

On the Accuracy of Dissipation Scale Measurements in IC Engines

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ABSTRACT

The effects of imaging system resolution and laser sheet thickness on the measurement of the Batchelor scale were investigated in a single-cylinder optical engine. The Batchelor scale was determined by fitting a model spectrum to the dissipation spectrum that was obtained from fuel tracer planar laser-induced fluorescence (PLIF) images of the in-cylinder scalar field. The imaging system resolution was quantified by measuring the step-response function; the scanning knife edge technique was used to measure the 10-90% clip width of the laser sheet. In these experiments, the spatial resolution varied from a native resolution of 32.0 μm to 137.4 μm , and the laser sheet thickness ranged from 108 μm to 707 μm . Thus, the overall resolution of the imaging system was made to vary by approximately a factor of four in the in-plane dimension and a factor of six in the out-of-plane dimension. The Batchelor scale was found to increase linearly with the laser sheet thickness; a beam half-width of less than six times the effective in-plane resolution was required for 10% accuracy. The in-plane spatial resolution of the imaging system does not need to conform to the Nyquist condition, where at least two pixels are required to measure a given turbulence length scale, when using a spectral analysis method to calculate the Batchelor scale. Rather, the turbulence length scales can be estimated with 10% accuracy at an effective resolution equal to 1.4 times the Batchelor scale. The major developments of this work are two methods to correct the measured Batchelor scale for finite resolution effects. Based on these results and guidelines, researchers can estimate the error of existing measurements in the literature and design experiments to faithfully resolve the turbulence in engine flows.

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INTRODUCTION

The turbulence of the in-cylinder flow field plays a significant role in the performance and emissions of an internal combustion (IC) engine. A better understanding of the turbulence is necessary to predict, manipulate, and control the evolution of the local fuel-oxidizer mixture fraction, a critical parameter of interest in the development of advanced modes of combustion. Significant research has been devoted to investigating the turbulence structure, and in particular, the length scales that characterize the rate of molecular mixing. Advanced optical diagnostic techniques such as planar laser-induced fluorescence (PLIF) and Rayleigh scattering have been performed to measure these dissipative length scales in non-reacting co-flowing jets [1,2], diffusion flames [3,4], and more recently, in IC engine flows [5,6]. However, the experimental resolution required to measure a quantity on the order of micrometers imposes significant technical challenges, and necessitates a detailed characterization of the experimental uncertainty due to optical blurring, out-of-plane resolution, and noise. This paper analyzes these issues within the context of IC engine flows for data sets with varying spatial resolution and laser-sheet thickness.

Background

First, it is instructive to briefly discuss the relevant turbulence theory. The conversion of a fluid's kinetic energy to internal energy is termed the viscous dissipation, and the physical length scale at which this process occurs in a flow is characterized by the Kolmogorov scale η given by [7]:

$$\eta = \left(\frac{\nu^3}{\varepsilon} \right)^{\frac{1}{4}} \quad (1)$$

where ν is the kinematic viscosity and ε is the turbulent kinetic energy dissipation rate. From dimensional arguments, this equation may be recast in terms of the turbulence Reynolds number Re_δ to give the traditional Reynolds number power scaling relation:

$$\frac{\eta}{\delta} = Re_\delta^{-\frac{3}{4}} \quad (2)$$

where δ is the integral length scale. Batchelor [8] studied the physics describing a passive scalar in a low Reynolds number flow, such as temperature or inert species concentration, and proposed

that the scalar field behaves similarly to the velocity field. The scalar energy analog to the kinetic energy of the velocity field may be defined $\zeta^2/2$, and the scalar energy conservation equation is:

$$\left(\frac{\partial}{\partial t} + u \cdot \nabla - \Gamma \nabla^2\right) \frac{1}{2} \zeta^2 = -\Gamma \nabla \zeta \cdot \nabla \zeta \quad (3)$$

where u is the velocity vector, t is the time, Γ represents molecular diffusivity (mass or thermal), and the $\Gamma \nabla \zeta \cdot \nabla \zeta$ term is the scalar energy dissipation rate, herein denoted χ . Hence, the length scale at which molecular diffusion causes the scalar energy in a flow to dissipate is analogous to the Kolmogorov scale, and has been called the Batchelor scale λ_B , which is defined in [Equation 4](#).

$$\lambda_B = \left(\frac{\nu \Gamma^2}{\varepsilon}\right)^{\frac{1}{4}} \quad (4)$$

Inspecting [Equation 4](#), it is apparent that by substituting the appropriate Prandtl (Pr) or Schmidt (Sc) number for the molecular diffusivity, the Batchelor scale also exhibits Reynolds number power scaling equal to $-3/4$, as demonstrated in [Equation 5](#).

$$\lambda_B = \left(\frac{\nu^3}{\varepsilon}\right)^{\frac{1}{4}} \cdot Sc^{-\frac{1}{2}} = \delta Re_\delta^{-\frac{3}{4}} Sc^{-\frac{1}{2}} \quad (5)$$

In conclusion, the fluid properties of the flow determine the comparative size of the Batchelor scale to the Kolmogorov scale. For IC engines, the Schmidt number is on the order of unity, and [Equation 5](#) reduces to $\lambda_B \sim \eta$.

Dissipation Length Scale Calculations

Two methods have been used to infer the dissipation length scale from scalar field image data: the spatial and the spectral methods. These two methods will be compared here to highlight their differences.

The spatial analysis technique involves several steps: conditioning the data with a digital filter and/or combining pixels (binning) to reduce noise; calculation of the gradient squared term $(\nabla \zeta)^2$ of the scalar dissipation rate χ , using a numerical stencil to approximate the derivatives; and lastly, direct measurement of the dissipation layer thicknesses, which are generally reported as the full-width of the layers at 20% of the local maximum of $(\nabla \zeta)^2$ and commonly abbreviated λ_D or $\lambda_{20\%}$. The statistical distribution of layer thicknesses has been shown to be self-similar [1] and follow $Re_\delta^{-3/4}$ scaling [2]. Note that the dissipation layer thickness is larger than the true Batchelor scale according to:

$$\lambda_D = C \cdot \lambda_B \quad (6)$$

where C is an empirical constant. The value of the constant has been the subject of much research, with values ranging from 3.7 [9] to 5.4 [2], depending on the geometry of the flow and the number of spatial dimensions imaged.

In the spectral analysis method, the scalar energy spectrum $E(\kappa)$ is calculated from the Fourier transform of the scalar field data, where $\kappa \equiv 2\pi/\ell$ is the wavenumber corresponding to distance ℓ . An interlacing technique, in which alternate rows of data are sampled in computing the energy spectrum, is recommended to reduce the effects of noise [4]. The dissipation spectrum $D(\kappa)$ follows from $E(\kappa)$ according to [Equation 7](#).

$$D(\kappa) = 2\Gamma\kappa^2 E(\kappa) \quad (7)$$

At the high wavenumber range of the dissipation spectrum a cutoff wavenumber may be defined as the scale at which higher wavenumbers are expected to contribute less than 2% to the cumulative dissipation [7]. Wang *et al.* [3] note that this occurs at $\kappa\eta=1$ of Pope's model spectrum [7], and, for flows with $Sc \approx 1$, define a dissipation length scale λ_β :

$$\lambda_\beta = \frac{1}{\kappa_{2\%}} = \frac{\lambda_c}{2\pi} \quad (8)$$

that is analogous to λ_B , where $\kappa_{2\%}$ is the cutoff wavenumber at 2% of the peak of the one-dimensional (1D) dissipation spectrum, and λ_c is the physical length corresponding to $\kappa_{2\%}$. Whereas λ_β is a 1D representation of λ_B , Petersen and Ghandhi [5] proposed fitting Pope's model spectrum to the measured dissipation spectrum to find the true, 3D value of λ_B . The model dissipation spectrum is insensitive to Re_δ at high wavenumbers, making λ_B the only parameter in the curve fit.

The values obtained for the dissipation length scales from the spatial and spectral methods have been compared for non-premixed jet flames, finding that $C = 7.4$ [4,10]. While both methods are equally valid, revealing different aspects of the dissipative structures in a flow, there are advantages to using the spectral method when considering the resolution effects.

Imaging System Resolution

Several metrics have been used in the literature to quantify the spatial resolution of an imaging system. One commonly used metric for quantifying the resolution [1,2] is to simply specify the pixel pitch, given by Δ , which quantifies the size of a pixel in the object plane, with units of length per pixel. Another metric, the image magnification m , is the ratio of the nominal pixel size δ , specified by the manufacturer, to the pixel pitch ($m = \Delta/\delta$). A more accurate measure of resolution is to take an image of a periodic black and white pattern, such as the

USAF-1951 3-bar pattern target. The contrast transfer function (CTF) is determined by calculating the contrast modulation as a function of the bar pattern spatial frequency, s , given by:

$$\text{CTF}(s) = \frac{C_i}{C_o} = \frac{(R_{i,\max} - R_{i,\min}) / (R_{i,\max} + R_{i,\min})}{(R_{o,\max} - R_{o,\min}) / (R_{o,\max} + R_{o,\min})} \quad (9)$$

where $R_{i,\max}$ and $R_{i,\min}$ are the maximum and minimum intensity of the imaged bar pattern, and $R_{o,\max}$ and $R_{o,\min}$ are for the object bar pattern [11]. An ideal image system perfectly reproduces the contrast of an object, and so the CTF equals one. In reality, there are limitations to the ability of an imaging system to discern contrast, largely due to diffraction effects and lens imperfections, which results in decreasing contrast (greater blur) at high spatial frequencies. The best metric for quantifying resolution, according to Clemens [12], is the modulation transfer function (MTF). Like the CTF, the MTF represents the ability of an optical system to accurately image the contrast of an object over a range of spatial frequencies. Clemens [12] recommends obtaining the MTF through the scanning knife edge technique. In this method, the signal intensity of a single camera pixel is recorded as a knife edge is translated across the field of view. A plot of the intensity versus knife edge position is called the step response function (SRF), and can be approximated by an error function. The MTF is calculated from the Fourier transform of the derivative of the SRF, which is called the line spread function (LSF). The equation for the LSF for an error function SRF is a Gaussian curve:

$$\text{LSF}(x) = \frac{1}{\sigma_{\text{LSF}} \sqrt{2\pi}} e^{-\frac{x^2}{2\sigma_{\text{LSF}}^2}} \quad (10)$$

where x is the knife edge position and σ_{LSF} is the width of the Gaussian LSF. If referencing a single value, as opposed to the full functional form of the LSF or MTF, the imaging system resolution should be quantified by σ_{LSF} or the spatial frequency (with units of cycles per length) at a specified value of the MTF, such as 5%. Both the LSF and MTF are Gaussian functions, related by σ_{LSF} so it is straightforward to cast the resolution in terms of either function. Finally, it is important to note that binning or smoothing of the raw image data during the post-processing must also be accounted for to yield an effective resolution [13] that is unavoidably degraded from the native resolution, however it may be quantified.

With these resolution metrics in mind, it is beneficial to consider the resolving power necessary to measure the dissipation length scales.

Resolution Requirements

The Nyquist criterion requires at least two data points for measuring a characteristic length without the problem of aliasing. This criterion is often the starting point for designing or assessing an experiment's resolving power, for both the spatial and spectral analysis methods, and may be expressed:

$$\Delta \leq \frac{\lambda}{2} \quad (11)$$

where λ is the characteristic length of interest. Of course, it is difficult to know what level of resolution is needed before an experiment is performed if there is no reliable way to estimate the dissipation scale beforehand.

There is sufficient data characterizing planar and circular co-flowing jets to predict the dissipation thickness using the $-3/4$ power scaling law, as was done in several studies to evaluate the resolution requirement according to Equation 11 for a particular experiment [1,2,14,15]. Depending on the value of the empirical constant in Equation 6, however, there can be a significant spread in the resolution requirement, leading to false estimates that the Nyquist criterion had been satisfied. Mi and Nathan [16] simulated the effect of finite resolution by low-pass filtering cold-wire data of temperature fluctuation. Their results suggest that spatial resolution should be at or near the true Batchelor scale, that is $\Delta \leq \lambda_B$, for accurate measurements of χ and λ_D . Wang and Clemens [11] estimated the relative error for χ and λ_D due to image system blur by modeling the scalar field with a simple error-function profile, and predicted that $\sigma_{\text{LSF}} \leq \lambda_D/6.1$ in order to limit measurement errors to less than 10% of the true thickness. Several others [4,10,13,17, 18, 19] have analyzed the effects of digital filtering, noting that the image data should be over resolved to counter the smoothing effects of filtering. Thus, it is apparent that a spatial analysis, which inevitably requires some form of conditioning to reduce noise, requires very highly resolved images of the flow.

Because of the factor 2π in the wavenumber, a spectral analysis relaxes the physical length requirement to resolve the Batchelor scale. Wang and co-workers [3, 13] applied the Nyquist criterion to this spectral analysis, yielding a minimum spatial resolution of $\Delta \leq C_e \lambda_c / 2$, where C_e is the effective resolution constant, in order to resolve the dissipation scale λ_β . Compared to the spatial analysis requirement, this resolution is estimated to be up to an order of magnitude less stringent—again depending on the value of the constant. Furthermore, the interlacing technique extends the noise floor to higher wavenumbers without attenuating the peak of the dissipation

spectra, enabling the cutoff wavelength to be identified without fitting the measured spectrum to Pope's model spectrum, rendering any digital filtering steps unnecessary [10,18].

The final consideration when analyzing the resolution of planar imaging measurements is the out-of-plane resolution, which is controlled by the laser sheet. In an analytical study, Wang *et al.* [13] argue that the spatial resolution matters only along the gradient direction, and that the resolution in the orthogonal directions has a minor effect on the direction of interest. Kaiser and Frank [20] experimentally tested this hypothesis for non-reacting jets and jet flames, and verified its validity for laser sheet thicknesses spanning a factor of four. Complementing the model introduced in [11], they extended the simulation to three dimensions to estimate iso-contours of the mean dissipation rate error as a function of the in-plane and out-of-plane resolution. In the case of planar imaging, their 3D model predicts elliptically shaped iso-contours of the dissipation error, due to the greater sensitivity of the measurement to the in-plane resolution as compared to the out-of-plane resolution.

This paper extends the analysis of resolution requirements to the spectral analysis of engine flows. Prior studies focused on canonical flows for which extensive experimental and modeling efforts have characterized the turbulent flow field with high accuracy. On the other hand, engine flows are comparatively less well understood. Additionally, the current work focuses on measurement of the 3D Batchelor scale, λ_B , derived from fitting the model spectrum, in contrast to the literature which focuses on the dissipation layer thickness, λ_D . Experiments were performed to examine the effects of finite resolution spanning from a native resolution of $\sigma_{LSF} = 32.0 \mu\text{m}$ to $137.4 \mu\text{m}$, and average laser sheet thickness covering a 10-90% clip width of $108 \mu\text{m}$ to $707 \mu\text{m}$. The error is estimated and resolution metrics are proposed to help predict the error in this and other experiments found in the literature.

EXPERIMENTAL SETUP

Fuel-tracer PLIF experiments were performed using a 4-stroke, 2-valve, single-cylinder optical engine, shown in Figure 1, featuring a disc-shaped combustion chamber. The engine was designed to acquire planar measurements parallel to the cylinder head deck at top dead center. Accordingly, optical access to the combustion chamber is provided through an ultraviolet-grade fused silica (UVFS) ring window that forms the top 16 mm of the cylinder liner, a 43.2 mm diameter sapphire piston window mounted in a Bowditch piston extension, and a 45° UV-coated aluminum mirror. Table 1 summarizes the dimensions of the engine architecture and the valve timing events, in crank angle (CA) degrees after top dead center (aTDC) of the compression stroke.

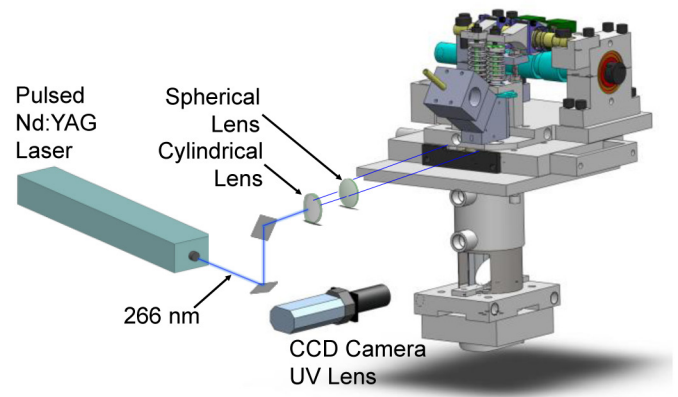


Figure 1. Experimental setup of the PLIF experiments.

Table 1. Engine geometry and valve timing in crank angle degrees after top dead center (aTDC) of the compression stroke.

Displacement	401 cm ³
Bore, B	82.0 mm
Stroke	76.0 mm
Connecting Rod	144.8 mm
Compression Ratio	10.0
TDC Clearance Height	8.4 mm
Intake Valve Diameter	35.0 mm
Exhaust Valve Diameter	28.0 mm
Maximum Valve Lift	7.9 mm
Intake Valve Open	335° aTDC @ 0.4 mm lift
Intake Valve Close	-125° aTDC @ 0.4 mm lift
Intake Valve Peak Lift	-255° aTDC
Exhaust Valve Open	125° aTDC @ 0.4 mm lift
Exhaust Valve Close	-335° aTDC @ 0.4 mm lift
Exhaust Valve Peak Lift	255° aTDC

The in-cylinder flow was doped with 99%-grade fluorobenzene using a low-momentum direct gaseous injection technique described in [6]. In short, the injection pressure equals the cylinder pressure at the end of injection, which occurs well before the time of image acquisition. Hence, the engine flowfield dominates the mixing event at the time of interest. The engine was motored at 600 rpm for a majority of the cases, and the coolant and intake air systems were heated to 50°C. The intake flow was pure nitrogen at atmospheric pressure, measured at the intake surge tank. A MotoTron ECM565-128 series electronic control module and Berkeley Nucleonics Corporation Model 565 digital delay/pulse generator were used to synchronize the engine with the injection, camera shutter and laser timings. Unless otherwise stated, image data were acquired at two operating points: during the compression stroke at CA -90° aTDC to generate a low dissipation rate, long length scale condition; and during the intake stroke at CA -255° aTDC to create a high dissipation, short length scale in-cylinder flow.

The fourth harmonic output ($\lambda_w = 266$ nm) from a dual-head Ekspla NL303/D Nd:YAG laser was formed into a sheet using two different lens arrangements. In the first arrangement, a 100 mm focal length circular plano-convex cylindrical lens and a 500 mm focal length plano-convex spherical lens were positioned so that the beam waist, W_0 , was centered in the combustion chamber. This arrangement, named f500, was selected to provide a long confocal length that coincided with the field of view (FOV) provided by an $m = 0.36$ magnification ratio. The second arrangement, named f300, included two plano-convex cylindrical lenses: a 300 mm focal length lens followed by a 100 mm focal length lens with a separation distance of 4 mm, for an effective focal length of 76 mm. The f300 lens arrangement was translated along the beam propagation direction to four positions (p1, p2, p3, and p4) to significantly vary the sheet thickness within the image FOV. The laser system fires at a fixed repetition rate of 10 Hz, and adopting the procedure developed by Petersen [21], the two 5 mJ/pulse laser beams were combined (for a total energy of 10 mJ) with a separation time of 200 ns to maximize the signal-to-noise ratio (SNR) of the data given the saturation and absorption behavior of fluorobenzene. The laser sheet entered the combustion chamber through the UVFS ring window on a plane parallel to the top of the piston surface. The distance between the laser sheet and the cylinder head deck was approximately 9 mm to avoid interference from the intake valve during image acquisition timings that coincided with maximum valve lift.

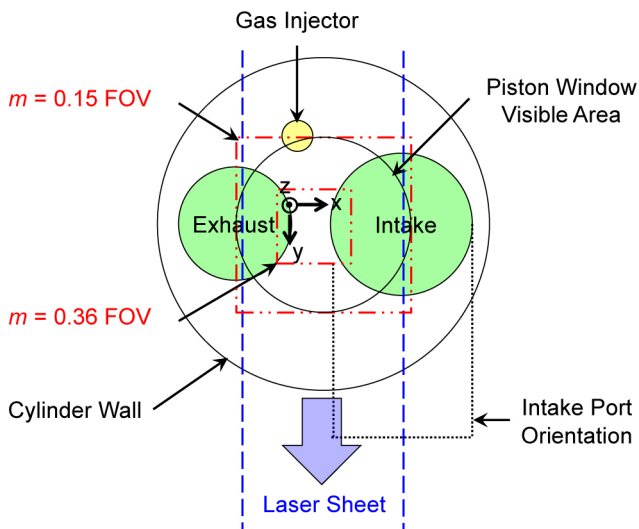


Figure 2. Top view of the combustion chamber showing the image fields of view for the $m = 0.15$ and $m = 0.36$ magnifications.

The laser-induced fluorescence, as viewed through the mirror and piston window, was imaged using a 105 mm f/4.5 UV-Nikkor lens and an Andor DV437 CCD camera, featuring a 512×512 pixel array with $\delta = 13 \mu\text{m}$ pixels. The camera was thermoelectrically cooled to -50°C to minimize dark noise. A WG280 Schott glass filter was attached to the lens to block spuriously scattered laser light and pass the fluorobenzene emission spectrum, which occurs in the 262-305 nm range [22]. The camera was translated along the optical path to

achieve four magnification ratios: $m = 0.09, 0.15, 0.36$, and 0.54 . The optical setup and outlines of the $m = 0.15$ and 0.36 FOVs are shown in Figure 1 and Figure 2, respectively.

As a final point, it is noted that the laser sheet thickness study was performed exclusively using the $m = 0.36$ FOV and the five sheet profiles. The image resolution study was performed using the f300 lens arrangement in the p1 position, denoted f300p1, and the four FOVs.

Laser Sheet Thickness

The sheet thickness, which defines the out-of-plane resolution of the imaging system, was measured for both lens arrangements by scanning a knife edge orthogonal to the plane of the laser sheet at several axial positions within the engine cylinder along the beam propagation direction. The measurements were made in the cylinder with the UVFS ring window installed; access to the combustion chamber was gained by removing the cylinder head. Image data (Andor AP7 camera and 105 mm f/2.8 Micro-Nikkor lens) of the fluorescence of a Schott glass filter from the unclipped portion of the beam were acquired as a surrogate for the beam energy. The function given in Equation 12 was fit to the normalized beam intensity P :

$$P(z) = \frac{1}{2} \left(1 + \operatorname{erf} \left(\frac{z}{\Lambda} \right) \right) \quad (12)$$

where erf is the error function, z is the knife edge clip position, and Λ is the characteristic width. Figure 3 shows an example of the knife edge data at the location 2.3 mm after the focal point (in the beam propagation direction) for the laser sheet profile f300; the fitted value of Λ is reported with its 95% confidence interval.

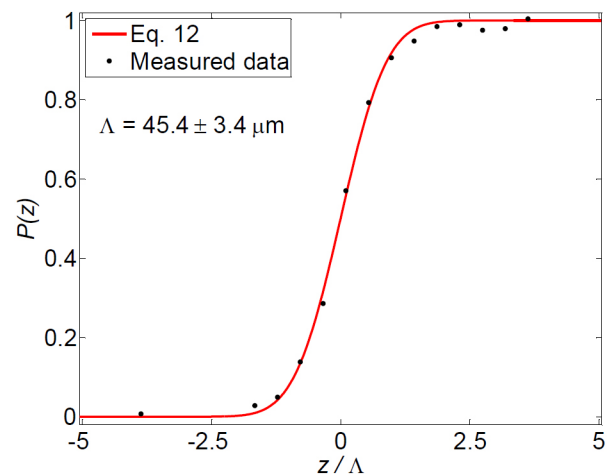


Figure 3. Beam intensity profile for the f300 laser sheet at the location $y = 2.3$ mm after the focal point.

The sheet half-width W is reported as: