Abstract

In order to understand turbulence in internal combustion engines, the average and turbulent kinetic energies associated with the instantaneous velocity data during consecutive engine cycles at every other crank angle from 69 °BTDC to 25 °BTDC from a particle image velocimetry experiment on a motored four-stroke, single-cylinder, four-valve gasoline stratified spark ignition direct injection engine were calculated. The kinetic energy spectra indicated that energy cascaded from larger to smaller length scales. However, more unexpectedly, they also showed that the kinetic energy was lowest between approximately 55 °BTDC and 40 °BTDC and the turbulent kinetic energy did not vary with crank angle. These results need to be further analyzed, and further experiments may need to be conducted, to fully understand them.

Introduction

The operation of internal combustion engines at their current speed range is made possible by turbulence. If complete combustion of the fuel-air mixture depended solely on the laminar flame velocity of the fuel, a typical four-stroke engine running on iso-octane (a hydrocarbon that approximates gasoline) would have a maximum speed of approximately 400 rpm [1]. However, turbulence wrinkles the flame front and causes entrainment of the fuel-air mixture by the flame front, leading to flame fronts with larger surface areas. This leads to higher burning rates and the high power densities of internal combustion engines. Turbulence occurs as the fluid jet coming through the intake valve separates from the valve seat, producing shear layers with large velocity gradients [1]. It increases as the engine speed increases, allowing internal combustion engines to operate over a large range of loads and speeds.

Proper combustion in internal combustion engines may be ensured by controlling turbulence in the flow within engines. If turbulence causes the surface area of flame fronts to become too large, excessive heat conduction out of the reaction zone causes premature flame extinction. Also, if the flame kernel from the early stages of combustion dwells near the spark plug for too long, it may be extinguished too quickly due to excessive heat loss, resulting in incomplete combustion. However, if the flame kernel moves away from the region near the spark plug too quickly towards regions of high ignition energy or low temperature, such as the cylinder walls, it may be extinguished too. Thus, a mean fluid velocity between 3 m/s and 5 m/s is optimal [1]. In direct injection engines, turbulence also controls the degree of mixing of the fuel spray with the air in the cylinder, thus controlling the equivalence ratio stratification and flame development.

As turbulence is very sensitive to initial conditions, there can be great cycle-to-cycle variability in turbulence in engines, leading to incomplete combustion or even misfires, and variations in the engine power. Accounting for cycle-to-cycle variability leads to design compromises that reduce engine power at full load and fuel efficiency at part load [1]. Understanding turbulence allows for the minimization of the effects of cycle-to-cycle variation in turbulence. This can lead to higher engine power, better fuel economy, and reduced emissions.

Turbulence may be studied by examining the fluid velocity fields in internal combustion engines. Particle image velocimetry (PIV) is a technique that uses a laser light sheet to illuminate tracer particles in the fluid in a transparent quartz cylinder and captures the movement of these particles using high-speed cameras. These images are then used to construct instantaneous fluid velocity fields. The experiment discussed in this report used a high-speed PIV technique that employed 355 nm lasers and silicone oil tracer particles to capture instantaneous velocity data in a motored four-stroke, single-cylinder, four-valve gasoline stratified spark ignition direct injection engine during consecutive engine cycles at every other crank angle from 69 °BTDC to 25 °BTDC. The engine was run at a speed of 2000 rpm with an intake pressure of 95 kPa and an intake temperature of 45 °C. Previous high-speed PIV techniques used lasers in the green range of the spectrum (510 nm, 527 nm, or 528 nm). However, lasers emitting green light cannot be used to capture reliable velocity fields in a fired engine as soot luminosity would interfere with the laser light scattered by the tracer particles. Using 355 nm lasers effectively circumvents this problem [1].

Analytical Procedure

Instantaneous velocity vector fields were obtained from the raw images of tracer particles using LaVision Davis 7.1, a commercial software package [1]. These velocity vector fields from consecutive cycles were organized according to crank angle. Gaussian filters of wavelengths varying from wavelengths close to the resolution of the velocity vector fields (1 mm) up to wavelengths close to the size of the vector fields were applied to them (33.1 mm). The resultant velocity vector fields illustrate the flow structure at different length scales in internal combustion engines. They were subtracted from each other to obtain band passes that had the same size in wave number space. For example, the velocity vectors resulting from the application of Gaussian filters of 1 mm wavelength (1 mm^{-1} wave number) and 16 mm wavelength (0.0625 mm^{-1} wave number) were subtracted from the velocity vectors resulting from the application of Gaussian filters of 1.00100 mm wavelength (0.999001 mm^{-1} wave number) and 16.3 mm wavelength (0.0613 mm^{-1} wave number), respectively, to obtain band passes, both with a size of 0.001 mm^{-1}, illustrating the flow structure at wavelengths 1.0005 mm and 16.15 mm, respectively. The following figure is a velocity vector field illustrating the flow structure at a wavelength of 8.03226 mm at a crank angle of 37 °BTDC:

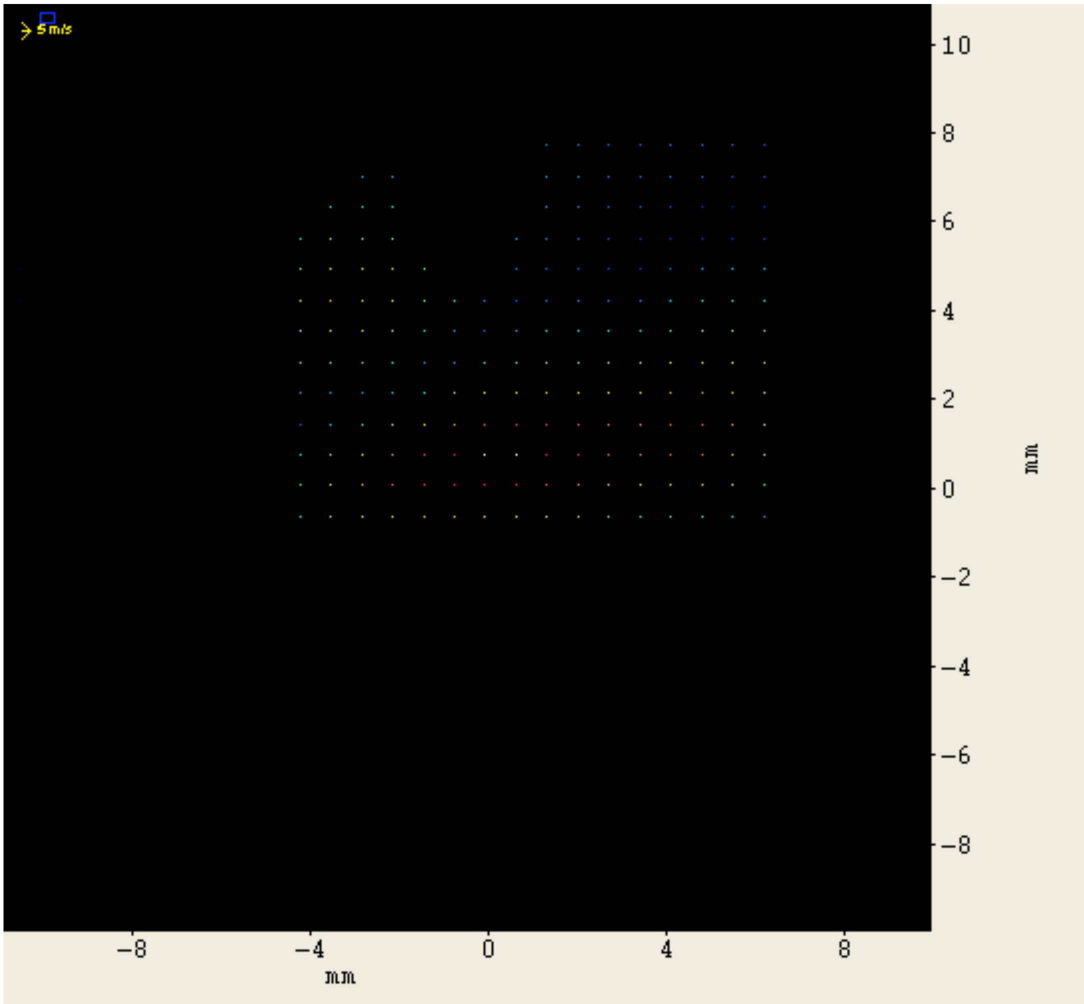

Figure 1: Velocity Vector Field at a Wavelength of 8.03226 mm at a Crank Angle of 37 °BTDC in a Motored Engine

Note that the larger area at the top of the image with an absence of velocity vectors denotes space occupied by the spark plug.

Next, mass-specific kinetic energy was calculated for each set of band pass velocity vector fields and for the unfiltered velocity vector fields at every other crank angle using the following equation:

$$ke = \frac{1}{2}(u^2 + v^2) \quad (1)$$

where,

ke = Mass-specific kinetic energy

u = Component of the fluid velocity in the x-direction

v = Component of the fluid velocity in the y-direction

The vector fields were divided into several smaller areas and the ensemble mean velocity and the rms of the velocity fluctuations about the ensemble mean were calculated for each of the smaller areas. Then, an ensemble average kinetic energy false-color image was constructed using the ensemble mean velocity and an ensemble turbulent kinetic energy false-color image was constructed using the rms of the velocity fluctuations about the mean. Examples of such images are shown in the figures below:

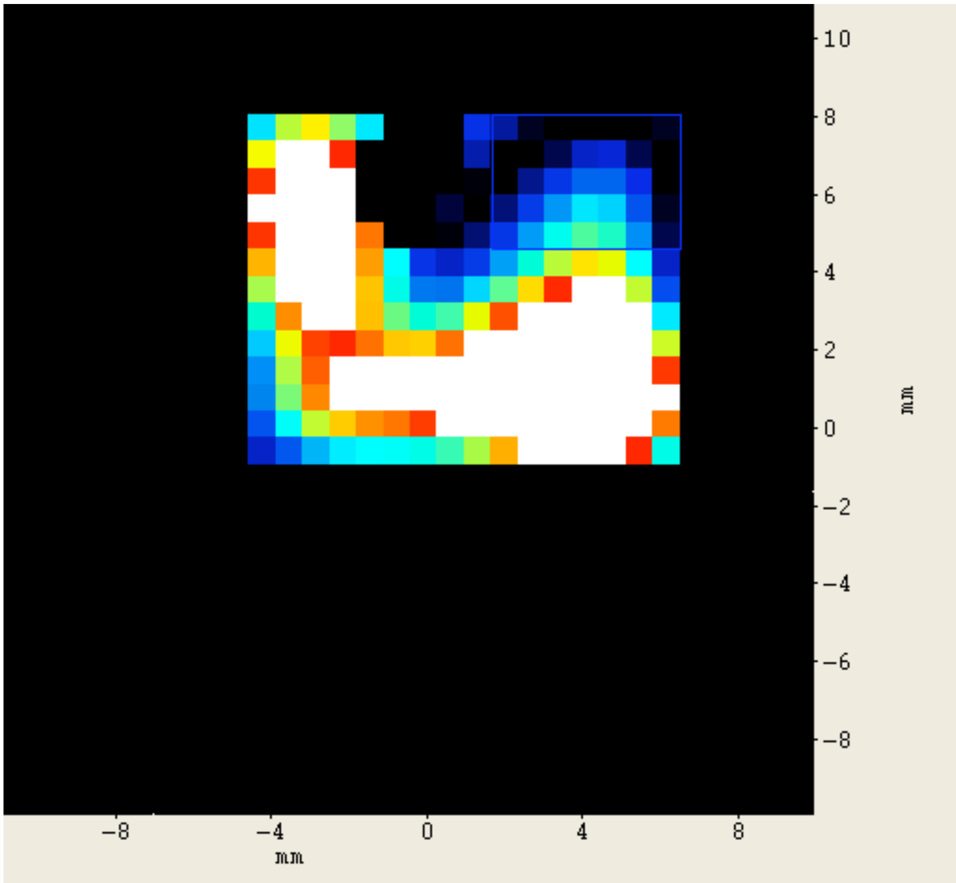

Figure 2: Ensemble Average Kinetic Energy False-Color Image Corresponding to the Velocity Vector Field at a Wavelength of 8.03226 mm at a Crank Angle of 37 °BTDC in a Motored Engine

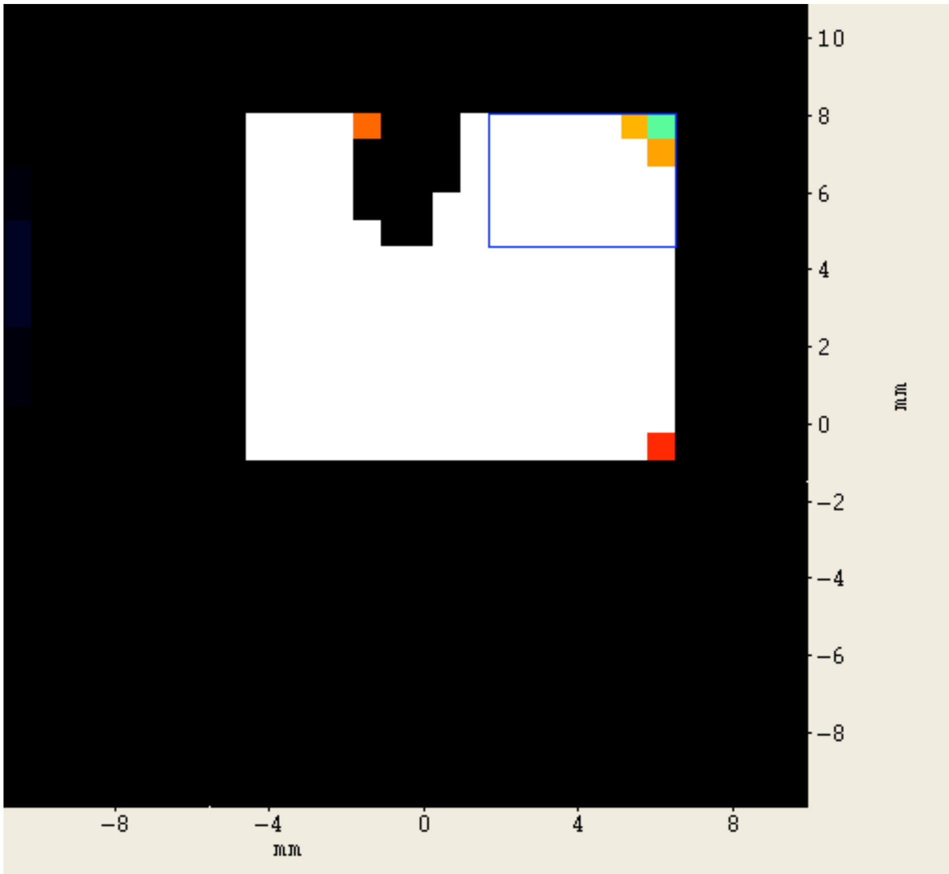

Figure 3: Ensemble Turbulent Kinetic Energy False-Color Image Corresponding to the Velocity Vector Field at a Wavelength of 8.03226 mm at a Crank Angle of 37 °BTDC in a Motored Engine

Figures 2 and 3 show a small rectangular area selected at the top right-hand corner of the ensemble average and ensemble turbulent kinetic energy false-color images. The spatial averages of the ensemble average and ensemble turbulent kinetic energies in this rectangular area are referred to as the average kinetic energy and the turbulent kinetic energy, respectively. If the spatial averaging was done over the entire ensemble average and ensemble turbulent kinetic energy false-color images, the larger amount of instantaneous velocity data available at crank angles further away from TDC would have had an effect upon the average and turbulent kinetic energies calculated. The average and turbulent kinetic energy values were plotted against crank angle and wave number to examine the variations in average and turbulent kinetic energies with time and length scale.

Results

The following figures show the average kinetic energy and turbulent kinetic energy values plotted against crank angle and wave number.

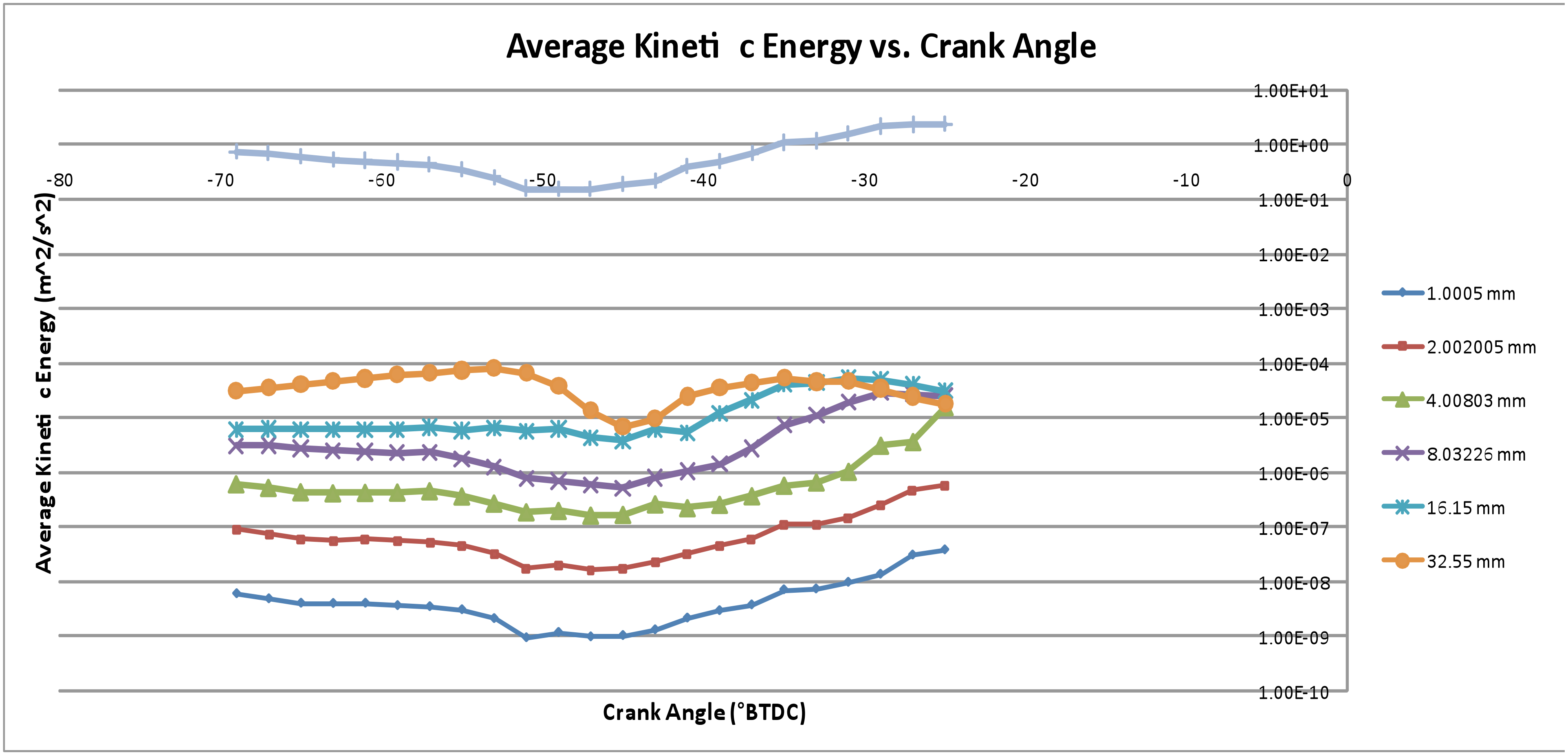

Figure 4: Average Kinetic Energy against Crank Angle for Filtered and Unfiltered Velocity Fields in a Motored Engine

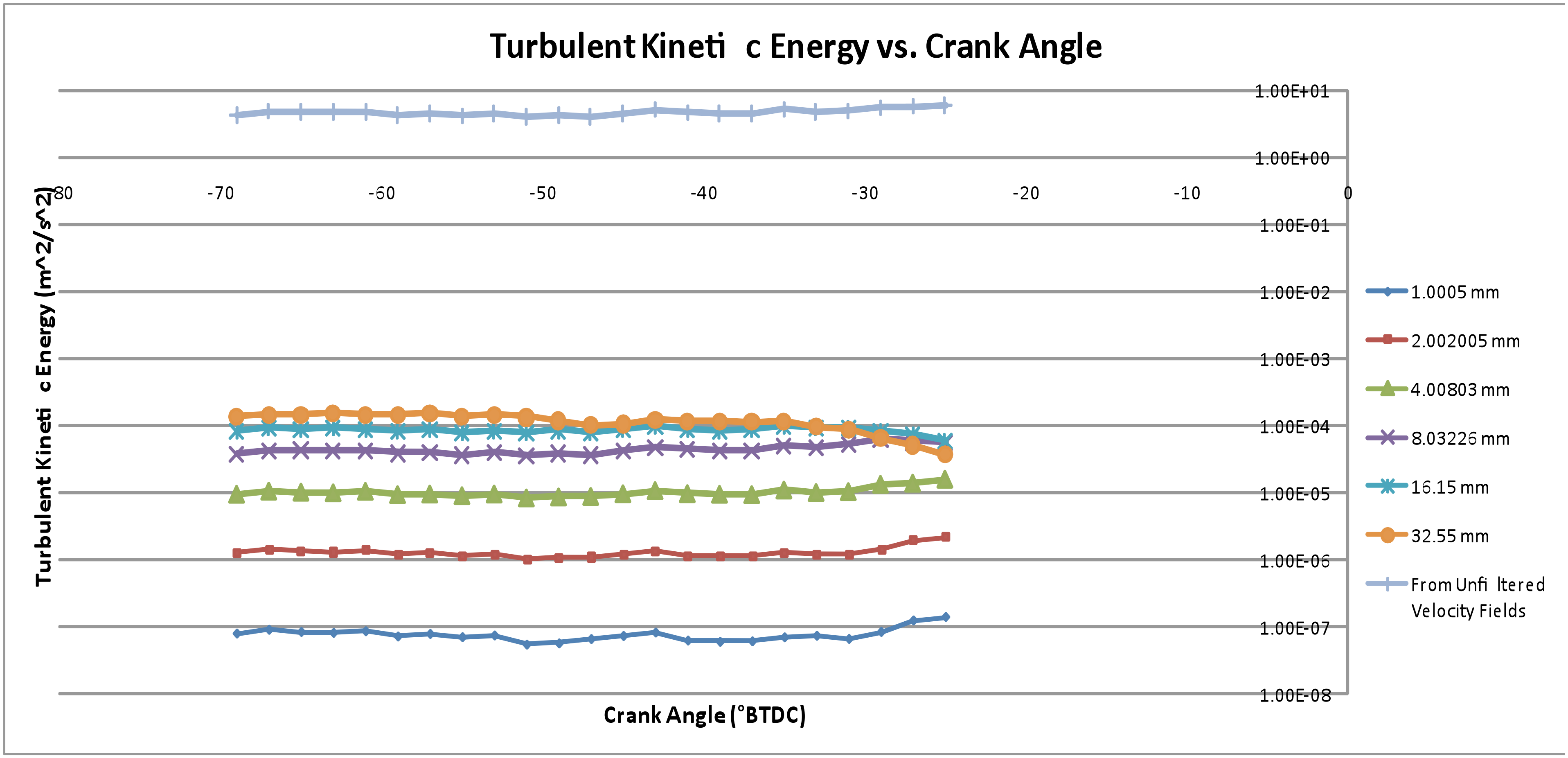

Figure 5: Turbulent Kinetic Energy against Crank Angle for Filtered and Unfiltered Velocity Fields in a Motored Engine

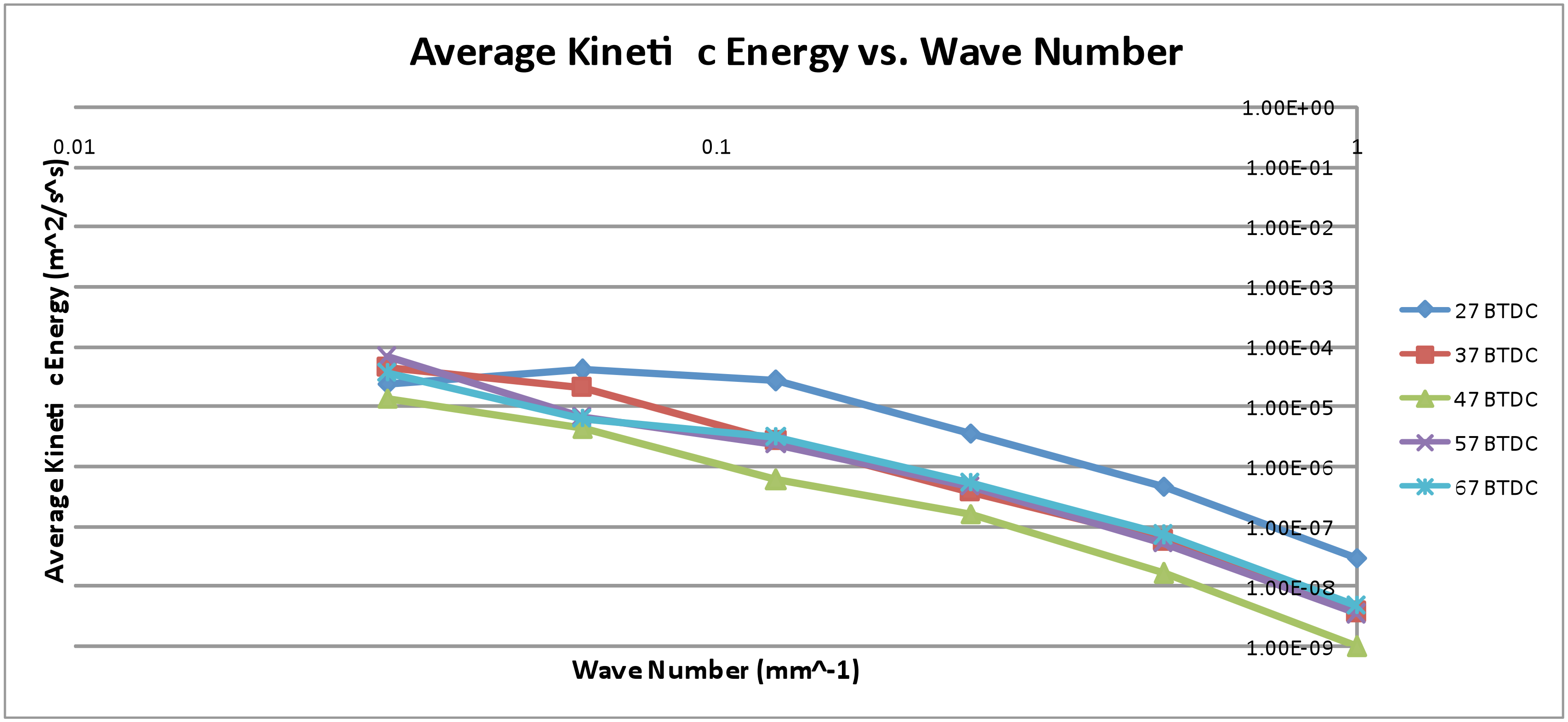

Figure 6: Average Kinetic Energy against Wave Number at Various Crank Angles for Filtered Velocity Fields in a Motored Engine

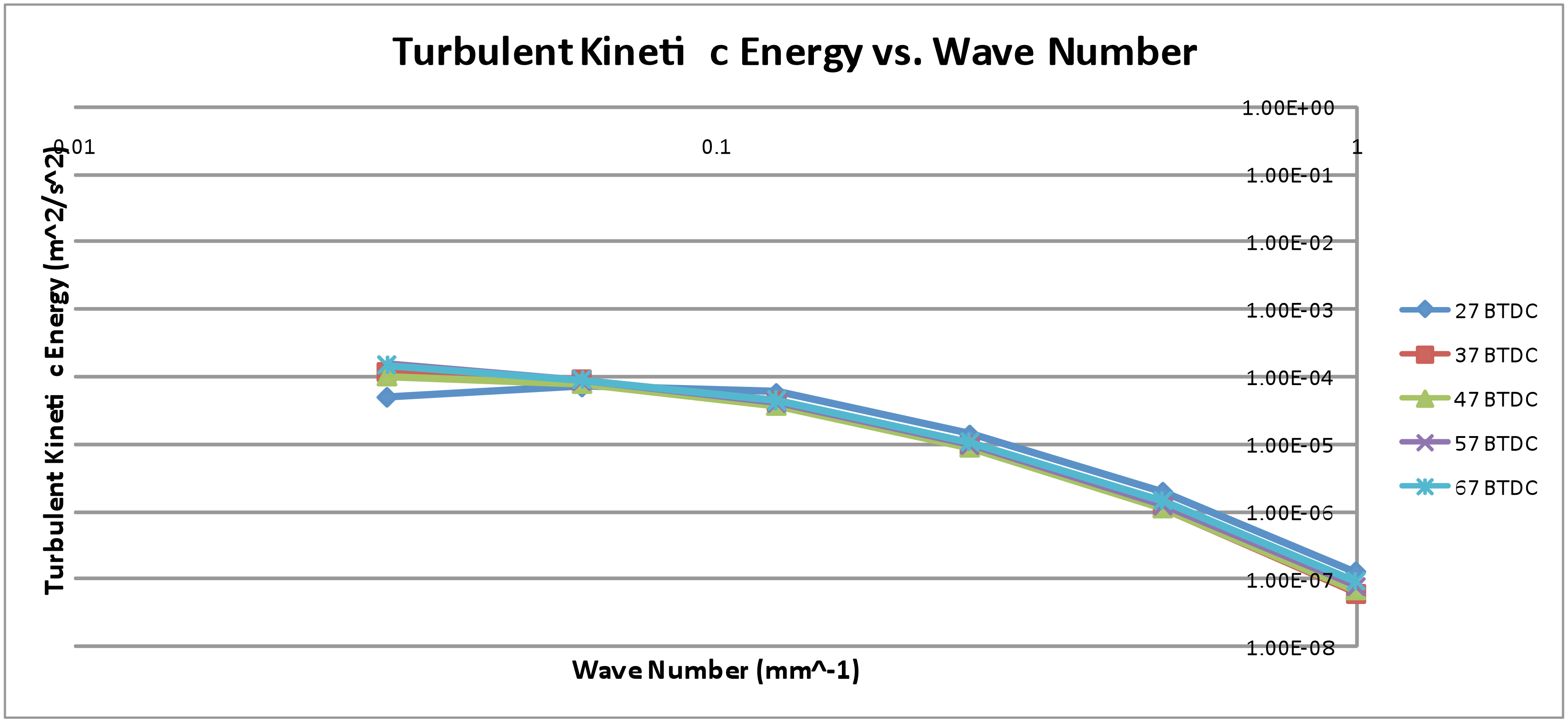

Figure 7: Turbulent Kinetic Energy against Wave Number at Various Crank Angles for Filtered Velocity Fields in a Motored Engine

Discussion of Results

Figure 4 shows that the average kinetic energy is highest for flow structures at higher length scales. This illustrates that as energy cascades from larger length scales to smaller length scales, some of it is dissipated [1]. However, the dip in the plots between approximately 55 °BTDC and 40 °BTDC is hard to explain, as the average kinetic energy of the fluid in an internal combustion engine depends directly on the piston speed which decreases in a sinusoidal fashion from about 90 °BTDC (depending on the piston eccentricity) to TDC.

Figure 6 again illustrates the energy cascade from larger to smaller length scales. It also shows the dip in average kinetic energy more clearly, with 27 °BTDC having the highest average kinetic energy and 47 °BTDC having the lowest average kinetic energy among the crank angles plotted.

Figures 5 and 7 lead to a most interesting conclusion: turbulent kinetic energy does not vary depending on crank angle. It is expected that turbulent kinetic energy would increase as the piston approaches TDC, compressing the fluid within the cylinder, and reach a peak, possibly, before decreasing as the dissipation rate increases. However, the turbulent kinetic energy was calculated using only the data available in a small rectangular portion of the velocity vector fields examined. This rectangular region may have been less representative of the larger velocity vector fields at crank angles further away from TDC. Also, the rectangular region under consideration was next to the spark plug, where a strong tumble flow generated by the initial intake valve events dominated the flow structure. Thus, the large initial turbulent kinetic energy associated with the tumble motion might overshadow any smaller changes in the turbulent kinetic energy that occur due to piston movement.

Conclusion and Future Work

The analysis of the data from the experiment under discussion indicates that the average kinetic energy reaches a minimum between approximately 55 °BTDC and 40 °BTDC, and the turbulent kinetic energy does not vary with crank angle. Reanalysis of the experimental data by finding the spatial mean velocity and the rms of the velocity fluctuations about this spatial mean and using these values to calculate the ensemble average kinetic energy and the ensemble average of the turbulent kinetic energy may confirm these conclusions. Examining the average and kinetic energies associated with a different, possibly larger, rectangular portion of the velocity vector fields and comparing them to the values presented in this report might also provide more insight. Further experiments may be required to confirm and understand these results. Calculating dissipation rates from the experimental data under discussion may also provide valuable information.

In order to develop a more complete understanding of turbulence in internal combustion engines, the high-speed PIV technique should be combined with high-speed planar laser induced florescence (PLIF) of biacetyl to simultaneously image the flow structure and the equivalence ratio distribution in a spark ignition direct injection engine in order to investigate events occurring near ignition, such as the interaction of the plasma channel produced by the spark with the surrounding fluid flow. Data obtained from such experiments may also be used to obtain kinetic energy and dissipation rate spectra that enhance the current understanding of turbulence in engines and help validate CFD models used to design and develop internal combustion engines [1].

Bibliography

1. Fajardo, Claudia M. (2007). "Development of a High-Speed UV Particle Image Velocimetry Technique and Application for Measurements in Internal Combustion Engines." University of Michigan.