

Simultaneous Planar Fluorescence, Phosphorescence, and Mie Scattering in Pressure-Atomized Sprays

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Abstract

While Mie scattering is sensitive only to the liquid phase within a spray, fuel fluorescence is typically sensitive to both the liquid and vapor phases. Hence, comparison of Mie scattering and fluorescence signals could theoretically be used to qualitatively distinguish the liquid and vapor phases within a spray. Unfortunately, subtraction of these two signals is subject to quantitative errors in polydisperse sprays because scattering is sensitive to droplet surface area (D^2) while fluorescence is sensitive to droplet volume (D^3). An improvement to this approach may potentially be achieved by employing phosphorescence for subtraction rather than Mie scattering since phosphorescence is proportional to droplet volume (D^3) and can, therefore, more accurately track the liquid volume distribution under polydisperse conditions. This approach relies on the fact that fluorescence will track both the liquid and vapor phases, whereas phosphorescence will yield signals only from the liquid phase because its signals from the vapor phase are quenched by the presence of oxygen. Previous efforts have explored the use of fluorescence and phosphorescence of acetone for vapor imaging. In the current work, we implement simultaneous fluorescence, phosphorescence, and Mie scattering and compare the relative merits of using a combination of techniques for vapor imaging in pressure-atomized sprays. Tests are performed using both acetone and a multi-component fuel, and it is shown that image subtraction of phosphorescence from fluorescence can be achieved in polydisperse sprays on a droplet by droplet basis. Hence, the simultaneous detection of these three techniques can yield new information regarding atomization and vaporization, although regions prone to multiple scattering present a significant challenge in signal interpretation. Data from cold and heated sprays are analyzed, and methods to improve and advance the approach are suggested.

Introduction

The study of fuel preparation often begins with characterization of the liquid phase via planar visualization [1,2] or phase-Doppler particle sizing [3]. Because of the strong scattering field typical of most engineering sprays, it is very difficult to extract information regarding the vapor phase distribution. The current work explores the possibility that multiple techniques with differing sensitivities to the liquid and vapor regions within a spray may allow visualization of the vapor phase. For example, planar laser-induced fluorescence is known to be sensitive to both the liquid and vapor phases of a spray, while Mie scattering is only sensitive to the liquid phase. Hence, it may be possible to extract information about the vapor phase from a comparison of these two techniques. Unfortunately, when there is a dense field of droplets, multiple scattering can lead to a diffuse background that gives the false appearance of the presence of vapor [4]. In addition, fluorescence is proportional to the droplet volume (D^3), up to a certain size limit, while Mie scattering is sensitive to surface area (D^2). Hence, in polydisperse sprays, the liquid phase signal from fluorescence and Mie scattering should be qualitatively inconsistent. As an alternative and under the proper conditions, phosphorescence can be used as a replacement for Mie scattering as a means of detecting the liquid phase because its vapor-phase signal can be quenched when mixed with oxygen [5-7]. Theoretically, fluorescence should reveal the liquid and vapor phases because its signal is fairly independent of the mixing environment, while phosphorescence can be used to detect the liquid phase. Since both are proportional to droplet volume (D^3), it may be possible to compare signals from these two techniques to cancel the liquid-phase signals and allow vapor-phase measurements. However, signals from unquenched vapor-phase phosphorescence can lead to uncertainties in this

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approach, and Mie scattering may then be necessary as a means of verifying that the phosphorescence signal is properly isolated only to the liquid phase. The goal of the current work, therefore, is to study the potential for simultaneous phosphorescence, fluorescence, and Mie scattering to yield additional information about fuel vapor in pressure atomized sprays based on the different photophysics for each technique. While a number of studies have utilized single-component tracers for studies of fluorescence and phosphorescence [5,6,8], the current work will consider both single- and multi-component fuels.

Materials and Methods

Figure 1 illustrates the experimental system used to simultaneously record fluorescence, phosphorescence, and Mie scattering (FPMS) for studies of vapor formation in pressure atomized sprays. Ultraviolet laser light is generated using the frequency quadrupled 266-nm output of a 10 Hz, Nd:YAG laser. This wavelength is ideal for strong excitation of acetone and Jet-A fuel, as shown in the absorption spectrum of Fig. 2. The 266-nm beam is formed into a thin laser sheet with a constant 1-mm thickness using a cylindrical telescope and a concave cylindrical lens. The laser sheet is passed through the spray of interest, leading to fluorescence/phosphorescence signals in the visible and Mie scattering in the ultraviolet. The Mie scattering signal is collected using an unintensified 2048x512 CCD camera (Andor) equipped with an internal mechanical shutter to ensure that only one pulse is captured from the 10-Hz pulse train. A dual-frame interline-transfer CCD camera (PCO-4000) equipped with an external mechanical shutter is used to collect the fluorescence (first frame) and phosphorescence (second frame) signals, which are separated in time due to inherent differences in the excited-state lifetimes. The interline-transfer CCD camera timing is designed to accept the fluorescence signal at the end of the first frame and allow the phosphorescence to be collected in its entirety in the second frame. Employing the same (dual-frame) camera to collect fluorescence and phosphorescence signals eliminates potential sources of error when using two separate cameras, including differences in alignment, magnification, lens aberration, sensitivity, and flatfield response. In addition to separating the fluorescence/phosphorescence signals using camera timing, the signal from Mie scattering is separated using a mirror coated on the front surface to reflect 266 nm and anti-reflection coated for 266 nm on the back surface. This beam splitter is shown schematically in Fig. 1. Strong scattering at the UV laser excitation wavelength is removed from the fluorescence/phosphorescence camera using a glass camera lens.

Tests are performed using a single- (acetone) and a multi-component (Jet-A) fuel. Measurements are performed in two different spray geometries, including a 0.95 to 3.8 liter-per-minute (LPM) pressure-atomized spray injected into a quiescent medium as well as a pressure-atomized spray injected into a heated environment with an air crossflow at 444 K and 556 K. In the case of the quiescent environment, the spray geometry is a solid conical core, whereas the spray injected into the heated cross-flow is of a hollow cone design.

Results and Discussion

As noted earlier, differences in the fluorescence and phosphorescence lifetimes allow separation of their signals using a single, dual-frame interline transfer CCD camera. The overall time decay of the recorded intensity is shown in Figure 3. Assuming that the functional dependence of the fluorescence and phosphorescence signals are single-exponentials in time, then the two signals can be deconvoluted into short and long lifetime components. As shown in Fig. 3, the fluorescence signal occurs primarily in the first 100 ns after laser excitation and has a significantly higher intensity than phosphorescence. Beyond 100 ns, the fluorescence signal becomes negligible while the phosphorescence extends to as long as 1 microsecond after excitation. The timing is such that the fluorescence occurs at the end of the first frame within the dual-frame camera, and the phosphorescence occurs at the beginning of the second frame. The ~200 ns interframe spacing ensures that no fluorescence signal occurs in the second frame while still allowing sufficient phosphorescence signals. As noted earlier, Mie scattering is collected on a second camera and is sufficiently strong so as to overwhelm the contribution from fluorescence and phosphorescence.

An example of successful measurements of simultaneous fluorescence, phosphorescence, and Mie scattering is presented in Fig. 4 for a pressure-atomized full-cone spray running jet-A fuel at 3.8 lpm. The fluorescence and phosphorescence images are clearly very similar, while the Mie scattering appears with more distinct droplets. If one were to compare the fluorescence and Mie scattering images, it would appear as though a significant amount of vapor is present in the spray, represented by broad regions of signal. However, at a temperature of 300 K the distillation curve for jet-A [9] indicates that negligible fuel vapor would be present. Also, the phosphorescence image, which is sensitive only to the liquid phase in the presence of oxygen, is nearly identical to the fluorescence image. These data show that the measurement of fuel vapor from differences in fluorescence and Mie scattering data can be misleading due to variations in how the signals from each technique propagate through the dense region of the spray. By utilizing phosphorescence in addition to these two techniques, it is possible to infer that regions, which appear to

consist of fuel vapor, may be attributable instead to diffuse or multiple scattering from the field of droplets within the spray. This gives the phosphorescent spray image the appearance of vapor regions which are, in fact, artifacts of signal rescattering, not from the excitation source, but from fluorescence or phosphorescence.

Similar results are obtained with the acetone spray shown in Fig. 5, where the fluorescence and phosphorescence signals are closely matched. Hence, it should be possible to perform image subtraction and eliminate the liquid phase. Because of jitter in the relative timing of the laser and dual-frame interline transfer CCD camera, the ratio of fluorescence to phosphorescence signals varies from shot to shot. However, phosphorescence should scale with fluorescence as a function of liquid volume fraction and droplet size, and it should be possible to use a single scaling factor for the phosphorescence signal prior to image subtraction. This scaling factor can be determined on a case by case basis so as to minimize the residual signal from droplets. The results of such a procedure using no scaling (factor of unity), scaling using the ratio of the average signal intensities (factor of 1.538), and scaling for the minimum peak intensities (factor of 3) are shown in Fig. 5. By adjusting the scaling factor to minimize peak intensities, it is possible to nearly eliminate the signal from the liquid phase, with only slight residuals remaining.

Evidence of the difficulties associated with multiple scattering is shown in Fig. 6, where a jet-A spray in a 46 m/s heated crossflow is probed with a laser sheet through the spray centerline as well as 25 mm away from the centerline in the transverse direction (into the page). The crossflow temperature (flowing right to left) is 444 K, which is near the lower limit of the jet-A distillation curve [9]. Hence, significant vaporization is not expected. As shown at the spray centerline in Fig. 6(a), the spray is a hollow cone, and the crossflow pulls the droplets downstream. At 25 mm from the jet centerline, shown in Fig. 6(b), the main part of the spray is lifted off the nozzle and the near-nozzle spray pattern should not be visible. However, it is still possible to see the outline of the spray exiting the nozzle in the lower part of the image even though the laser sheet is not passing through this region. Hence, it appears that there is some signal originating near the spray centerline at a location 25mm away from the centerline, indicating definitively that rescattering of the fluorescence and phosphorescence signals can play a significant role in data collection and interpretation. With simultaneous detection of both signals, it may be possible to eliminate the effects of rescattering, although the vapor signals are sufficiently low in this case that this becomes infeasible.

Based on these data, it is possible to conclude that simultaneous fluorescence, phosphorescence, and Mie scattering can eliminate ambiguities between droplet rescattering and fuel vapor. With improved camera sensitivity and dynamic range, it may also be possible to utilize fluorescence and phosphorescence image subtraction to remove the droplet signal as well as signal rescattering. Another approach is to utilize this technique along with dense spray measurement techniques such as that proposed in Ref. 4. Nonetheless, the use of phosphorescence instead of or in addition to Mie scattering is clearly helpful in ensuring that vapor concentrations are not overpredicted in fluorescence signals.

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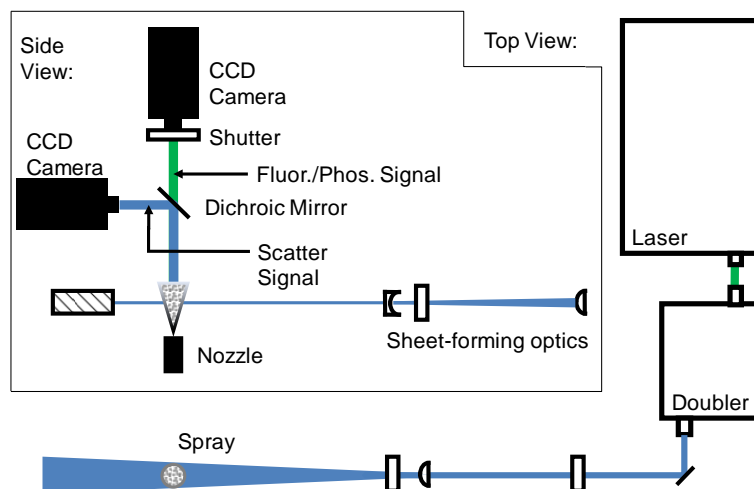


Figure 1. Experimental diagram for simultaneous detection of fluorescence, phosphorescence, and Mie scattering in single- and multi-component fuels.

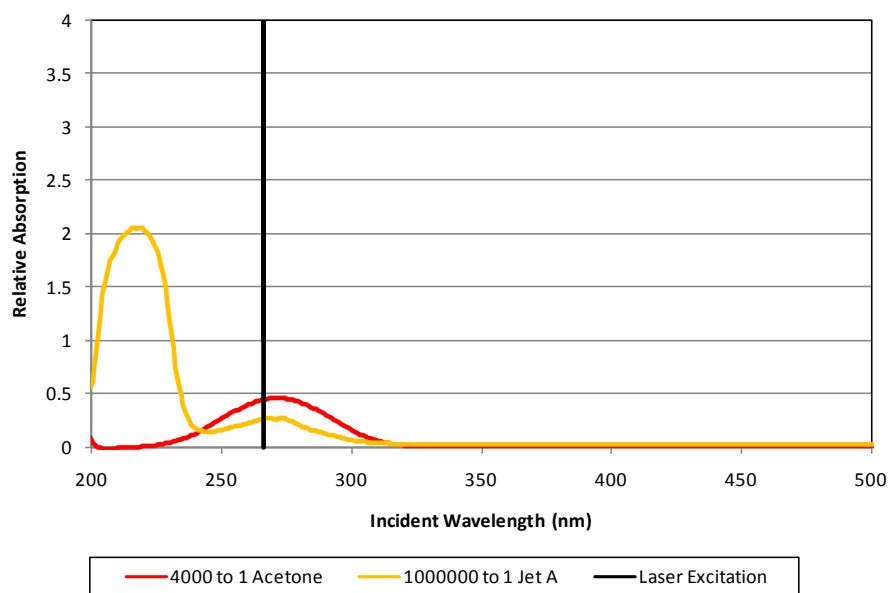


Figure 2. Ultraviolet absorption profile of acetone and Jet-A fuel.

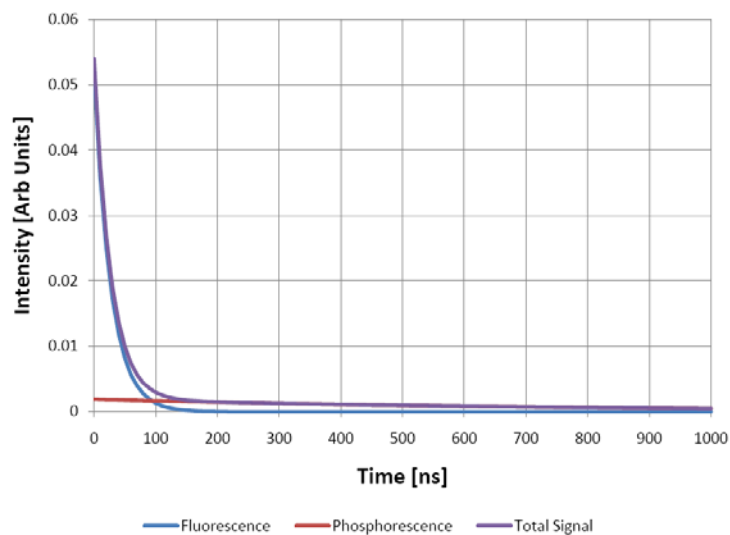


Figure 3. Lifetimes of fluorescence and phosphorescence from fuel vapor with excitation at 266 nm.

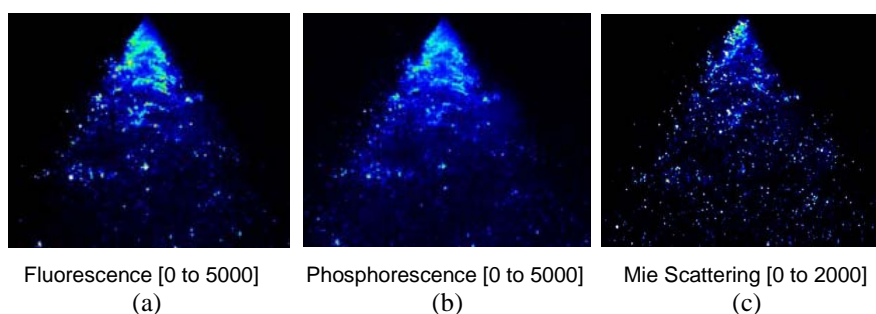


Figure 4. Simultaneous images of (a) fluorescence, (b) phosphorescence, and (c) Mie scattering of jet-A fuel in a pressure-atomized full cone spray at 3.8 lpm and 40 psi injection pressure.

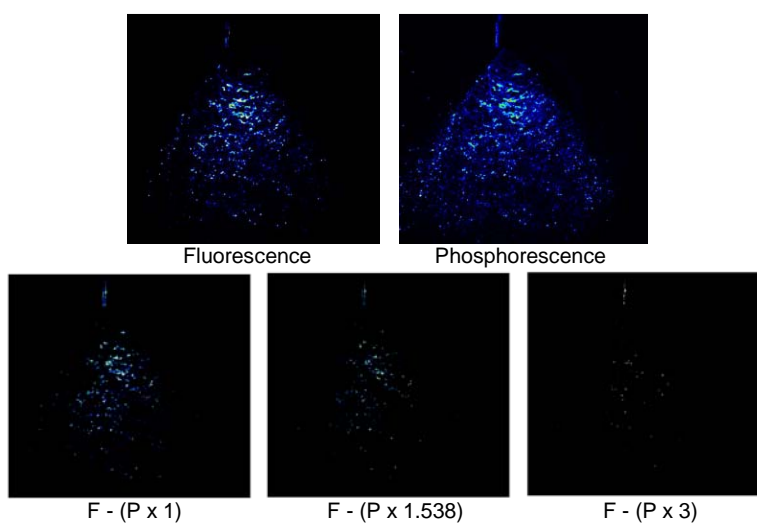


Figure 5. Images resulting from the subtraction of the acetone phosphorescence signal from the fluorescence signal using a variable scaling parameter. Intensity scaling is the same (0 to 5000) for all images.

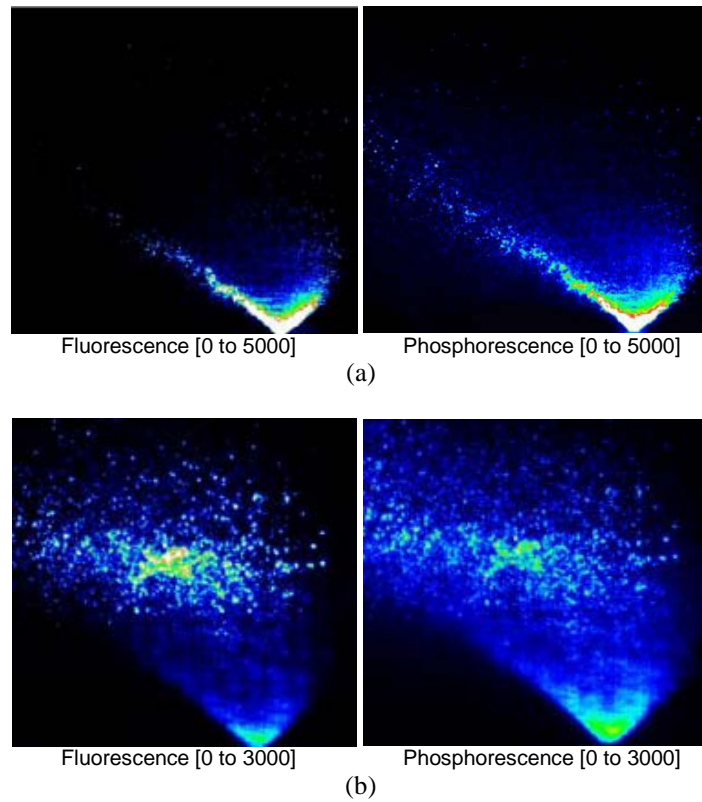


Figure 6. Fluorescence images of a pressure-atomized spray in a moderately heated (444 K) crossflow (46 m/s from right to left). The laser sheet is (a) aligned with the centerline and (b) offset in the transverse direction (into the page) by 25 mm. Signal near the nozzle exit represents rescattering of fluorescence and phosphorescence.