycle variations in combustion [1].

As the in-cylinder turbulence was not experimentally determined in this study, the average turbulence intensity was simply set equal to 1.8 m/s, which was approximately half the mean piston speed. The turbulence intensity near the spark plug for each cycle was then determined using the hypothesis that a larger local gas convection velocity indicates a larger local turbulence intensity [1]. However, using an optical diagnostics method, such as particle image velocimetry, would have provided more accurate information about the in-cylinder flow field.

In order to understand how cyclic variations in turbulence intensities affect cycle-to-cycle variations in combustion, in-cylinder flow fields and turbulence need to be studied more closely. A study by Y. Li, H. Zhao, et al. characterizes tumble and swirl flows in a motored four-valve spark ignition engine. In this study, the single-cylinder engine's intake valve shrouds were designed to enhance tumble motion. Swirl motion was created by plugging one of the intake ports. Particle Image Velocimetry (PIV) was used to find the two-dimensional velocity distribution every 30 crank angle degrees (CAD) during the intake and compression stroke for 80 cycles at 1200 rpm. It was found that swirl motion is generated at the end of the intake stroke and continues till the end of the combustion stroke, while tumble motion is created early in the compression stroke and breaks up in the later part of the stroke [2].

This study also found that while the cyclic variation of swirl motion is significant, cyclic variation of tumble motion is much larger. This cyclic variation includes both turbulence and cycle-to-cycle variation of bulk flows. The ensemble-averaged mean velocity distribution may be used to represent the swirl motion in individual cycles, but the mean velocity field is not really representative of individual cycles with tumble motion. This may be due to the moderate tumble ratio of 0.9 used in this experiment, or due to some out-of-plane velocities resulting from the tumble vortex axis not being perpendicular to the plane in which the velocity distribution was measured [2].

It was also found that the root-mean-square (RMS) velocity fluctuations for swirl motion becomes homogeneous over the field of measurement during the later part of the compression stroke, while the RMS velocity fluctuation distribution for tumble motion remains heterogeneous [2]. This further indicates the difficulties of characterizing tumble motion using average values. In fact, cyclic flow variations may be better understood by focusing on instantaneous calculations that do not refer to measurements from previous cycles. However, repeating this experiment for larger tumble ratios while calculating the orientation of the tumble axis may also provide valuable information.

While the study discussed above used ensemble statistics based Reynolds decomposition to characterize the velocity distributions, a study by X. Baby, A. Dupont, et al. uses POD to separately examine small-scale turbulence and cycle-to-cycle variations in macroscopic flow patterns, which depend on geometry and unsteady initial conditions. A single-cylinder engine designed to enhance tumble motion was used in this study. Velocity distributions at 220 and 270 CAD were obtained using PIV at four different measurement planes for 1000 motored cycles at 1200 rpm. These velocity distributions are then expressed in terms of a linear combination of deterministic functions, which are eigenmodes. The first mode represents the mean motion, following modes represent macroscopic flow structures related to cycle-to-cycle variations, and higher modes represent turbulent flow structures. By looking for asymptotic behavior, it was found that the mode separating cycle-to-cycle variations from turbulence was the fourth mode [3].

On calculating kinetic energies from the turbulent velocity fluctuations and the cycle-to-cycle velocity variations, it was found that both had the same order of magnitude. While the turbulent kinetic energy fluctuations appear more isotropic, the kinetic energy associated with cycle-to-cycle variations is larger in the upper part of the cylinder. These higher values seem to be associated with a jet flapping phenomenon [3].

POD appears to be a useful method by which turbulence and macro-scale cyclic variations may be separated. It can also predict the temporal evolution of flow structures [3]. However, it is unclear what advantages it has over other spectral decomposition schemes such as Fourier decomposition, or Gaussian filtering, which allows for the separation of velocity fields into flow structures of various scales.

A study by J.B. Ghandhi, R.E. Herold, et al. used both spatial and temporal filtering to examine the turbulent kinetic energy associated with a velocity distribution. The flow fields in a horizontal plane in a motored single-cylinder engine running throttled and unthrottled at 600 and 1200 rpm were captured using PIV. The velocity vector fields from each cycle were filtered using Gaussian filters. Other filtering methods, such as Fourier analysis, were not used as the number of consecutive images available from one cycle was insufficient [4].

The high-pass filtered data was taken to be the fluctuating velocity, and a corresponding fluctuation kinetic energy was calculated. This kinetic energy was found to increase with increasing cutoff length and decreasing cutoff frequency, as expected. Normalization of the fluctuation kinetic energy by one-half the square of the mean piston speed, and normalization of the temporal cutoff frequency by the engine rotation frequency effectively merged the graphs associated with different cycles and operating conditions. In order to investigate the relationship between temporally and spatially filtered data, temporally filtered data with a cutoff time equal to the integral time scale was visually compared to spatially filtered data with a comparable level of fluctuation kinetic energy. Similarly, spatially filtered data with a cutoff length equal to the integral length scale was compared to temporally filtered data with a comparable level of fluctuation kinetic energy. Both the low-pass and high-pass data thus compared were very similar to each other [4].

By establishing that spatial and temporal filtering processes result in similar data, the study discussed above justifies choosing between the two processes based on convenience. This study also effectively demonstrated the dependence of fluctuation kinetic energy on mean piston speed, and allows data from different engine operating conditions to be compared to each other.

A study by S. Jarvis, T. Justham, et al. also made use of cycle-resolved velocity data to examine cyclic flow variations. Using time-resolved digital PIV (TRDPIV), velocity data was acquired every 1.8 CAD over 100 successive cycles from the primary tumble plane of a single-cylinder motored engine running at 1500 rpm. The instantaneous velocity fields were decomposed into high and low frequency components using a filtration method involving FFT. A cutoff frequency of 300 Hz was utilized. The high frequency velocity was assumed to be associated with turbulence, while the low frequency velocity was assumed to be associated with the cycle average flow field, including any cyclic flow variations [5].

In order to isolate cyclic flow variations, the cycle average flow field from a particle cycle was subtracted from the ensemble mean cycle average flow field. It was felt that the mean cycle average flow field was a better representation of bulk motion that the Reynolds decomposition-based ensemble average flow as the ensemble average is unable to separate turbulent and mean flow. In fact, the mean cycle average flow field is smoother in appearance than the ensemble average flow field, without small scale velocity gradients associated with turbulence [5].

In order to be able to compare data from this study to future work, an RMS cyclic variation was calculated. Further, the RMS cyclic variation was normalized by the mean cycle average flow so that the magnitude of cyclic variations from different parts of the cycle could be compared to each other. It was found that the normalized cyclic variation is high near the intake valve jet during the intake stroke, with a large spatial variation in the flow field. This is believed to be due to variations in the intake jet flow and tumble motion. The normalized cyclic variation decays to globally lower levels during the compression stroke as the flow is driven by piston movement [5].

The study discussed above demonstrates a more accurate alternative to Reynolds decomposition that may be used to extract cycle-resolved flow field information. Future work comparing cyclic flow variations for varying inlet conditions [5] should yield some useful results.

A study by K. Naitoh, Y. Kaneko, and K. Iwata links lower combustion variability to an improved understanding of cyclic flow variations. An Implicit Large Eddy Simulation (ILES) model was used to solve the compressive Navier-Stokes equations in order to describe flow fields over six consecutive cycles. This model used density contour data acquired using Mach-zehender interferometry from an engine with a square piston and a single intake/exhaust opening. An orthogonal, homogeneous, fixed computational grid was used. The computational results for the first cycle matched well with the experimental results. Freon 12 was used as the working fluid as it produced more density variations [6].

Flow velocities from three different points within the cylinder, from the compression stroke of the six computed cycles, were compared on graphs. It was found that a point on the cylinder axis 15 mm below the cylinder head displayed relatively weak cyclic flow variations. The area near this point was then referred to as a 'silent domain'. It was suggested that this area might be at the edge of a rigid vortex core, where velocities are more constant. On further examination, it was found that a point slightly to the right of the cylinder axis, 15 mm below the head had the least cyclic flow variations. These results are similar to those obtained from computations based on an actual four-valve engine with a circular cylinder [6].

The process used to determine cyclic flow variations in the study discussed above might be helpful in reducing cyclic flow variations and choosing an ignition location with low cyclic flow variations in engines under development [6]. However, separating turbulence from macro-scale cyclic flow variations would lead to better results.

Examinations of cyclic flow variations are mostly confined to spark ignition engines, but a study by I. Cosadia, J. Borée, et. al looks into cyclic flow variations in a four-valve, plate roof optical Diesel engine with a compression ratio of 20. In-cylinder velocity fields in the middle of the compression stroke and velocity fields in the piston bowl at top dead center were captured using PIV. The engine uses a transparent piston with a simplified cylindrical shape as a realistic piston shape would have lead to strong optical distortions. The engine was motored at 1200 rpm. Five horizontal planes were used to record velocity data in the middle of the compression stroke, and three horizontal planes were used at top dead center. In addition, six vertical measurement planes were used [7].

It could be seen from the ensemble-averaged velocity fields that the in-cylinder flow in the middle of the compression stroke had essentially a swirl motion. However, comparing the average velocity fields to the instantaneous flow fields showed that there were significant cyclic flow variations, with the flow structure switching from 'vortex type' to 'annular type' from one cycle to the other. The flow variations were quantified by calculating the mean and standard deviation of the circulation within circles of various sizes surrounding the swirl structure's center. POD analysis of the circulation data converged rapidly, with the third and fourth modes dominating [7].

The mean flow within the piston bowl at TDC shows strong three-dimensional motion due to the squish phenomenon leading to a tumble motion interacting with the swirl motion of the flow. Cyclic fluctuations of the swirl flow persist even after the squish phase. Circulation statistics for TDC in-piston flow show that the circulation within the piston bowl is approximately half that of the flow in the middle of the compression stroke. POD analysis of the in-piston flow was also completed [7]. As cyclic flow fluctuations at TDC can cause combustion variability in Diesel engines, studies such as the one discussed above can add to the understanding and control of cyclic flow variations for more efficient combustion.

Conclusion

This report analyzes studies using various methods used to quantify cyclic flow variations, such as POD, Gaussian filtration, and filtration following FFT. While some studies study flow field velocities directly, others use different flow structure measure such as swirl ratio and circulation. A study by J.B. Ghandhi, R. E. Herold, et al. showing that spatial and temporal filtering of velocity data give similar results, and a study by S. Jarvis, T. Justham, et al. using a method of normalizing cyclic variations by the mean flow velocity allow various data sets to be compared. A study by K. Naitoh, Y. Kaneko, and K. Iwata show that accurate models may be created from in-cylinder flow data, allowing for the design of engines with minimal cyclic variations. It is hoped that further research will lead to an accurate and widely applicable method by which velocity data gathered under various operating conditions from different engines may be compared. Further study of cyclic flow variations in Diesel engines is also essential.

Future Work

A better understanding of in-cylinder flow fields would be achieved by concentrating on cycle-resolved data processing. Gaussian filtering with appropriate cut-off frequencies may be used to isolate cycle mean flows, macro-scale cyclic variations, and small scale turbulence. Characterizing the flow in the vicinity of the spark plug will be especially important. Correlating the flow field with flame development and combustion efficiency and quantifying cyclic variation levels and variations in turbulence intensity from cycle to cycle may help predict cycles resulting in misfires or incomplete combustion. It would also be useful to further explore the 'silent domain' concept.

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