

Impact of Fuel Sprays on In-Cylinder Flow Length Scales in a Spark-Ignition Direct-Injection Engine

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ABSTRACT

The interaction of fuel sprays and in-cylinder flow in direct-injection engines is expected to alter kinetic energy and integral length scales at least during some portions of the engine cycle. High-speed particle image velocimetry was implemented in an optical four-valve, pent-roof spark-ignition direct-injection single-cylinder engine to quantify this effect. Non-firing motored engine tests were performed at 1300 RPM with and without fuel injection. Two fuel injection timings were investigated: injection in early intake stroke represents quasi-homogenous engine condition; and injection in mid compression stroke mimics the stratified combustion strategy. Two-dimensional crank angle resolved velocity fields were measured to examine the kinetic energy and integral length scale through critical portions of the engine cycle. Reynolds decomposition was applied on the obtained engine flow fields to extract the fluctuations as an indicator for the turbulent flow. For the early injection condition, the average kinetic energy is increased by the fuel injection for 40 CAD, but the turbulent kinetic energy is not enhanced significantly. When the fuel is injected in the compression stroke, both average and turbulent kinetic energy are elevated for 70 CAD after start of injection (aSOI). The spatial mean of the turbulent integral length scale varies from 2-10 mm during intake and compression stroke without fuel injection. Strong spatial variations of the turbulent integral length scale are observed. Early fuel injection lowers the spatial mean integral length scale by as much as 2 mm within 40 CAD aSOI, while the maximum decrease of that scale during late injection is about 3 mm within 30 CAD aSOI.

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INTRODUCTION

The internal combustion engine has been the most widely adopted machine to convert chemically stored energy into kinetic energy for the use in vehicle propulsion. The increasing demand for vehicles along with concerns about fuel supplies and greenhouse gas emissions calls for better fuel efficiency of engines. After decades of development, various novel technologies have been invented and were introduced on automotive engines. Among those, the Spark-Ignition Direct-Injection (SIDI) technique, also known as Gasoline Direct Injection (GDI), provides substantial fuel consumption improvement compared with the conventional Port Fuel Injection (PFI) technique [1, 2]. Flexible and precise control of injection amount and timing, reduced pumping losses, and other benefits make SIDI attractive to achieve increased fuel economy. Given that the consumption of the fuel is driven by turbulent flame propagation, it is essential to optimize the flow and turbulence conditions for best mixing of fuel and air and subsequent combustion [3].

Therefore, the study of in-cylinder flow is an important aspect of internal combustion engine research. In particular, key questions here include the impact of fuel injection strategy on in-cylinder kinetic energy and on integral length scales with their subsequent roles in

burning behavior. Turbulent flows have been studied by generations of scientists and engineers. While much progress has been made at all levels, from experimental investigations to the development of simulation strategies, there is still a lack of understanding that would allow accurate and fully predictive simulations for engine design work. In conventional studies of fluid mechanics, turbulence is interpreted as any deviation from the mean flow, determined by a Reynolds decomposition that separates the instantaneous flow into a mean component and a fluctuating component. In the context of internal combustion engines, this decomposition is typically performed on the engine flow captured for an ensemble of cycles at a fixed crank angle degree. The ensemble averaged flow is taken as the mean component, while the fluctuating component contains everything else. This fluctuating component contains cycle-to-cycle fluctuations and 'true' turbulent fluctuations. A clear separation of these two components is not easy to define and various approaches have been discussed in the literature [4]. Nevertheless, the turbulence obtained by the Reynolds decomposition is still widely used as the input to turbulence closure models, models for turbulent flame speed, and so on. Therefore, this paper follows this decomposition to calculate the turbulence. In addition, it is noteworthy to mention that the magnitude of the fluctuations in reciprocating engines are

often greater than that of the mean flow. As a consequence, high turbulence intensities at low Reynolds numbers are seen in internal combustion engine flows [5].

Optical experimental capabilities for flow measurements have helped engine researchers to gain deeper insight into in-cylinder turbulence. In particular, Laser Doppler Velocimetry (LDV) was carried out to explore engine turbulence properties. For example, two-point, single probe-volume LDV was employed to measure the turbulence flow in the swirl plane at the mid plane of the TDC clearance height inside a pancake-shaped engine chamber. Integral length scale, homogeneity, and isotropy were discussed in that engine for several compression ratios [6, 7, 8]. The subsequent implementation of Particle Image Velocimetry (PIV) provided spatially resolved visualization of engine flow fields [9]. More recently, high frame rate cameras and high repetition rate lasers enabled time-resolved PIV measurements [10, 11, 12]. Based on these visualization techniques, researchers are able to gain deeper understanding of the flow characteristics inside an engine cylinder. Imaging techniques are particularly useful to investigate the interaction between in-cylinder gas flow and fuel sprays [13, 14, 15, 16].

The turbulent integral length scale is an important quantity to present the size of large eddies in turbulent flow. In classic turbulence theory, two-point correlation is used to obtain the integral length scale [17]. The choice of the reference point is crucial in yielding length scale. Benefitting from the 2D PIV measurements, 2D maps of the turbulent integral length scale can be determined by selecting each vector point in the flow field as the reference point for the correlation function. Such maps of integral length scale can spatially resolve the distribution of the turbulent flow length scales [5, 18, 19].

In the present study, in-cylinder air flow within a tumble plane was measured in a SIDI optical engine by a crank-angle resolved PIV technique. The engine flow kinetic energy and turbulent integral length scale maps were obtained to spatially and temporally investigate the impact of fuel injection on the flow. These engine flow properties were determined for all crank angle degrees (CAD) from -360° after top dead center firing (aTDCf) to 0° aTDCf to analyze the flow evolution. A baseline measurement for motored engine operation at 1300 rpm with intake manifold absolute pressure (MAP) at 95 kPa was performed. Two tests with the start of injection (SOI) at -310° aTDCf (SOI -310) and -90° aTDCf (SOI -90), respectively, were conducted to assess the impact of the injection on the flow. The experimental configuration and operating conditions are described next, followed by PIV error analysis. Then a detailed explanation of how to calculate integral length scale map is presented, followed by the analysis and discussion of the results. Finally, conclusions are drawn to summarize how the engine flow turbulent characteristics are affected by fuel injection.

EXPERIMENTAL SETUP

The PIV experiment is carried out in an optical engine operating at 1300 rpm under 95 kPa intake manifold absolute pressure (MAP). The engine is motored by a hydraulic dynamometer, and the

fluctuation of the speed is controlled to within ± 5 rpm. It is a four-valve (two intake valves and two exhaust valves) SIDI engine configured with the injector and the spark plug located near the center. The injector is mounted between of the intake valves, and the spark plug is between the exhaust valves, as shown in Figure 1. Key parameters for the engine and its operation in this study are summarized in Table 1. Further details of the engine can be found in previous publications [20, 21]. Figure 1 also shows the schematic layout of the optical setup. A double-pulsed high-speed Nd:YLF laser (Darwin-DUO-527-80-M, 527 nm, 4.8 mJ/pulse) was operated at 7,800 Hz to obtain PIV image pairs every crank angle degree and the beam was formed into a sheet light of 2 mm thickness using sheet forming optics. This laser sheet was directed by a Bowditch design 45° mirror setup into the cylinder through the quartz piston window and illuminated a vertical tumble plane bisecting the injector and the spark plug over the entire height of the cylinder. Silicon oil droplets ($\sim 1 \mu\text{m}$ diameter) were doped into the engine intake air system with a TSI 6-jet atomizer (model 9306A). A high-speed monochromatic camera (Phantom V1610, Vision Research) operating at the 15.6 kHz was used to collect Mie scattering signals from the pulse-illuminated silicon oil droplets. Signals were collected using a Nikon AF Micro-Nikkor 200 mm f/4D ED lens with the aperture set to f/8 to balance between enough depth of focus and sufficient light intensities on the camera. The camera has a full sensor resolution of 1280×800 pixels with 12-bits dynamic range. Each CMOS pixel size is $28 \mu\text{m}$ and the magnification of the setup used here was 0.36. The camera back was tilted upwards to reduce detection of the laser light reflections from the pent-roof. A Scheimpflug adaptor was then required between the camera and the lens to ensure that all signals from the illuminated tumble plane were in focus. Moreover, since the PIV data was taken in the tumble plane through an optical liner, correction of the distortion introduced by the cylindrical transparent liner was also required. Therefore, a calibration image of a regular dot matrix was taken prior to the test with the optical liner on, and the correction was applied to the particle images to correct the image distortion from the optical liner and the Scheimpflug setup.

Table 1. Engine parameters and experimental conditions

Parameter	Value
Bore	86 mm
Stroke	86 mm
Clearance volume	66.2 cm^3
Compression ratio	8.7
Engine speed	1300 rpm
Fuel	Iso-octane
Fuel injection pressure	12 MPa
Fuel mass / cycle	10.7 mg
Intake manifold absolute pressure	95 kPa
Oil and coolant temperature	45°C
Intake air temperature	45°C
Start of injection (SOI)	-310° aTDCf -90° aTDCf

An eight-hole injector with nominal spray angle of 90 degrees was installed and operated under the fuel injection pressure of 12 MPa. The injector was oriented such that two of the eight plumes symmetrically straddled the spark plug. The gap of the spark plug was facing the injector. Two injection timings at -310° and -90° aTDCf were selected to represent early and late injection conditions, respectively. Each injection introduced 10.7 mg pure iso-octane to the cylinder resulting in a global equivalence ratio of 0.34, a good value for stratified operation. This injection amount was also chosen to form a homogeneous stoichiometric air-fuel mixture with early injection when the engine was running at 40 kPa intake MAP. Engine oil & coolant temperature and intake air temperature were set to be 45°C .

The onboard memory of the camera limits the number of cycles that can be recorded during one engine run to 92 consecutive cycles. The raw particle image pairs were recorded and post-processed by a commercial software, DaVis 8.3 (LaVision). Areas outside the illuminated regions were masked before processing to speed up the analysis. Besides, the images were saturated in the locations where dense liquid spray existed during injection. An algorithmic mask was applied to block the saturated pixels since no meaningful PIV cross correlation could be obtained there anyway. A multi-pass, decreasing interrogation window size cross-correlation procedure was then implemented to calculate the flow fields out of the particle images. The final interrogation window size was 32×32 pixels with 50% vector overlap, corresponding to a 16-pixel distance (~ 1.24 mm) between adjacent vectors. This spatial resolution ($\sim$ interrogation window size of 2.49 mm) is enough to resolve the in-cylinder turbulent integral length scale, which is on the order of ~ 5 mm [5, 7, 18]. However, it is not enough to study smaller scales like Taylor micro scales or Kolmogorov length scales. The parameters of the PIV experiment are summarized in Table 2.

Table 2. PIV experiment parameters

Parameter	Value
Particle type	Silicone oil (Dow Corning 510, Fluid, 50 CST)
Averaged particle diameter	$\sim 1\ \mu\text{m}$
Particle image density	7-15 particles per interrogation window
Stokes number	~ 0.02 at 20 m/s flow velocity
Laser wavelength	527 nm
Laser repetition rate	7,800 Hz, double pulse mode
Laser sheet thickness	2 mm
Laser pulse energy	4.8 mJ/pulse
Laser pulse temporal interval	Dynamic, 6 μs to 55 μs
Camera aperture	f/8
CMOS pixel size	28 μm
Number of sampled image pairs	361 image pairs/cycle, 92 cycles
PIV interrogation strategy	64×64 with 25% overlap to 32×32 with 50% overlap
Field-of-view	62 mm $\times$ 99 mm
Camera resolution	800 pixel $\times$ 1280 pixel
Spatial resolution	0.0778 mm/pixel 2.49 mm/interrogation window
Magnification	0.36

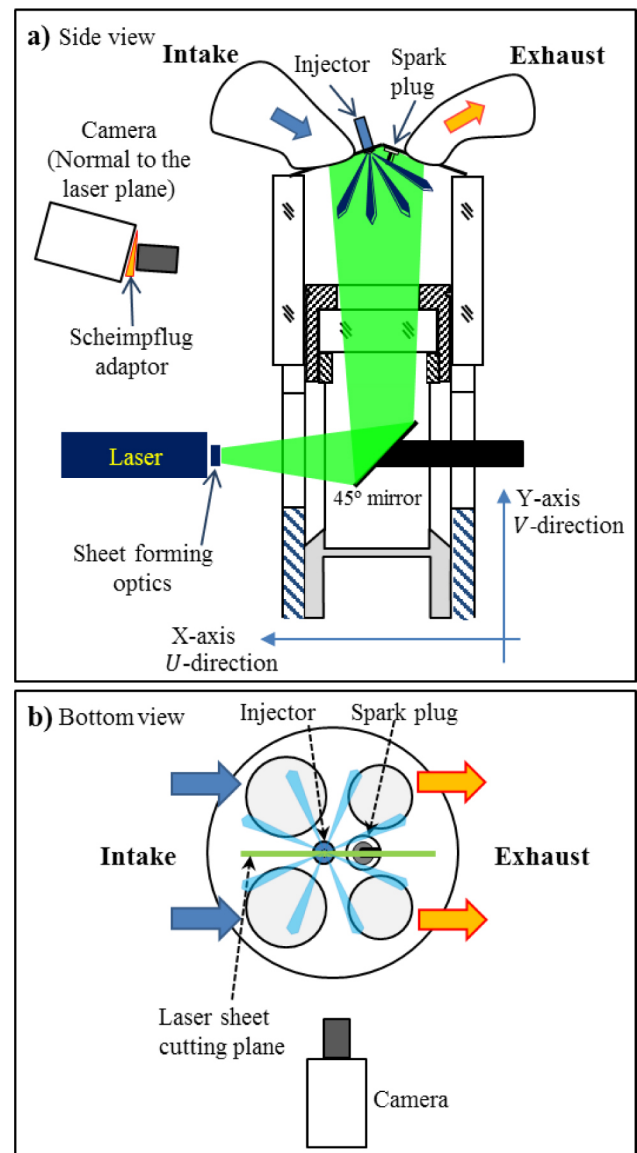


Figure 1. Schematic layout of the experiment setup, engine configuration, and flow field sign convention. a) Side view; b) Bottom view.

PIV DATA ERROR ANALYSIS

To enable the analysis of the impact of fuel sprays on in-cylinder flow it is important to first determine the uncertainty of the PIV measurements. The perspective error introduced by the particle out-of-plane movement is discussed first. The perspective error can be estimated according to Equation (1) and (2) [22, 23]:

$$e_x = \frac{\Delta z}{\Delta x} \frac{x_p}{d_o} \quad (1)$$

$$e_y = \frac{\Delta z}{\Delta y} \frac{y_p}{d_o} \quad (2)$$

The error in X- and Y-direction are noted as e_x and e_y , respectively. Δx , Δy , and Δz are the displacements in X-, Y-, and Z-direction, respectively. Z-axis indicates the out-of-plane direction which is normal to the X-Y plane and pointing towards the camera. x_p is the distance between the intersection point of the optical axis with the focal plane, and the projected point of seeding particles on the X-axis. y_p is obtained similarly, but by projecting the seeding particles on the Y-axis instead. d_o is the distance between the object plane and the camera lens plane which can be calculated from the magnification (M) and the focal length (f) by Equation (3):

$$d_o = \frac{(1 + M)f}{M} \quad (3)$$

Due to the implementation of a Scheimpflug adaptor, the non-uniformity of magnification will lead to a variable d_o . In order to simplify the error estimation, the overall magnification of 0.36 is used by taking the ratio of camera sensor dimension and the field-of-view. The optical axis is adjusted aiming at the piston bowl bottom when the piston is at TDC to reduce the reflections from cylinder head. Therefore, the maximum y_p is about 80 mm when the piston is at bottom dead center (BDC). At BDC, the in-plane motion is dominated by the intake tumble flow while the out-of-plane is relatively small since the engine is not running with strong swirl motion. According to previous investigations in this engine using stereo-PIV near TDC, the out-of-plane motion is at a similar level of the in-plane motion [24]. Considering that the tumble flow is stronger at BDC than at TDC, it is reasonable to assume that the in-plane displacement of Δy is at most as large as the out-of-plane displacement Δz at BDC. Under this assumption, the maximum perspective error in the Y-axis direction can be calculated to be 10%. For the perspective error in X-axis direction, the maximum x_p is half of the illuminated region in this direction, which is 20 mm (see Figure 7 for reference). The largest displacement ratio $\Delta z/\Delta x$ at TDC is unity, therefore, the resulted maximum perspective error in X-direction is 3%.

The camera field-of-view was set to include the entire stroke of the engine. As the piston moves upward from BDC the number of vectors decreases since PIV measures on a fixed spatial grid. Moreover, in regions of dense fuel sprays the camera saturates and the number of vectors is further reduced. These saturated image regions are masked out before the PIV analysis is performed. As illustrated in Figure 2, the number of vectors decreases significantly during the fuel spray presence. Comparing the number of vectors obtained during injected engine runs to the numbers obtained for just motored runs indicates a conservative evaluation of the timing when the average flow fields are no longer affected by spray induced image saturation.

The time interval between the two laser pulses, i.e. delta T was optimized for each CAD based on the velocity at this CAD [23]. This dynamic time interval setting ensures optimum PIV conditions with

the maximum pixel shift close to but less than 8 pixels (a quarter of PIV interrogation window) for all CADs. The minimum displacement that can be resolved by the PIV algorithm reliably is 0.15 pixels [25]. Therefore, the dynamic velocity range is a factor of $8/0.15 \approx 53$. Note that the in-cylinder flow field also has strong spatial variations, especially during early intake stroke or fuel spray injection. Therefore, the delta T was set short enough to resolve the maximum possible velocity in the whole field-of-view. Figure 3-a) shows the ensemble mean of the spatial maximum and minimum velocity magnitudes for each crank angle. The ensemble averaged maximum velocity falls within the envelope of the velocities calculated based on 0.15- and 8-pixel displacements. It indicates that the maximum velocities for most the cycles are in a reliable range. The delta T was reduced during fuel injection to resolve higher flow velocities. With the fuel injected early during the intake stroke and by late during mid-compression stroke, the ensemble means of the spatial maximum velocity were then also within the maximum 8-pixel displacement at each crank angle, as shown in Figure 3-b) and c), respectively.

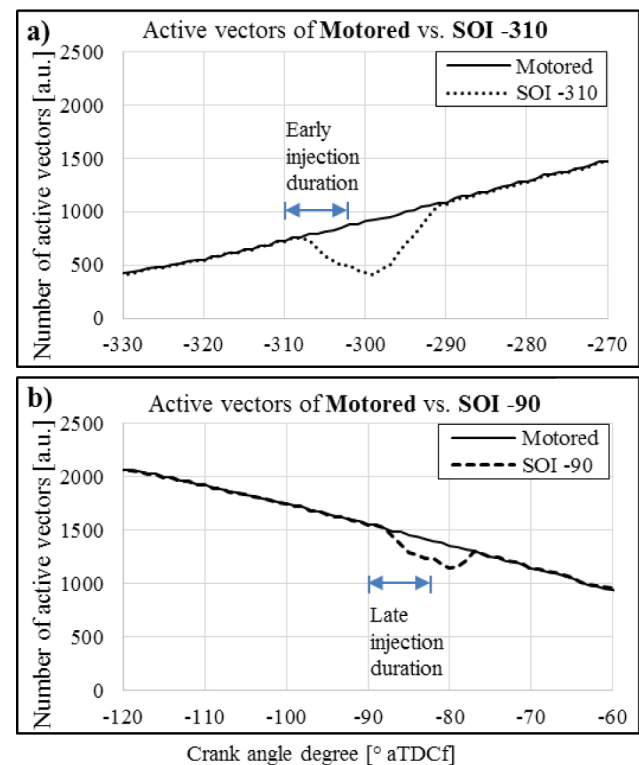


Figure 2. Number of active vectors for a) early injection condition and b) late injection condition.

The velocities lower than the 0.15-pixel displacement were considered as noise velocities. The percentage of the noise vectors in the flow field of each cycle was calculated and then ensemble averaged. These ensemble averaged noise vector percentages at each crank angle are illustrated in Figure 4. The noise vectors were at a quite low level except during the early intake and late compression stroke when the piston is close to the cylinder head and overall velocities are low.

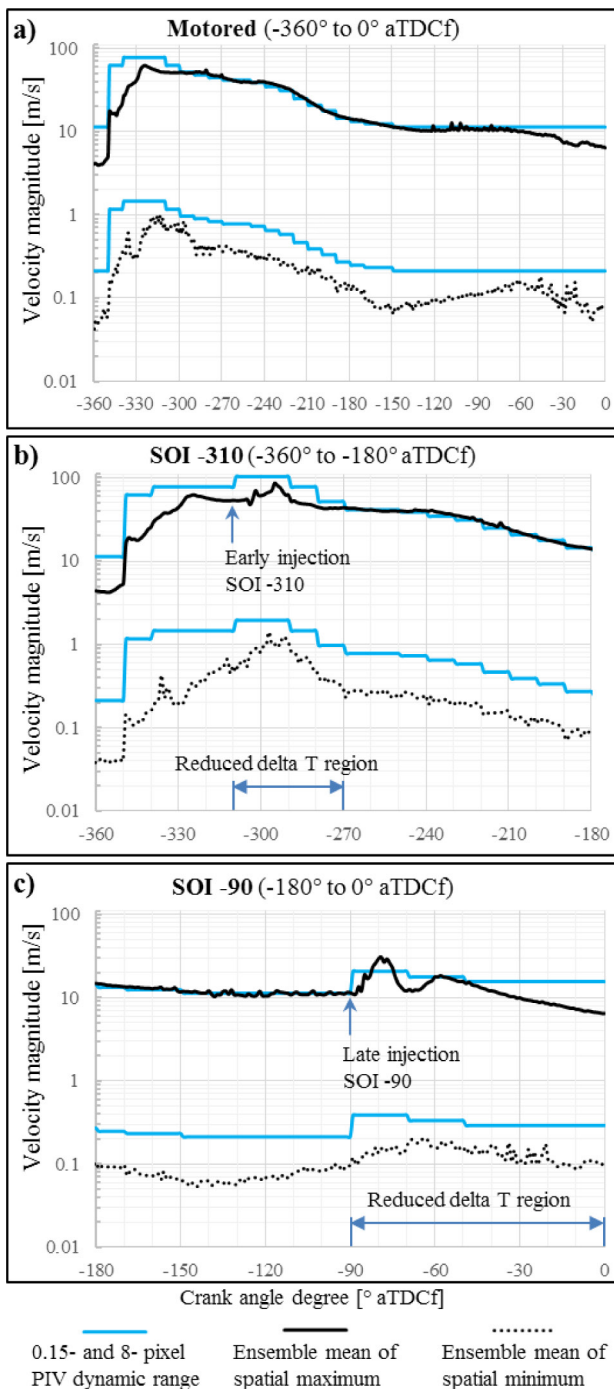


Figure 3. Ensemble means of the maximum and minimum velocity magnitude compared with the PIV dynamic range of a) motored, b) early injection, and c) late injection conditions at different crank angle degrees.

The uncertainty of the PIV results was estimated according to the analysis principle that assesses the PIV correlation function [26]. A respective algorithm is implemented in the processing software that was used in this study (DaVis 8.3, LaVision GmbH). This estimation provided a velocity magnitude uncertainty value at each interrogation

window of the flow field. The concept of this method maps the interrogation windows of the two frames of a particle image pair onto each other based on the calculated displacement. Ideally, after this mapping frame #1 should be identical with frame #2. However, in a real application, there will be a disparity between the mapped frame (e.g. frame #1) and the other frame (frame #2). By evaluating the level of this disparity, the uncertainty at this interrogation window can be obtained. Then repeating this process for the entire vector field generates a scalar field of the velocity uncertainty. The spatial means of these uncertainty maps are provided in Figure 5. Higher uncertainty regions exist during early intake and late compression under motored condition. Early injection resulted in elevated PIV uncertainty for about 20 CAD, while late injection affects the uncertainty for an even longer time, both times right after SOI. The flow field uncertainty during fuel injection can be 3-4 times higher than that of motored flow field at the same crank angle. This increased uncertainty likely is caused by several factors. Scattered light levels from the cylinder head, piston, gasket, spark-plug, and the liner increase due to scattering from the fuel droplets and adds noise to the raw PIV images. Moreover, the fuel injection introduces extra momentum to the engine air. During injection, the fuel droplets exchange momentum with surrounding air. It will lead to the fuel droplets and seeding particles inside the same interrogation window having different velocities. Then, the uncertainty calculation is significantly biased towards a larger value. Two-color PIV measurements [27, 28] could be used to separate the air and fuel motion, but is beyond the scope of the current study.

Note that the uncertainty analysis is presented as spatially averaged data. Regions including or near a spray contribute a lot to the uncertainties. Those regions were avoided in the analysis of kinetic energy and integral length scales. Therefore, the PIV data from -310° to -290° aTDCf for early injection condition, and from -90° to -75° aTDCf for late injection condition will be considered as biased regions and will not be discussed quantitatively in the results and discussions section.

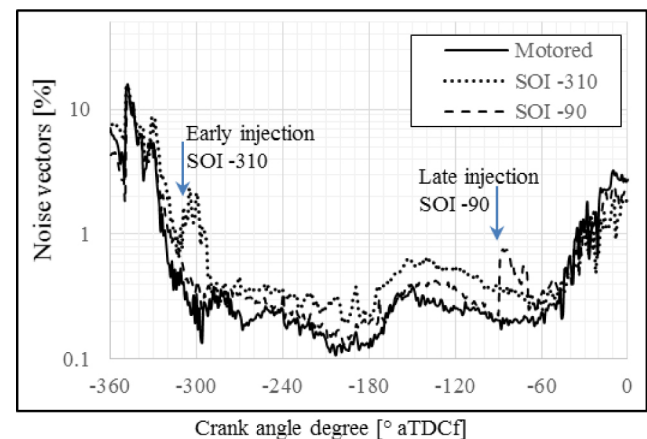


Figure 4. Ensemble mean of noise vector percentages of motored, early injection, and late injection conditions at different crank angles.