

# Guidelines for Interpreting Soot Luminosity Imaging

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## ABSTRACT

One way to develop an understanding of soot formation and oxidation processes that occur during direct injection and combustion in an internal combustion engine is to image the natural luminosity from soot over time. Imaging is possible when there is optical access to the combustion chamber. After the images are acquired, the next challenge is to properly interpret the luminous distributions that have been captured on the images. A major focus of this paper is to provide guidance on interpretation of experimental images of soot luminosity by explaining how radiation from soot is predicted to change as it is transmitted through the combustion chamber and to the imaging. The interpretations are only limited by the scope of the models that have been developed for this purpose.

The end-goal of imaging radiation from soot is to estimate the amount of soot that is present. The method selected for making such estimates is to model the combustion and sooting events with computational fluid dynamics (CFD), post-process the CFD results to generate 3D distributions of the soot-radiation field, model the transformation of the 3D distribution to a 2D distribution that is representative of luminosity captured by the camera, derive a relationship between the projected 2D luminosity and the amount of CFD-predicted in-cylinder soot, and finally, apply that relationship to experimental images thus giving an estimate of actual amount of in-cylinder soot that is present. Model descriptions, how the models are implemented and results of their application are included in this paper.

**CITATION:** Hessel, R., Yue, Z., Reitz, R., Musculus, M. et al., "Guidelines for Interpreting Soot Luminosity Imaging," *SAE Int. J. Engines* 10(3):2017, doi:10.4271/2017-01-0716.

## INTRODUCTION

Improving the ability to interpret soot-natural luminosity (soot-NL) images is the focus of this paper. To accomplish this task, it is necessary to understand what issues currently limit the ability to interpret soot-NL images and to have a clear and reliable set of images to base improved interpretations on. Such a set of images has been acquired from experiments reported on in reference [1]. One sample image from the dataset is given in [Figure 1](#).

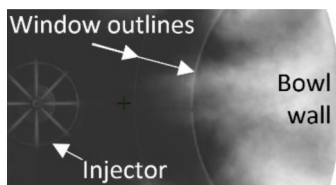


Figure 1. Sample soot-NL image of one of eight diesel jets impinging on bowl wall at 364.5 CAD. Injector, liquid fuel spray and cylinder-head window outlines are also visible [1].

It may appear challenging to estimate the actual distribution of soot within the cylinder by viewing a soot-NL image like the image in [Figure 1](#). Certainly, it is a challenge, not because of the optical resolution of the image, but for several other reasons.

A rather obvious reason is that the image is two-dimensional (2D) but the soot distribution that generates it is three-dimensional (3D). The light captured by a pixel of the imaging camera is not from a single point source, but it is from an accumulation of light from all emitting soot particles that propagate toward the pixel, i.e., from along a line of sight (LOS).

Typically, soot initially forms at various locations in the combustion chamber and is thereafter transported to varying degrees throughout the combustion chamber. Consequently, soot particles along a LOS are at different distances from the imaging camera. From an imaging perspective, the difference in distance by itself is typically small relative to the imaging depth of field, and is thus inconsequential. Emission from soot that is located further from the camera has more

opportunity to be attenuated by other soot in the intervening medium between the soot and the camera. This issue is illustrated and discussed in the ‘Transmissivity’ sub-section and in the ‘Results’ section.

The temperature of the emitting particles is also important, because hotter particles emit with greater intensity [2], i.e., they increase image brightness locally. Increased soot concentration at a particular temperature also increases local image brightness, so there is inherent uncertainty as to the actual cause of brightness variation over the field-of-view, whether due to variations in temperature or in concentration or both. Together, the ‘Line-of-Sight (LOS) and Transfer Function (TF) Model Descriptions and Implementation’ and ‘Results’ sections address these effects to the degree the employed models allow.

Previous work by Matsui et al. [3] showed that when no LOS temperature gradients exist, the two-color laser diagnostics technique can correctly measure mean volume fraction, even with gradients in volume fraction along the LOS. New computational findings suggest that this might also hold for soot-NL imaging, where along a near-constant temperature LOS, soot volume fraction is found to scale almost linearly with soot-NL along the LOS, with soot volume fractions varying from 0 up to 20 ppm (sub-section ‘370.0 CAD’).

**Table 1. Engine & injector specifications and operating conditions.**

|                                             |                                   |
|---------------------------------------------|-----------------------------------|
| Engine base type                            | Cummins N-14, DI diesel, 4 stroke |
| Swirl ratio                                 | 0.5 (approximate)                 |
| Bore                                        | 139.7 mm                          |
| Stroke                                      | 152.4 mm                          |
| Geometric compression ratio                 | 11.2:1                            |
| Bowl width                                  | 97.8 mm                           |
| Bowl depth                                  | 15.5 mm                           |
| Fuel Injector                               | Delphi DFI-1.5 (light duty)       |
| Fuel injector type                          | Common-rail, solenoid actuated    |
| Cup (tip) type                              | Mini-sac                          |
| Number of holes & arrangement               | 8, equally-spaced                 |
| Spray pattern included angle                | 156°                              |
| Nominal orifice diameter                    | 0.13 mm                           |
| Engine Speed                                | 1200 RPM                          |
| Engine Load                                 | 5 bar gIMEP                       |
| Intake O <sub>2</sub> (volume / mass basis) | 18 / 20 %                         |
| Fuel Pressure                               | 1200 bar                          |
| Nominal TDC Motored Density                 | 16.6 kg/m <sup>3</sup>            |
| Nominal TDC Motored Temperature             | 900 K                             |

In the work of Yan and Borman [4] temperature and volume fractions were found to be biased toward hot-soot values. New computational results support this finding and show that under combustion conditions, when temperatures and soot concentrations are both high, soot-NL along a LOS appears to be more sensitive to changes in temperature than to changes in volume fraction. And, the total soot-NL signal appears to be more heavily weighted by conditions on the side of the combustor jet that is closest to the detector (sub-sections ‘360.0 CAD’ through ‘367.5 CAD’). This prediction is

similar to Murphy and Shaddix’s prediction [5]. They analyzed two soot slabs at different temperatures and found that the bias toward hot soot was greater when the hot slab was closer to the detector.

Besides temperature and local volume fraction integrated along a LOS, the radiative emission spectra of hot soot particles can also depend on variations in soot material properties [6]. Variations in soot properties are not addressed in this paper.

## ENGINE TEST FACILITY/OPERATING CONDITION

Figure 2 shows the experimental setup of the single-cylinder engine that is simulated. Engine and injector specifications are listed in Table 1. Aspects of the setup and operating condition that are relevant to the modeling effort are described in this section.

For the experiments described here, a centrally-located, eight-hole Delphi DFI1.5 common-rail injector delivers 70 mg of n-heptane per skip-fired cycle (Fig. 2). Intake gas is diluted with N<sub>2</sub> so the resulting O<sub>2</sub> concentration is 18% by volume, which helps promote soot formation and limit soot oxidation when compared to the undiluted state.

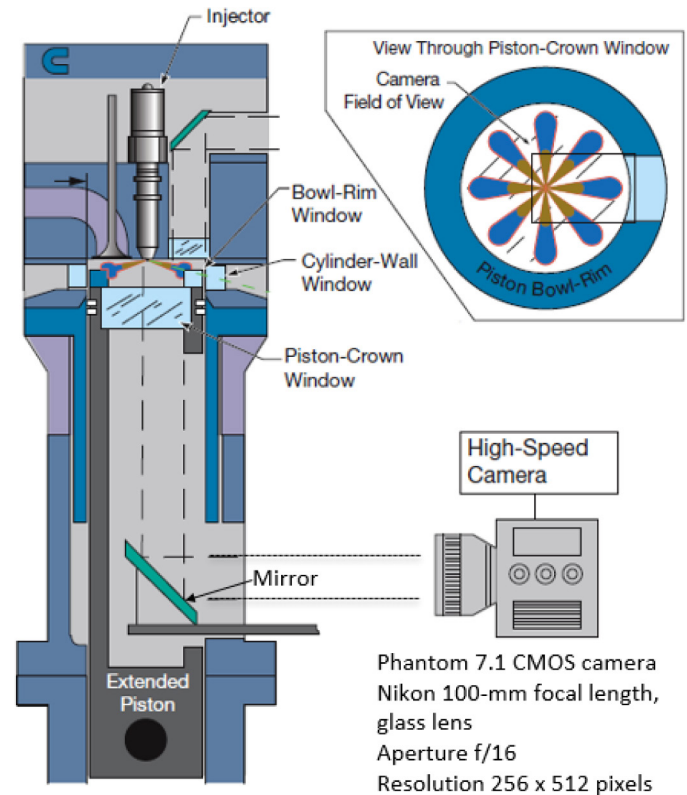


**Figure 2. Schematic of experimental facility. Luminosity propagates downward through piston-crown window, reflects off mirror and collected by camera.**

With the engine running at 1200 revolutions-per-minute (RPM) and start-of-injection at 350 CAD (crank-angle degrees after-top-dead-center of valve overlap), the pre-mixed burn begins near 355 CAD (Fig. 3). Injection ends at 366.3 CAD at which time the diffusion burn tails off (also Fig. 3). It is important to show that the model predictions agree well with the measured cylinder pressure and

apparent heat release rate (AHRR), because the calculation scheme to predict soot distribution and soot's radiation properties rely on the predicted flow and temperature fields (Fig. 3).

In the experiments, soot-NL is within the dynamic range of the camera for a single optical setup with little saturation at peak soot luminosity from approximately top-dead-center (TDC) to approximately 385 CAD. It is over this range that the soot-NL from the CFD predictions are analyzed.

The radiation of interest is the component that travels downward, through the portion of the piston-crown window that is within the camera field of view indicated in Figure 2. After passing through the piston-crown window, the soot-NL reflects off of the mirror located below the piston and is imaged by the high-speed Phantom 7.1 complementary metal-oxide-semiconductor (CMOS) camera (Fig. 2) using a 105-mm focal-length glass lens set to  $f/16$ . Notice that the field of view encompasses one full jet from the eight-hole injector, along with small portions of its two neighbors.

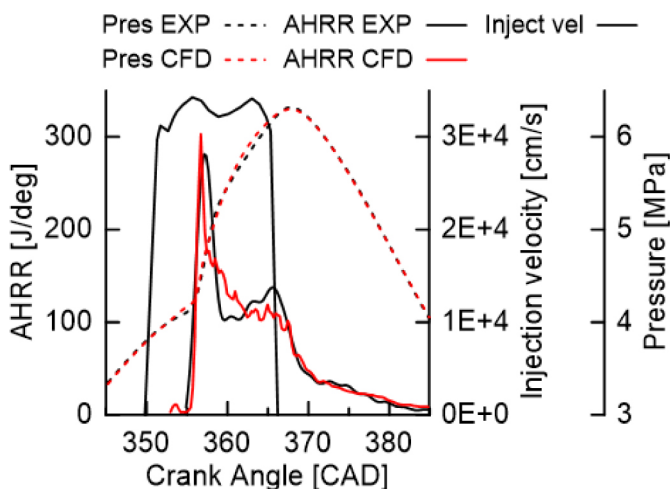


Figure 3. Comparison of predicted and measured cylinder pressure and AHRR. The injection velocity model input, which is derived from the measured injection momentum, is also shown.

## CFD-SPECIFIC MODEL DESCRIPTIONS

Three types of models are used in this work. A brief summary of the CFD model is provided in the following two paragraphs; more detailed descriptions can be found elsewhere [7]. The subsequent section describes in greater detail the two post-processing and analysis methods that are unique to this study, the LOS and TF models.

Spray processes are modeled by applying the assumptions of local phase equilibrium and jet theory [7]. Experimental studies [8, 9] have shown that the vaporization process of a high injection pressure engine spray is controlled by the entrainment of hot ambient gas into the spray and the overall mixing of fuel and air throughout the spray cross-section, as opposed to being controlled by interphase transport rates of mass and energy at droplet surfaces. In this approach, liquid is injected as Lagrangian parcels, and transitioned into a Eulerian framework while moving away from the nozzle, which is controlled by a liquid-jet model [7]. The phase change between liquid and vapor is solved under the Eulerian system using a phase-equilibrium solver

[10]. A gas-jet model [11, 12] is applied for the momentum exchange between parcels and gas to reduce grid dependency. The non-equilibrium processes of droplet breakup, collision and interfacial mass transfer are neglected.

A generalized-RNG  $k-\epsilon$  turbulence model [13] is used for turbulence modeling. The pressure-volume-temperature relationship is described using the Peng-Robinson Equation of State, to account for real gas effects under high pressures and high temperatures [14]. The wall heat transfer is calculated by applying a temperature wall function [15]. A sparse analytical Jacobian chemistry solver [16] is integrated with the CFD code and the chemical reactions are solved with the well-mixed assumption. A reduced toluene-reference-fuel mechanism [17] with 109 species and 543 reactions is used, which also includes the pathways of polycyclic-aromatic hydrocarbons (PAH). Soot emissions are predicted by a semi-detailed soot model [18] that accounts for soot inception through pyrene, surface growth through acetylene and PAHs, coagulation, and oxidation by  $O_2$  and OH.

## LINE-OF-SIGHT (LOS) AND TRANSFER FUNCTION (TF) MODEL DESCRIPTIONS AND IMPLEMENTATION

This section is organized by sequentially introducing terms, each building on the previous, so that by the end of the section there is an understanding of how the LOS and TF models are formulated and implemented. The goal of this section is to explain how soot concentration and radiation values are predicted by and extracted from the models and subsequently how the model values are applied to experimental images of soot luminosity for estimating in-cylinder soot distributions. Some definitions might differ slightly from those in common use, but they are defined as such in order to work within the context of this paper.

### Soot

Soot is defined as particles formed as a result of combustion of the fuel and are large enough to be considered separate from gas-phase species. Other sources of soot, like lubricating oil, are not accounted for by the present models.

### Soot Cloud

A region within the combustion chamber that contains a significant amount of soot. Here, soot clouds are specified according to amount of soot mass contained within them.

### Soot-Volume-Fraction ( $f_v$ )

For a specified region of space,  $f_v$  is the volume occupied by soot divided by the region's total volume. In the experiments, the specified regions are along lines of sight (which is described next). In CFD, the regions are typically computational cells, or groups thereof.

As will be seen in the Results section,  $f_v$  is an important measure of soot. With it, locations where relative concentrations of soot are high can be identified at any time in the engine cycle, and soot emissivity and transmissivity correlate with  $f_v$ . The correlations facilitate using measured luminosity as an indicator for soot.

The unit of  $f_v$  used here is parts-per-million (ppm). Equation (1) is used for extracting ppm from CFD results.

$$f_v = \text{soot}_{\text{cell\_density}} / \text{soot}_{\text{particle\_density}} * 1.0\text{e}6 \quad (1)$$

Where,

|                                                   |                                                                                               |
|---------------------------------------------------|-----------------------------------------------------------------------------------------------|
| $\text{soot}_{\text{cell\_density}}$              | mass of soot divided by volume of computational cell, g/cm <sup>3</sup>                       |
| $\text{soot}_{\text{particle\_density}}$<br>1.0e6 | mass of soot divided by soot-particle volume, g/cm <sup>3</sup> converts to parts per million |

### Line-of-Sight (LOS), Lines-of-Sight (LsOS)

A soot-NL image is essentially multiple measurements taken along many lines-of-sight (LsOS) across the image. In the experiment, the piston-crown window provides access to a near right-cylinder-shaped region of the combustion chamber, with the firedeck and piston-crown window forming the top and bottom of the cylinder, respectively. The LsOS are situated between and roughly perpendicular to these parallel surfaces. Soot-NL that leaves this region through the window is collected by the camera's sensor, which is a long distance (700 mm) from the combustion chamber compared to the diameter of the camera lens aperture (at most 12 mm). Given that the collection angle spans at most  $\pm 1.5^\circ$ , to greatly simplify the calculations, the soot-NL is treated as leaving the measurement volume in parallel beams.

The number of beams in the experiment, i.e., the number of LsOS, is equivalent to the number of pixels that resolve the piston-crown window, which is  $256 \times 512$ . The LsOS in the CFD model are defined similarly, but rather than corresponding to pixels, the LsOS in the model correspond to the computational cells that resolve the combustion chamber, which are far fewer than the number of pixels ( $10 \times 20$ ). Figure 4 shows an example comparison of the scales of the experimental (thin) and computational (thick) LsOS, color coded according to the CFD-predicted  $f_v$  along the LsOS.

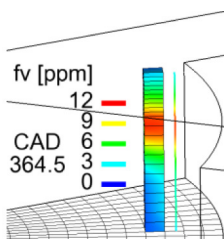


Figure 4. Comparison between an example experimental LOS (thin column) and computational LOS (thicker column of cells).

### A Measure of Soot ( $f_v L$ )

The product of soot volume fraction and LOS path length, or  $f_v L$ , is a quantitative measure of soot along the line of sight. With typical  $f_v$  values of up to 50 ppm and typical LOS path lengths ( $L$ ) in the range of 10–20 mm, microns ( $\mu\text{m}$ ) are a convenient unit for  $f_v L$ , with  $f_v L$  having values up to about 0.5  $\mu\text{m}$ .

Three  $f_v L$  measures of interest are the value along a LOS in the experiment,  $f_v L_{\text{exp}}$ , the value of one computational cell in the model,  $f_v L_{\text{cfld\_cell}}$ , and the value along a vertical column of computational cells in the model,  $f_v L_{\text{cfld}}$ . These  $f_v L$  variations are described next.

#### $f_v L_{\text{cfld\_Cell}}$

Referring to Figure 4,  $f_v L_{\text{cfld\_cell}}$  is the product of  $f_v$  for one (colored) cell and the vertical length of the LOS through the computational cell, which in this case, is the cell height.

#### $f_v L_{\text{cfld}}$

Referring again to Figure 4,  $f_v L_{\text{cfld}}$  is the sum of the  $f_v L_{\text{cfld\_cell}}$  values in one column of cells along the CFD LOS. This definition is consistent with that used in previous experimental studies [19].

$$f_v L_{\text{cfld}} = [\sum (f_{v\_cfld\_cell} * \text{cell}_{\text{volume}}) / \text{LOS}_{\text{volume}}] * L \quad (2)$$

Where the sum is over all cells along a LOS, and:

|                               |                                         |
|-------------------------------|-----------------------------------------|
| $f_{v\_cfld\_cell}$           | $f_v$ of a cell                         |
| $\text{cell}_{\text{volume}}$ | Volume of a cell                        |
| $\text{LOS}_{\text{volume}}$  | Volume of a column of cells along a LOS |
| $L$                           | Distance along LOS                      |

The term in square brackets is the average  $f_v$  along a LOS.

In the mesh, each cell in a LOS is stacked on top of each other so that the top and bottom cell-faces are perpendicular to the LOS and have equal surface-areas, and the other cell-faces are parallel to the LOS (Fig. 4). Therefore, the above equation reduces to (see Appendix A for details):

$$f_v L_{\text{cfld}} = \sum (f_v L_{\text{cfld\_cell}}) \quad (3)$$

#### $f_v L_{\text{exp}}$

The value of  $f_v L_{\text{exp}}$  corresponding to the thin column in Figure 4 is not directly measured here. Rather, as described below, the characteristic TF derived from the model predictions is applied to experimental soot-NL images to estimate  $f_v L_{\text{exp}}$ , as described in the Results section.

### Soot Natural Luminosity (Soot-NL)

The previous three terms are quantitative measures of soot itself.

Following, terminology related to the visible luminosity characteristics of soot is described. At the end of this section, the two topics are brought together in the discussion of the transfer function.

Experimentally-obtained images of soot-NL, for example Figure 1, is due to soot heated by combustion (natural) emitting radiation by incandescence (luminosity), which is transmitted through the combustion chamber gases and piston-crown window and reflected off the mirror, and is ultimately captured by the imaging camera according to its spectral sensitivity over the visible wavelength range. Brighter regions of soot-NL images have more soot-NL recorded by the camera's sensor, and darker regions, less. A primary goal of this work is to improve general interpretations of such images (see Results section).

## Radiation

Radiation, described here in terms of radiant energy transfer, is the complete process in which energy is emitted by one body, transmitted through an intervening medium or space, and absorbed by another body [20]. For this study, the form of energy is electro-magnetic energy, and, unless stated otherwise, the emitting and absorbing bodies are soot and the intervening medium consists of products of combustion within the combustion chamber. Radiation has different measures and some of them are described in the following sub-sections.

### Intensity of Radiation ( $I_{bb}$ )

The intensity of radiation is the rate of emitted energy from unit surface area through unit solid angle [21] per unit wavelength. Where radiation is defined as a complete process (see its description above), here, intensity is defined only for the emission portion of the process.

While individual soot particles can be treated as blackbody emitters, the model does not predict soot-NL from individual particles. Rather, it considers soot as an aerosol assumed to be uniformly distributed throughout each computational cell. Soot-NL is predicted applying the wavelength-dependent emissivity of the soot aerosol to Planck's Law for blackbody radiation (Planck's law is given in Appendix B).

Over the temperature and wavelength ranges of interest, Planck's Law predicts  $I_{bb}$  to increase monotonically with increasing wavelength (Fig. 5a) and with increasing temperature (Fig. 5b). All else being equal, Planck's law predicts that soot radiation should be dominated by hotter soot, and should be strongest at longer wavelengths within the visible wavelength spectrum. Later, in the Emissivity and Camera's Spectral Response sub-sections, this expectation is shown to be an over-simplification.

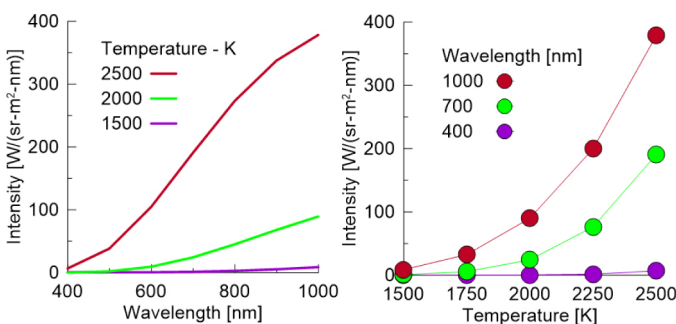


Figure 5.  $I_{bb}$  graphs over wavelengths and temperatures that occur during the combustion event and that are relevant to soot-NL.

## Radiance

Where  $I_{bb}$  is an ideal measure of black-body radiant emission, radiance is an approximation of the actual radiant emission from matter, from soot to be specific (radiance is given in terms of soot emissivity in the next sub-section). Radiance has the same units as  $I_{bb}$ , but its magnitude is less. The renderings in Figure 6 compare  $I_{bb}$  (Fig. 6a) to radiance (Fig. 6b) at 364.5 CAD. Both quantities are integrated from 400 to 1000 nm, so the units become W/(sr·m²). The color-scales are different for  $I_{bb}$  and radiance to highlight similarities in their distributions, while also demonstrating the change that emissivity imposes on their distributions.

To be clear,  $I_{bb}$  and radiance are calculated in each cell. The renderings of Figures 6a and 6b show the values as calculated in each cell. The results are shown for a 45 degree sector mesh simulation due to the assumed symmetry of the injector and geometry. The renderings display no accounting for radiation absorption. Some renderings presented later do include absorption and that fact will be pointed out when appropriate.

### Soot Emissivity ( $\epsilon_{soot}$ )

Soot emissivity is the ratio of radiance to  $I_{bb}$ . Emissivity from soot is estimated in each computational cell using Equation 4 [19].

$$\epsilon_{soot} = \frac{radiance}{I_{bb}} = 1 - \exp\left(-\frac{g \cdot f_v L_{cfd, cell}}{\lambda^\alpha}\right) \quad (4)$$

Where,

|               |                                                                                                                  |
|---------------|------------------------------------------------------------------------------------------------------------------|
| $g$           | Constant, $6.3 \mu\text{m}^{-1}$                                                                                 |
| $f_v L_{cfd}$ | $f_v L$ of computation cell                                                                                      |
| $\lambda$     | Wavelength                                                                                                       |
| $\alpha$      | Wavelength-dependent empirical function, specifically, $\alpha = 1.22 - 0.245 * \ln(\lambda [\mu\text{m}])$ [19] |

Its value increases as the relative amount of soot within a cell,  $f_v$ , increases, or if the size of the cell along the LOS increases. Figure 6c reveals the predicted distribution of emissivity at 364.5 CAD for a wavelength of 700 nm (the most dominant wavelength for this optical system, as is discussed in the Camera's Spectral Response sub-section).

Notice that emissivity is high along the spray axis and along the bowl wall (green to red), where  $f_v$  is also high (Fig. 6d), which is consistent with Equation 4. The height of all cells within the bowl are the same, so  $L$  in Equation 4 does not contribute to the variation of emissivity within the bowl. There is a large difference in magnitude between  $I_{bb}$  and radiance, because soot emissivity values are low (color legend of Fig. 6c) and because highest emissivity and highest  $I_{bb}$  regions do not overlap.

In addition to accounting for reduced emission from soot, emissivity also alters the radiant emission character over wavelength (compare curve shapes, Figures 7 and 5a). This is an important part of the model, because the amount of natural luminosity predicted to reach

the camera is an integration of spectral luminosity at specific wavelengths within the 400 to 1000 nm band. Emissivity then changes the wavelength-weighted contribution to predicted soot-NL.

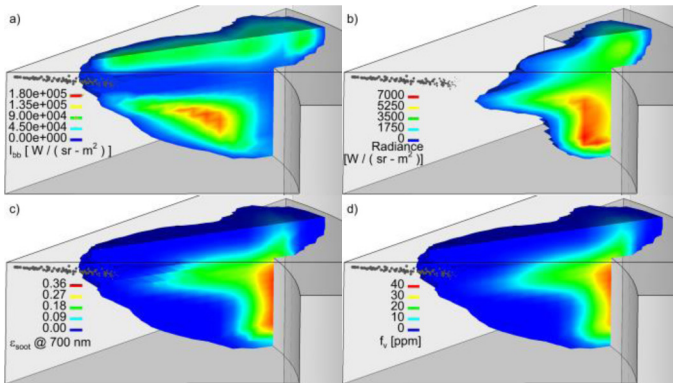


Figure 6. a)  $I_{bb}$  iso-volume  $> 1.0e4$  W/(sr-m<sup>2</sup>). b) Radiance iso-volume  $> 500$  W/(sr-m<sup>2</sup>). c)  $I_{bb}$  iso-volume colored by  $\epsilon_{soot}$  of radiation at 700 nm. d)  $I_{bb}$  iso-volume colored by  $f_v$ . All at 364.5 CAD. Renderings highlight relationships among quantities.

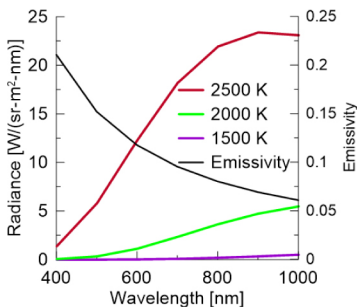


Figure 7. Left axis: Radiation. Right axis: Emissivity. When compared to Figure 5a, this demonstrates the impact emissivity has on magnitude and profile of radiation emitted from soot.  $f_v$  for emissivity calculation is 0.01.

### Transmissivity ( $\tau_{soot}$ )

Once emitted, radiation travels in all directions through combustion chamber gases. The direction of travel of interest is toward the camera's sensor. In the model, and in the experiment, this direction is vertically downward.

Of the radiation initially emitted from soot, only a portion of it passes through the medium in which it travels. In the combustion chamber, the fraction transmitted is estimated as the complement to the emissivity of soot (Eq. 5), according to Kirchhoff's Law [2] and neglecting scattering. Since transmissivity is the complement of emissivity, all of the characteristics of emissivity that were described in the previous sub-section also apply here.

$$\tau_{soot} = 1 - \epsilon_{soot} \quad (5)$$

The renderings in Figure 8 attempt to describe the role of transmittance in the LOS model. The crank angle is 364.5 CAD. The full iso-volume, only half of which is shown in Figure 8a, encompasses 99% of in-cylinder soot starting from the highest soot concentration (the red region of the iso-volume). The iso-volume is

cut in half to view inside the soot-cloud. As was pointed out for Figure 6d, soot concentration is highest along the spray axis and near the bowl wall.

Figure 8b shows the same iso-volume as Figure 8a, but now, colored by temperature. Comparing Figures 8a and 8b show the high-soot concentration gases along the spray axis to be relatively cold. A temperature-colored cut-plane of the soot-cloud through the spray axis is included in Figures 8c through 8g as a visual reference.

Both  $f_v$  and temperature are used for reference because the radiation quantities presented in the figure are functions of these two quantities. The temperature-color legend of Figure 8b applies to the cut-plane and to its contour lines, although the colors on the plane are dimmed to make the plane easier to distinguish from the colored column of cells.

Figure 8c adds a column of cells colored by  $I_{bb}$  at 700 nm. The cells constitute a computational LOS. Comparing the color of the cells to the colors on the cut-plane, a strong relationship between temperature and  $I_{bb}$  is apparent, meaning that low temperatures correlate with low intensity, etc., which is an expected outcome from applying Planck's equation (Eq. B1).

Figure 8d colors the cells by radiance. Similar to the observations when comparing Figures 6a and 6b, the  $I_{bb}$  and radiance distributions of Figures 8c and 8d differ along the LOS, with radiance being weighted toward high  $f_v$  regions. This weighting of radiance along the LOS can be appreciated by comparing the LOS distributions from Figures 8c – 8e; emissivity is, at this crank angle, transposing the location of highest emission up toward the spray axis.

The quantities of Figures 8a – 8e are cell-based quantities and are post-processed by simply visually displaying their values. But recall that luminosity, as used here, results from radiation-in-transit and therefore its distribution is determined by accumulating radiation contributions from neighboring cells along LsOS (Fig. 8f).

Being a measure of radiation-in-transit, radiance-in-transit to be specific, the distribution of soot-NL is noticeably different compared to the other more static representations of radiation (Fig. 8c – 8e). In Figure 8f, luminosity is relatively low near the head (dark-blue). A portion of the radiance from the near-head cells propagates downward, adds to radiance that is emitted from the cells below and the color transitions from dark- to medium-blue. A significant fraction of radiance is transmitted to cells below, because transmissivity near the head is high (Fig. 8g, red).

Recall that transmissivity is the complement of emissivity (compare Figs. 8e and 8g). In the cold portion of the spray, transmissivity is relatively low (Fig. 8g) and the radiance is also relatively low there (Fig. 8d) due to cooler temperatures (Fig. 8b). As a result, soot-NL stays nearly constant (Fig. 8f, medium-blue) while traversing the spray along this LOS. Below the spray, soot-NL again increases (Fig. 8f, medium-blue to red).

The visual observations of Figures 8a-g are presented as line graphs in Figure 8h. The vertical axis represents its distance from the head, zero at the top of the axis being the head surface, and the piston showing