

High Resolution Scalar Dissipation Measurements in an IC Engine

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ABSTRACT

The ability to make fully resolved turbulent scalar field measurements has been demonstrated in an internal combustion engine using one-dimensional fluorobenzene fluorescence measurements. Data were acquired during the intake stroke in a motored engine that had been modified such that each intake valve was fed independently, and one of the two intake streams was seeded with the fluorescent tracer. The scalar energy spectra displayed a significant inertial subrange that had a $-5/3$ wavenumber power dependence. The scalar dissipation spectra were found to extend in the high-wavenumber regime, to where the magnitude was more than two decades below the peak value, which indicates that for all practical purposes the measurements faithfully represent all of the scalar dissipation in the flow. The scalar energy and scalar dissipation spectra were found to agree quite well with Pope's model spectrum at all but the highest wavenumbers where the effects of random noise (dominated by shot noise) overwhelms the measurement. The wavenumber where the dissipation reaches 2% of the peak value was used to estimate the Batchelor scale. The measured range of Batchelor scale, encompassing a range of engine speeds from 300 – 1800 rpm and intake pressures from 54 – 109 kPa, was 20 – 42 μm . The measurements required high spatial resolution and high signal-to-noise ratios, and the experimental efforts required to achieve this are discussed in detail. A set of parametric investigations was performed by varying the intake flow conditions. The results follow an expected trend, but the quantitative scaling with Reynolds number was incorrect, suggesting that the definition of the characteristic Reynolds number has to be considered carefully.

INTRODUCTION

Turbulent mixing processes in internal combustion (IC) engines have been studied extensively because of their impact on the combustion process. The complex evolution of the fuel/air mixture controls phenomena including ignition, combustion rate, fuel consumption, and pollutant species formation. Mixing is enabled by the underlying turbulent flow field. The relevant length scales of the in-cylinder turbulent flow field, and the associated combustion processes, range from the large, energy-containing integral length scales ($\sim 1\text{--}6$ mm near top dead center (TDC) [1,2]) to the small, dissipative inner (or Kolmogorov) scales. Small-scale phenomena are especially important because this is the scale where molecular mixing, which is necessary for chemical reactions, takes place; mixing that occurs at longer length scales is more appropriately referred to as stirring. Consequently, the focus of this research is to investigate fine-scale mixing within the combustion chamber of an IC engine.

The majority of earlier studies of the turbulent flow field in IC engines have rationally concentrated on the underlying velocity field to examine turbulence properties. Techniques such as laser Doppler velocimetry (LDV) [1,2], particle image velocimetry (PIV) [3,4], and hot-wire anemometry (HWA) [5] have been used to enhance our understanding of the in-cylinder velocity field, but do not have sufficient resolution to examine the finest scales of turbulence. The scalar field, however, provides an opportunity to make measurements over a much wider range of length scales. Optical techniques such as Rayleigh scattering and laser-induced fluorescence (LIF) are capable of making scalar measurements that can resolve length

scales down to approximately 20 μm in two dimensions. Previous investigators have used these scalar techniques to investigate dissipation-scale phenomena in jet flows [6-14], turbulent non-premixed flames [8,15-19] and gas jet and spray mixing in engines [20,21].

In this study highly resolved, high signal-to-noise ratio one dimensional LIF measurements have been performed to study the mixing between the flow inducted through the two intake valves of a motored engine, where one of the intake streams was seeded with a fluorescent tracer. The spectral behavior of the scalar field and the scalar dissipation field were investigated, and compared to a model turbulent spectrum. The agreement between the measured and model spectra through the inertial subrange and most of the dissipation range allows for an estimate of the inner length scale. The requirements for the optical system are discussed in detail. Parametric studies are presented for a range of intake-based Reynolds number.

BACKGROUND

THEORY

A dynamically passive scalar is a variable that is conserved throughout a flow and does not participate in changing the flow itself. The scalar field is made random by the action of turbulence and acquires statistical behavior corresponding to the velocity distribution. Therefore, many of the concepts initially developed for the velocity field can be extended to the scalar field. A passive scalar's value only changes through convection and diffusion according to the transport equation [22]:

$$\frac{\partial \xi}{\partial t} + \mathbf{u} \cdot \nabla \xi = \Gamma \nabla^2 \xi \quad (1)$$

where ξ is the passive scalar variable, $\mathbf{u}$ is the velocity vector, and Γ is the appropriate molecular diffusivity. Examples of passive scalars include mixture fraction, inert tracer concentration, and in certain cases temperature. A scalar energy can be defined as $\xi^2/2$ analogous to the definition of kinetic energy in the velocity field. The transport equation that governs scalar energy dynamics is given in Eq. (2).

$$\left[\frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla - \Gamma \nabla^2 \right] \xi^2(\mathbf{x}, t) = -2\Gamma \nabla \xi \cdot \nabla \xi(\mathbf{x}, t) \quad (2)$$

The term on the right-hand side of Eq. (2) acts to decrease scalar gradients and is referred to as the scalar dissipation rate χ , as in Eq. (3).

$$\chi = -2\Gamma \nabla \xi \cdot \nabla \xi(\mathbf{x}, t) \quad (3)$$

Batchelor applied the ideas of an energy cascade and the hypotheses of Kolmogorov's universal equilibrium theory to investigate the spectral behavior of the turbulent scalar energy field, arguing that the basic assumptions employed by Kolmogorov are valid for the scalar energy distribution as well [22]. As a consequence of Kolmogorov's theory, the statistical behavior of the scalar field is assumed to be isotropic, homogeneous, and universally similar at the smallest scales provided the Reynolds number is sufficiently large. As in the kinetic energy cascade, the energy in the scalar field is introduced by the larger (low wavenumber) length scales and transferred downward to ever-smaller (higher wavenumber) scales until molecular interactions dissipate the scalar energy. Scalar dissipation is the rate at which scalar energy is transferred from larger to smaller scales and then dissipated in the energy cascade model. Scalar dissipation is important at the smallest length scales and is often considered as a molecular mixing rate since it acts to make the scalar field more homogeneous by decreasing scalar gradients.

The Batchelor length scale, λ_B , is often considered the smallest scale that a scalar gradient can be sustained over [23] and, therefore, scalar dissipation is important at scales comparable to λ_B with

$$\lambda_B = \eta \text{Sc}^{-1/2} = \Lambda_B \delta \text{Re}^{-3/4} \text{Sc}^{-1/2} \quad (4)$$

where η is the Kolmogorov length scale, Re is the characteristic Reynolds number, Sc is the Schmidt number $\text{Sc} \equiv \nu/\Gamma$ with kinematic viscosity ν , δ is the integral length scale, and Λ_B is a constant. An additional length scale that represents the scale of dissipation structures incorporates a second proportionality constant, $\Lambda = C\Lambda_B$, and is defined as the strain-limited diffusion scale, λ_D , in Eq. (5).

$$\lambda_D = \Lambda \eta \text{Sc}^{-1/2} = \Lambda \delta \text{Re}^{-3/4} \text{Sc}^{-1/2} \quad (5)$$

Turbulent kinetic energy and dissipation spectra can be used to identify the important length scales involved in the velocity field, and the parallel has been found to extend to the scalar field [24]. For flows with high Reynolds numbers there exists a range of length scales, the inertial subrange, that has universal statistics solely dependent on the turbulent kinetic energy dissipation, ε . This gives rise to the classic form of the kinetic energy spectrum, $E(\kappa)$, for the inertial subrange via dimensional arguments

$$E(\kappa) = C_\nu \varepsilon^{2/3} \kappa^{-5/3} \quad (6)$$

where C_ν is a constant, and κ is the wavenumber associated with the length scale $2\pi/\kappa$. The scalar energy spectrum, $F(\kappa)$, has a similar subrange that has the form [22,24]

$$F(\kappa) = C_\varepsilon \chi \varepsilon^{-1/3} \kappa^{-5/3} \quad (7)$$

where C_ε is a constant and χ is the turbulent scalar dissipation rate. It should be noted that both spectra have the same wavenumber dependence. The spectra of turbulent kinetic energy dissipation, $D(\kappa)$, and scalar dissipation in a normalized form, $D^*(\kappa_B^*)$, are given by [24,25]

$$D(\kappa) = 2\Gamma \kappa^2 E(\kappa) \quad (8)$$

$$D^*(\kappa_B^*) = 2(\kappa_B^*)^2 F^*(\kappa_B^*) \quad (9)$$

where κ_B^* is the wavenumber normalized by the Batchelor wavenumber, κ_B ($\kappa_B = 1/\lambda_B$).

The upper wavenumber range of the dissipation spectra has been used to estimate the Batchelor scale. For flows with unity Schmidt number the Batchelor and Kolmogorov length scales coincide (see Eq. 5). The identification of these length scales is more rigorous when it can be shown that the spectra are in agreement with established turbulent spectra, and are not corrupted by measurement noise.

Pope [25] developed a model spectrum for the velocity field that covers the full range of important length scales. This spectrum has been shown [25] to approximate velocity data from a variety of flows very well. Subsequent investigators [24] have assumed that the dissipation-normalized form of Pope's kinetic energy spectrum has the same form as the turbulent scalar energy spectrum for flows with $Sc \sim 1$, as was suggested above. Pope's normalized scalar energy spectrum [24], F^* , is given by:

$$F^*(\kappa_B^*) = C_P (\kappa_B^*)^{-5/3} f_\delta \left(\kappa_B^* \frac{\delta}{\lambda_B} \right) f_\eta (\kappa_B^*) \quad (10)$$

where C_P is suggested by Pope to be 1.5 [25], and f_δ and f_η are non-dimensional functions provided in [25] with a discussion on appropriate constant values. The associated dissipation spectrum is found using Eq. (9). Investigating the model dissipation spectra one finds that at $\kappa_B^* = 1$ the dissipation has a value that is 2% of its peak value, and that there is negligible dissipation at higher wavenumbers.

PREVIOUS MEASUREMENTS

Early gas-phase ($Sc \sim 1$) scalar dissipation studies focused on the topology of the scalar dissipation field in gaseous jets. Using multi-dimensional measurements [6-13] it was found that high levels of scalar dissipation were confined to thin, convoluted, laminar-like sheets with high levels of intermittency. This canonical sheet, or

layer, structure was attributed to, and later confirmed [6-8,12,13] to, arise from a local strain field that is compressive in one direction and extensional in the remaining dimensions.

The full width of the dissipation structures (based on the points defined by 20% of the local maximum), λ_{20} , was measured [6,7,9] and assumed to correspond to the strain-limited mass diffusion length scale, λ_D . Using these measurements the constant Λ in Eq. (5) was found to be distributed over the range 5 – 40 [6,7,9-11,13,23], i.e., λ_D was measured to be 5-40 times the Batchelor scale. The most commonly quoted mean values of Λ are 11.2 from imaging in a round jet [7] and 14.9 from measurements in a slot jet [9].

The probability density function (PDF) of the scalar dissipation rate has been found to follow a nearly log-normal form, and is self-similar when scaled by the mean dissipation rate [6,7]. Deviations from log-normality in the PDF, in the form of a slight negative skewness, have been observed.

There have been limited high-resolution measurements of the scalar field in IC engines. Probst and Ghandhi [26] demonstrated that the scalar field produced from the direct injection of gasoline in an engine displayed the same structure as observed in the jet flow studies. The scalar dissipation field exhibited the sheet-like structure and the dissipation PDFs were shown to have a nearly log-normal distribution. For late injection timings the PDFs agreed quite well with those from jet flow studies, but for early injection cases where the field was approaching a well-mixed state the PDFs acquired a different structure, which had a more pronounced negative skewness. The cause for this difference was shown to be the effect of shot noise in the measurements. The study of Wiles *et al.* [27] extended these measurements and applied the mixedness criteria introduced by Probst and Ghandhi to show that the underlying flowfield was an important part of spray mixing in engines for the relatively modest pressures typical of gasoline direct injection systems.

Recent advances to scalar dissipation measurements have been made in the study of turbulent non-premixed combustion. The complexity of the problem has led investigators to use the scalar energy and scalar dissipation spectra [16-18,24] to analyze the inner length scales and the effects of noise on the measurements. Wang and co-workers have demonstrated measurements that closely matched the model dissipation spectrum of Pope [25] past the high-wavenumber 2% criteria discussed above. Further, they have shown that the presence of random noise (predominately due to shot noise) is confined to high wavenumbers, and can be identified in the dissipation spectra by a positively sloped, κ^2 behavior in the spectrum, which arises from the relations in Eq. (8). These observations allow minimally biased, independent estimates of the Batchelor length scale.

flows. Wang *et al.* [17] define the wavenumber where the dissipation reaches 2% of its peak as the dissipation cutoff wavenumber, κ_β , which corresponds to a Batchelor scale estimate given by $\lambda_\beta = 1/\kappa_\beta$. This estimate is inferred from Pope's model spectrum and the physical length scale corresponding to the cutoff wavenumber, κ_β , is given by $\lambda_c = 2\pi/\kappa_\beta$. Using this criterion it has been shown that the inner scale in reacting jet flames, determined by several measurements (temperature determined from Rayleigh scattering measurements, the inverse of the Rayleigh scattering signal, and mixture fraction determined by a series of coupled 1-D measurements) is comparable to estimates made using jet theory when the appropriate properties are used to define the Reynolds number.

These initial studies, and many others, have provided a better understanding of the structures and statistics of scalar dissipation flow fields. The quantitative accuracy of dissipation measurements is critically controlled by the effects of spatial resolution, random noise, and the data processing algorithms, which are discussed in the following three sections.

Resolution

Inadequate resolution of the scalar field has been found to reduce measured scalar gradients and, thus, the scalar dissipation [18,28,29]. Spatial resolution is defined as the ratio of the inner length scale to the maximum measurement dimension. A major issue is the determination of the appropriate inner length scale; in complicated flows such as in an engine *a priori* estimation is difficult.

A criteria for adequate resolution is imposed by the need to adequately resolve the scalar gradient. Using an isolated, noise-free strained analytical scalar field profile, Dahm and Southerland [30] and Ghandhi [29] have shown that undersampling of the scalar field results in an underestimation of the dissipation rate. It has been shown that a resolution of $\sim 6\times$ better than λ_D is required to achieve 90% of the dissipation magnitude [29]. Ghandhi also showed that inadequate resolution, in the absence of noise, caused an increase in the measured dissipation layer thickness.

Mi and Nathan [23] presented cold-wire, jet temperature data that were resolved to λ_B with $\Lambda_B = 2.4$ and showed that resolution levels below this attenuated the scalar dissipation values, but had a much less significant effect on the second moment of the scalar distribution. In comparison with the measured values of Λ above, this suggests that in terms of λ_D the resolution criteria is near the sampling-limit of 6 proposed by Ghandhi.

Wang *et al.* [24], using the spectral analysis, tested the effect of resolution on jet flame measurements by filtering their data with increasing box filter widths to simulate degraded resolution. They determined that a resolution of approximately $\lambda_\beta \equiv 1/\kappa_\beta$ was necessary to

resolve the dissipation statistics. Since λ_β has been shown to be similar to λ_B with $\Lambda_B = 2.3$ [17], this resolution criteria is consistent with that given above. The spectral method of estimating the Batchelor scale and the resolution criteria, λ_β , is especially useful because it can be applied *a posteriori*.

Wang and Clemens [31] pointed out the importance of properly characterizing the resolution of the imaging system with the line spread function (LSF), a measure of the blur introduced by the optical system. They used an analytical scalar profile and an assumed Gaussian LSF with a standard deviation of σ and determined that the true dissipation structure thickness, λ_{20} , must be greater than 7.5σ in order for the peak scalar dissipation errors to remain under 10%. It was also noted that low $f/\#$ optics, which are traditionally used in high resolution applications to increase signal levels, produce more optical blur due to their relatively large thickness [31]. Optical blur must, therefore, be considered carefully in all high-resolution LIF experiments to properly characterize an imaging system's effective resolution.

In summary, previous jet studies have provided a consistent criterion for resolving scalar dissipation statistics. Authors [23,24] have shown that scalar dissipation measurements must resolve lengths approaching the Batchelor scale, λ_B , to reduce errors associated with undersampling. This is consistent with the $\lambda_D/6$ resolution criterion proposed by Ghandhi [29] since the ratio of Λ/Λ_B has been shown to be roughly 6 in jet flow measurements. The resolution criterion, λ_B , can be estimated as $\lambda_\beta \equiv 1/\kappa_\beta$ from the cutoff wavenumber, κ_β , at the 2% point in measured dissipation spectra according to Pope's model [25]. This method of spectrally estimating λ_B is useful in the design of high resolution scalar measurements.

Noise

The calculation of scalar dissipation from measured data allows noise to artificially increase the scalar dissipation magnitude. Hence, the effect of noise is opposite to the dissipation suppression associated with inadequate resolution. This resolution-noise competition makes assessing the accuracy of scalar dissipation measurements very difficult [15]. The measured dissipation, χ_m , can be represented as the sum of the true dissipation, χ , and an apparent dissipation, χ_a , that is artificially generated by noise. Equation (11) shows how noise in adjacent points contributes to the measured scalar dissipation [15]:

$$\chi_m = \chi + \chi_a = 2\Gamma \left[\left\langle \left(\frac{\partial \xi}{\partial x} \right)^2 \right\rangle + \frac{\langle \delta \xi_1^2 + \delta \xi_2^2 \rangle}{(\Delta x)^2} \right] \quad (11)$$

where $\delta \xi_i$ is the noise at location i , and Δx is the distance between the two adjacent points and represents the measurement system's resolution. Equation (11) shows



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that not only does the noise affect the apparent scalar dissipation, but it is also resolution dependent. As the resolution is increased (Δx reduced) the apparent scalar dissipation grows without bound. This motivates an over-sampling resolution criterion, akin to the under-sampling effect of insufficient resolution, in order to decrease the sensitivity to noise.

Investigators [24,29] have analyzed the effects of noise on measured scalar and dissipation values. Ghandhi [29] considered the effects of photonic shot noise on an analytical scalar profile using a Monte Carlo approach and found that while the peak scalar dissipation artificially increased in the presence of noise, the layer thickness, λ_{20} , decreased. It was also shown that the global scalar signal-to-noise ratio was an inappropriate measure of the signal quality in scalar dissipation measurements because the shot noise scales with the local signal value, thus a local signal-to-noise estimate is required. A local spread in scalar values, $\Delta\xi$, represents the magnitude of the scalar dissipation values. The spread-noise factor in Eq. (12) was introduced to define the relative contribution of noise to scalar dissipation measurements

$$\kappa_{noise} = \frac{\Delta\xi}{\delta\xi} \quad (12)$$

where $\delta\xi$ represents the noise level. At a spread-noise factor of approximately 10, the Nyquist resolution (*i.e.*, $\lambda_D/\Delta x = 2$) was found to be a good compromise between noise and resolution effects.

Wang *et al.* [24] investigated the effects of the noise—resolution competition on scalar and scalar dissipation spectra by adding a white noise floor to the normalized scalar energy spectrum. The scalar dissipation spectrum was again found to be much more sensitive to noise effects than the corresponding scalar energy spectrum. The addition of noise was found to drastically overshoot the true dissipation at high resolutions and be insignificant at low resolution levels. Wang *et al.* [17] also made scalar dissipation measurements in non-premixed jet flames using three different simultaneous techniques that had differing signal-to-noise ratios (SNR). The dissipation spectra developed from the inverse Rayleigh signal, which had the smallest noise contribution of the three measurements, followed Pope's model spectrum furthest into the high wavenumber range and past the 2% power level in the scalar dissipation spectrum. The other measurements deviated from the model spectrum at lower wavenumbers due to their inferior SNR levels.

Data Processing

Data reduction and post-processing of scalar field data are important topics that affect the resolution and overall noise content of measurements. The main data reduction process in scalar dissipation measurements

involves the determination of the spatial derivative of the scalar field. Due to the discontinuous nature of measured data sets the derivative must be determined using numerical techniques. Wang *et al.* [24] tested several types of numerical derivative stencils and found that high-order spectral-like numerical methods, like those suggested by Lele [32], performed superior to lower-order techniques such as the central difference method. The constants determined by Wang *et al.* [19] produce a stencil that has a resolving efficiency of 90% (*i.e.* 90% of the length scales are resolved to within 1%).

Kaiser and Frank [19] used an interlacing technique to effectively reduce the effects of noise in thermal dissipation spectra calculated from two-dimensional Rayleigh scattering images. They calculated the power spectrum (PSD) by multiplying the Fourier transform of a single row of data by the complex conjugate of the Fourier transform of an adjacent row as shown in Eq. (13):

$$PSD = \Im(I_i(x))\Im^*(I_{i+1}(x)) \quad (13)$$

where $\Im$ represents the Fourier transform, $\Im_i^*$ represents the complex conjugate of the Fourier transform, and $I_i(x)$ is the signal profile in row i . This technique takes advantage of the fact that noise in neighboring pixels is largely uncorrelated, and cancels when averaged over many data sets. They emphasized the necessity of the relevant length scales being over-resolved, and the technique only works when calculating ensemble-average spectra; it is not an effective shot-to-shot noise reduction technique [19].

The processes mentioned here and any additional data processing schemes must be included in the examination of the effective resolution of the measurements. Wang *et al.* [24] provides a good review of how each process in the measurement of scalar dissipation contributes to the experimental system and effective resolution.

FLUORESCENCE MEASUREMENTS

Tracer-based LIF is a common technique that has been used in a wide range of applications including flow measurements in IC engines [20,21,33,34]. A general LIF experimental setup includes a laser beam focused within a flow field that contains tracer molecules with well-characterized fluorescence properties. A CCD or CMOS camera captures the fluorescence normal to the excitation beam propagation direction. The resolution of an LIF measurement is defined by the thickness of the excitation beam and the effective resolution of the imaging system. For high-resolution measurements this calls for a tightly focused laser beam and relatively high levels of image magnification. The high energy densities created by tightly focused laser beams can induce saturation of the fluorescence process [33,35]. Saturation of the fluorescence process is unfavorable

because the overall signal level is reduced (compared to a linear process), which reduces the shot-noise-controlled signal-to-noise ratio. Further, the temporal and spatial extents of a beam profile are also difficult to saturate causing a variation in fluorescence behavior throughout the beam profile. For these reasons, saturation and the laser fluence limits of saturation, Γ_{sat} [mJ/mm²], must be considered when using fluorescence for scalar dissipation measurements.

The simple two-level model of single-photon LIF provides a conceptual model of the important fluorescence processes including saturation. Although the two-level model introduces the important concept of saturation, further analysis of the photophysics of some molecules suggests the saturation fluence predicted by the model is overestimated [36]. Processes such as intersystem crossing cause the rate of repopulation of the ground energy state to be drastically reduced, resulting in the saturation threshold to be significantly reduced [36,37]. The complex nature of the photophysical processes that affect fluorescence make it difficult to accurately estimate the saturation threshold intensity from simple two-level models.

EXPERIMENTAL APPARATUS

The main issues (resolution, noise, data processing) mentioned in the previous section combine to determine the overall quality of scalar dissipation measurements. Each of these issues was considered in the experimental design for the current study. A brief description of the engine and optical systems is provided here, followed by a discussion on how each of the experimental issues was characterized for the experimental arrangement.

ENGINE

The one-dimensional fluorescence experiments were performed in a motored optical engine used previously for in-cylinder mixing studies [38,39]. The main geometric specifications and valve timings are given in Table 1 and a cross section of the piston-combustion chamber portion of the engine is provided in Fig. 1. Optical access to the pent-roof combustion chamber was achieved through a sapphire window ($d = 58.3$ mm) in the top surface of the Bowditch-type piston. The combustion chamber was imaged via a 45 degree plane mirror (UV anti-reflection coating) at the bottom of the extended piston. Additional optical ports include two coaxial UV-grade fused silica (UVFS) windows ($d = 3.0$ mm) contained within the engine head and an UVFS ring window which comprises the top 20 mm of the engine cylinder; the ring window was replaced by a steel ring for the current study.

Table 1. Main geometric specifications and valve timings of port-fueled optical engine.

Compression Ratio	11.0	Clearance Volume	55.23 cm ³
Bore	86 mm	Connecting Rod Length	152.5 mm
Stroke	94.6 mm	Intake Valve Diam.	35.1 mm
Displacement	550 cm ³	Exhaust Valve Diam.	30.0 mm
Exhaust Valve Open	131° aTDC	Intake Valve Open	360° aTDC
Exhaust Valve Close	375° aTDC	Intake Valve Close	540° aTDC

The intake manifold of the engine was divided into two flow streams such that each of the two intake valves was fed independently. Each intake valve is connected to its own intake runner and surge tank. Fuel was injected upstream of one of the surge tanks and a valved flow path could be configured to feed each intake stream with either similar or different air/fuel mixtures. The intake system uses six heating tapes to allow the temperature of the intake charge to be controlled. The exhaust system consisted of a single stainless-steel runner connected to a mixing diffuser and surge tank, with the exhaust flow exiting through the building exhaust system.

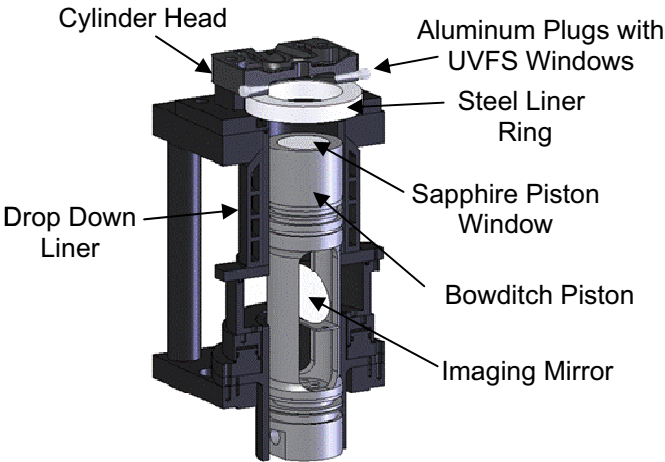


Figure 1. Model of Bowditch piston and pent-roof combustion chamber of the optical engine.

A mixture of spectroscopic-grade iso-octane and fluorescence tracer was delivered to the engine using a Mercury Marine Optimax air-assisted fuel injector. The air-assisted injection provides a well atomized spray to aid vaporization, and the fuel was injected against the intake flow ~1 m upstream of the intake valve to ensure complete mixing of the injected fuel.