# Differential Infrared Thermography of Gasoline Direct Injection Sprays

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#### Abstract

Advances in experimental techniques and simulations are necessary building blocks for the overall effort to reduce the  $CO_2$  and pollutant emissions of future Gasoline Direct Injection (GDI) engines. Wall wetting and inhomogeneous fuel distribution are two known causes of particulate emissions whose prediction within three dimensional computational fluid dynamics (3D CFD) can be made more reliable based on accurate droplet temperature data. Results from Differential Infrared Thermography (DIT) of a hollow cone and multi-hole gasoline direct injector are presented. Compared to previous applications of DIT, the data processing and temperature calculation methods have been refined. Interpretation of the results is supported by ray tracing simulations based on the light scattering and absorption properties of small droplets given by Mie theory.

## 1 Introduction

Increasing the energy efficiency of internal combustion engines and thus decreasing the  $CO_2$  emissions is one of the most challenging tasks that has to be addressed regarding the limited amount of crude oil available and the ongoing climate change. A well-known way to increase fuel efficiency is to equip gasoline engines with a direct injection system. However, GDI provides additional degrees of freedom that increase the overall complexity of the engine. Furthermore, the exact properties of the spray have a much higher influence on the subsequent combustion process. Thus, engine development increasingly relies on sophisticated simulations and no longer only on test runs and experience. The correct prediction of droplet temperatures in typical sprays is required for an accurate simulation since these temperatures are closely linked to the evaporation process. Evaporation is rather important, not only for the internal cooling of the engine, but also for the distribution of fuel vapour and remaining liquid droplets. Hence, the generation of particulate matter – which in GDI engines is mostly due to wetting of surfaces within the combustion chamber – is directly linked to the vaporisation process.

#### 2 Theory

In conventional infrared thermography, temperatures of objects are determined from the thermal radiation they emit. The two main assumptions are that the captured infrared radiation is solely due to the thermal radiation of the objects in question and that the emissivity of these objects is close to unity. Typically, a value of 0.9 is assumed for the emissivity of opaque objects [1]. The geometric effects of distance and orientation cancel out in most situations. For typical fuel sprays, the emissivity – which is equal to the absorbance according to Kirchhoff's law – cannot be assumed to be known a priori. Quite to the contrary, a wide range of values ranging from zero to one are to be expected depending on the process of the air fuel mixing.

In differential infrared thermography, no assumptions are made about the absorbance. Instead it is calculated from a comparison of two images recorded at different background temperatures. As in conventional thermography, temperature calculation is based on Planck's law of radiation in its formulation for photon fluxes *j* emitted by a black body of surface area dA with temperature *T* at the wavelength  $\lambda$ 

$$j(\lambda,T) \,\mathrm{d}\lambda\mathrm{d}A = \frac{2\pi c}{\lambda^4} \frac{1}{\mathrm{e}^{hc/\lambda k_{\mathrm{B}}T} - 1} \mathrm{d}\lambda\mathrm{d}A \,, \tag{1}$$

where *c* is the speed of light in vacuum, *h* the Planck and  $k_{\rm B}$  the Boltzmann constant.

As photons travel through any medium they have a certain chance to be absorbed or scattered. The according probabilities can be expressed by the corresponding scattering cross sections  $\sigma$  for each molecule. Taking a volume of cross sectional area dA and width dx filled with molecules of number density *n*, the infinitesimal extinction is given by the differential form of the Beer-Lambert law:

$$dj_x = -j_x n(\sigma_s + \sigma_a) dx$$
<sup>(2)</sup>

Scattering and absorption coefficients of organic substances are not constant with respect to the photon wavelength in the mid infrared. An additional effect that has to be taken into account when calculating the photon flux is the emission of photons according to Kirchhoff's law of thermal radiation. It states that the emissivity of a surface dA in thermal equilibrium is equal to its absorbance. Some care has to be taken when spontaneous and induced emission is considered in non-equilibrium cases [2]. In this paper, Einstein's notation is adopted where stimulated emission and stimulated absorption are considered to be the same effect which is simply called 'absorption'. A direct consequence is that the absorption cross section may become negative in the case of population inversion. However, this is rarely seen in DIT experiments.

A plot of the absorption coefficient of 10% ethanol in gasoline together with the expected photon flux for various temperatures is shown in Fig. 1. The absorption of the C-H stretching vibration frequency has a peak at 3.4 µm but is quite low at other wavelengths. On the one hand, this is a limiting factor for the temperature determination as the photon flux in the 3.4 µm-range is rather low at relevant temperatures. On the other hand, this fact can be used to separate liquid and gaseous fuel: Gaseous fuel has nearly no contribution to the signal apart from the absorption due to the C-H bonds. In broad band detection this contribution is much smaller compared to the scattering of the droplets and thus the gas remains nearly invisible. This is in contrast to narrow band detection using the filter where the contribution from the gas phase is always important.

In the case of vanishing scattering cross section ( $\sigma_s = 0$ ) the photon flux is given by the solution of the differential Eq. (2). For simplification we write

$$\alpha = n\sigma_a \quad \text{and} \quad j_{x_0} = j_x(x_0) \tag{3}$$

and then obtain

$$\frac{j_x(x)}{dx} = \underbrace{-\alpha(x)j_x(x)}_{Absorption} + \underbrace{\alpha(x)j(T(x))}_{Emission} \quad .$$
(4)

Integration of (4) yields: 
$$j_x = j_{x_0} \exp\left(-\int_{x_0}^x \alpha(\zeta) d\zeta\right) + \int_{x_0}^x \alpha(\zeta) j(T(\zeta)) \exp\left(-\int_{\zeta}^x \alpha(\xi) d\xi\right) d\zeta$$
 (5)

Eq. (5) can be interpreted as an exponential decay along the path of a light ray according to the absorbance  $\alpha$ . Additionally, at each location in space photons are generated with the probability  $\alpha_j(T)$  which will also 'decay' exponentially as they propagate through the medium. Equation (5) can be rewritten to a simpler form by defining an emissivity  $\varepsilon$  and an effective photon flux  $j_{\text{eff}}$ :

$$j_x = (1 - \varepsilon)j_{x_0} + \varepsilon j_{\text{eff}}$$
(6)

with

$$\varepsilon := 1 - \exp\left(-\int_{x_0}^x \alpha(\zeta) \,\mathrm{d}\zeta\right) \tag{7}$$

$$i_{\text{eff}} := \frac{\int_{x_0}^{x_0} \alpha(\zeta) j(T(\zeta)) \exp\left[-\int_{\zeta}^{x} \alpha(\zeta) \, \mathrm{d}\zeta\right] \, \mathrm{d}\zeta}{1 - \exp\left[-\int_{x_0}^{x} \alpha(\zeta) \, \mathrm{d}\zeta\right]}$$
(8)

and

These new quantities defined by Eqs. (7) and (8) have the following physical interpretation:  $\varepsilon$  is the emissivity of a hypothetical semi-transparent sheet with equal influence as the observed media and  $j_{eff}$  is the photon flux that would be emitted by that sheet if its emissivity were unity. Equation (8) defines a weighted mean of j(T), as the losses due to ab-



Fig. 1: The spectral photon flux according to Eq. (1) for the wavelength interval detectable by the used camera. The extinction of gaseous E10 (10% ethanol in gasoline) was detected at room temperature using an FTIR.

sorption within the object itself are accounted for.

The temperature can be calculated from the photon flux  $j_x$ , if the absorbance of the object is known. The absorbance in turn can be calculated by a simple variation of the background temperature. However, the intensity seen by the camera is not the photon flux but an integral over the wavelength range of the photon flux  $j_x$  multiplied by the camera sensitivity  $\kappa$  and the integration time  $t_{int}$ :

$$I \propto t_{int} \int_{\lambda_0}^{\lambda_1} \kappa j_x d\lambda$$
(9)

For simplicity, it is assumed that the image is recorded within a very narrow wavelength interval. This means that Eq. (6) can be interpreted in terms of intensities seen by the camera instead of photon fluxes. Furthermore, one has to take a certain background intensity  $I_{noise}$  into account which has several sources: First, the temperatures of the camera housing and filters in front of the sensor are above 0 K, hence they emit infrared radiation. Second, the image digitisation is subject to read-out noise and third, the CCD chip itself generates a significant number of counts due to thermal noise. If an ideal black body at the temperature  $T_B$  with corresponding image intensity  $I_{BB}$  is considered as the background source, Eq. (6) can be rewritten as:

$$I_x = (1 - \varepsilon)I_{BB}(T_B) + \varepsilon I_{BB}(T_{eff}) + I_{noise}$$
(10)

Note that the effective photon flux has been replaced by the intensity emitted by a hypothetical black body at an effective temperature  $T_{\text{eff}}$ . For opaque bodies this temperature is equal to the surface temperature.

The basic idea of differential infrared thermography (DIT) is to record images at different background temperatures. If images at two background temperatures and an image (or a region of an image) with and without any absorbing object ( $\varepsilon = 0$  and  $\varepsilon \neq 0$ ) are available, one obtains three equations for three unknowns. Thus,  $I_{noise}$ ,  $\varepsilon$  and  $I_{BB}(T_{eff})$  can be determined and by inversion of the known dependence of the intensity signal of a black body to its temperature, the effective temperature  $T_{eff}$  is obtained. There are some more specific properties to be considered when windows are present (compare Sec. 4). As the aim of this paper is to describe a suitable set-up for the measurements of spray temperatures, not only gaseous molecules have to be considered but also droplets. An advantage of the formulation in terms of cross sections used throughout this paper is that no assumption needs to be made on the nature of the particles that absorb and emit radiation. The preceding discussion is just as valid for non-scattering droplets as for gaseous molecules.

Droplets usually have a different index of refraction than the surrounding medium and a rather large surface to volume ratio. Hence, scattering is not completely negligible. In order to calculate the scattering and absorption cross sections, Mie theory can be used. For spherical particles, the absorption cross section equals the emission cross section [3]; however both can be larger or smaller than the geometric cross section as shown in the left panel of Fig. 2. Droplets with a diameter approximately equal to the wavelength of the light have a high scattering to extinction ratio. Additionally, large droplets have a large scattering probability because the latter is approximately proportional to the geometric cross section. Scattering is to some extent compensated by two effects: First, smaller droplets are usually surrounded by a cloud of gaseous fuel at a temperature close to the droplet surface temperature because they result from evaporation of larger droplets. Second, scattering is biased towards forward scattering for large droplets which has a lesser effect on the detected signal. The differential cross section per solid angle  $d\sigma/d\Omega$  which is also predicted by Mie theory can be used to evaluate the direction of the scattering and is shown in the right panel of Fig. 2. Droplets with radii larger than the wavelength of the light show multiple resonances of  $d\sigma/d\Omega$ . With increasing radius the number of resonances increases and their distance decreases while the overall probability for forward scattering increases as well. The total cross sections section is a shown in the right panel of Fig. 2.



Fig. 2: The left panel shows normalised scattering and absorption cross sections of n-heptane in vacuum according to [7] at a wavelength of 3.4  $\mu$ m for varying droplet radii r (red and black lines). The right panel shows the angular distribution of the scattered photons into a solid angle against the scattering angle  $\theta$ . Note that a factor of  $2\pi \sin \theta$  has to be taken into account when calculating the intensity scattered into the interval [ $\theta$ ,  $\theta$ +d $\theta$ ] instead of the solid angle d $\Omega$ . All values are calculated assuming unpolarised light.

tion  $\sigma$  is the integral of the differential cross section  $d\sigma/d\Omega$  over all solid angles.

Scattering can be taken into account by interpreting  $\alpha$  as extinction rather than absorption. This directly leads to the fact that the source term in Eq. (6) has to be replaced by an extended expression with the scattering cross section  $\sigma_s$  and the environmental photon flux  $j_e$ 

$$j(\lambda, T(x)) \Rightarrow j(\lambda, T(x)) \frac{\sigma_{a}(x)}{\sigma_{s}(x) + \sigma_{a}(x)} + j_{e}(\lambda, x) \frac{\sigma_{s}(x)}{\sigma_{s}(x) + \sigma_{a}(x)}$$
(11)

Depending on the temperature of the environment this may lead to an over- or underestimation of the object's true temperature  $T_0$ . In the case of single scattering and a particle embedded in an ideally black cavity of temperature  $T_E$  in front of an infinitesimally small background, the apparent object temperature  $T_A$  is given by:

$$T_{\rm A} = I_{\rm BB}^{-1} \left( I_{\rm BB}(T_{\rm O}) \frac{\sigma_{\rm a}(x)}{\sigma_{\rm s}(x) + \sigma_{\rm a}(x)} + I_{\rm BB}(T_{\rm E}) \frac{\sigma_{\rm s}(x)}{\sigma_{\rm s}(x) + \sigma_{\rm a}(x)} \right)$$
(12)

and for 
$$T_{\rm E} \approx T_{\rm O}$$
  $T_{\rm A} \approx T_{\rm O} + \frac{\sigma_{\rm s}(x)}{\sigma_{\rm s}(x) + \sigma_{\rm a}(x)} (T_{\rm E} - T_{\rm O}) + O((T_{\rm E} - T_{O})^2)$  (13)

or for 
$$\sigma_a \ll \sigma_s$$

$$T_A \approx T_E + \frac{1}{\frac{dI_{BB}}{dT}} \left( I_{BB}(T_O) - I_{BB}(T_E) \right) \frac{\sigma_a}{\sigma_s} + O\left(\sigma_a^2\right)$$
(14)

and similarly for 
$$\sigma_{\rm s} \ll \sigma_{\rm a}$$
  $T_{\rm A} \approx T_{\rm O} + \frac{1}{\frac{dI_{\rm BB}}{dT}} (I_{\rm BB}(T_{\rm E}) - I_{\rm BB}(T_{\rm O})) \frac{\sigma_{\rm s}}{\sigma_{\rm a}} + O(\sigma_{\rm s}^2)$  (15)

An interpretation of Eqs. (13) to (15) is that the influence of scattering is similar to that of a mirror. The higher the ratio of scattering to absorption, the more the detected intensity equals the intensity emitted by the environment. Hence, scattering may be a serious problem even in the case of a perfectly cooled environment. One way to reduce the errors induced by scattering is to control the temperature of the whole environment instead of only a small background. However, most often this is not possible. Furthermore, for objects that are not infinitesimally small, scattered radiation from the object itself remains even in the case of a temperature controlled environment.

Another option to increase the accuracy of temperature determination indicated by Eq. (13) is to limit the detection to wavelengths where the ratio of scattering to absorption is small. Typically, this is the case when the imaginary part of the index of refraction is maximal and the real part is matched to the refractive index of the surroundings. For typical fuel sprays this can be achieved by using a wavelength filter centred at the C-H stretching or bending frequency. Attention should also be paid to the fact that the sensitivity depends on the first derivative of the ideal black body intensity  $I_{BB}$  with respect to T [1]. Especially at very low and very high temperatures this may limit the accuracy of the temperature determination in combination with a filter.

#### 3 Experimental Set-Up

In contrast to conventional thermography [1], the emissivity  $\varepsilon$  of the spray is assumed to be variable and not known a priori. In differential thermography, emissivity and temperature are calculated from comparisons of images recorded at different background temperatures. For an instationary and not perfectly reproducible process such as fuel injection, this implies that the technique can only be used on averaged images.

The experimental set-up consists of a pressure chamber with heated gas, an infrared light source, an injector



Fig. 3: A schematic top view of the set-up shown together with exemplary rays of infrared radiation. The spray is generated with injectors from Bosch inside a pressurised chamber which has windows made of CaF<sub>2</sub>. Thermal radiation can be transmitted, emitted and scattered by the spray. Depending on the temperature of the chamber, scattering can increase or decrease the photon flux j<sub>x</sub> at the camera.

for spray generation and an MWIR camera as shown in Fig. 3. Hollow cone sprays are created by outwardly opening piezo injectors and multiple-hole injectors with magnetic actuators are used to generate eight 'fingered' sprays. Both injector types are operated at fuel pressures up to 200 bar. The injection chamber is filled with nitrogen whose pressure and temperature can be varied between 1 to 10 bar and 300 to 650 K. The windows are made of  $CaF_2$  to increase the transmission as the fused silica typically used as a window material absorbs more than 90% of the radiation in the mid infrared. An ImageIR 6300 (up to 100 fps, sensitive from 3 to 5 µm) from Infratec is used for image acquisition and a high emissivity 6" IR calibrator from Fluke (320 to 770 K) provides the background illumination. The camera's integration time can be adjusted down to 1 µs to avoid motion blur. Additionally, a band pass filter centred at the absorption maximum of the C-H-bond (3.4 µm) can be inserted into the beam path. For comparison, a Fastcam SA1.1 from Photron was used in a pre-study to record high-speed, visible light images of the injection process. An external trigger unit synchronises the injector with the camera. During the experiment the chamber is permanently flushed with pre-heated, pressurised nitrogen. Another pressure vessel filled with fuel and highly pressurised nitrogen generates injection pressures of up to 200 bar.

### 4 Data Processing

All intensity data is post processed with MATLAB. Due to the nature of the algorithm no instantaneous evaluation is possible. Because of the high dimensionality of the data (typically 640x512 pixels with 5 different background temperatures and averages of 10 individual images) the process to determine a single temperature map takes approximately five minutes.

Consider Eq. (10) again: For the purpose of determining the temperature of a spray inside a pressure vessel it has to be adapted to accommodate for three more effects: Infrared radiation is reflected by the windows, absorbed by the air and the background is not an ideal black body. The background emissivity  $\varepsilon_B$  (0.99) can be determined with a calibrated camera. The transmissivity of the windows  $\gamma$  can be obtained by a simple comparison of the intensity of an object seen through a window and seen directly by the camera while all other parameters are kept constant. In a similar way the transmissivity of the air (outside the vessel)  $\beta$  can be obtained, however this will not be required for the algorithm, because  $\beta$  is very close to unity and it can be accounted for by the calibration function. The adapted version of Eq. (10) including these effects reads:

$$I_x = \beta \gamma^2 (1 - \varepsilon) \varepsilon_{\rm B} I_{\rm BB}(T_{\rm B}) + \beta \gamma \varepsilon I_{\rm BB}(T_{\rm eff}) + I_{\rm noise}$$
(16)

By recording two images, one with an object  $(I_1)$  and one without  $(I_0)$ , one can calculate an intensity difference:

$$\underbrace{I_1 - I_0}_{y} = \underbrace{(-\varepsilon\gamma)}_{m} \underbrace{\beta\gamma\varepsilon_{\rm B}I_{\rm BB}(T_{\rm B})}_{x} + \underbrace{\beta\gamma\varepsilon_{\rm B}I_{\rm BB}(T_{\rm eff})\frac{\varepsilon}{\varepsilon_{\rm B}}}_{L}$$
(17)

This intensity difference depends on the background temperature. A linear fit of the data is then carried out to obtain the spray temperature and emissivity. The intensity difference  $I_1$ - $I_0$  is taken as the dependent variable while the intensity of the background  $\beta\gamma\epsilon_B I_{BB}(T_B)$  is taken as the independent variable.

The slope yields the emissivity of the spray  $\varepsilon$  if the transmissivity of the windows  $\gamma$  is known. Combining this information with the offset of the linear fit leads to the intensity at an effective spray temperature  $I_{BB}(T_{eff})$ . This function can be inverted as it is a monotonically increasing function which results in  $T_{eff}$ . For every pixel in an image this algorithm has to be repeated. The calibration function  $\beta \varepsilon_B I_{BB}(T)$  is shown in Fig. 4 while data for an exemplary pixel is shown in Fig. 5. The current algorithm uses a linear interpolation between reference points for the calibration function  $I_{cal}$ . Most previous works assumed a Stefan-Boltzmann ( $T^4$ ) dependency and used the camera calibration to obtain the temperature of two reference points. That method works fine when limited to a narrow temperature range but has drawbacks over a wider temperature range as can be seen in Fig. 4. The exemplary  $T^4$  fit does not describe the calibration data satisfactorily.



Fig. 4: The calibration function of the camera is interpolated between measured reference points. The figure shows these reference points using the wavelength filter and an integration time of 25 μs compared to a Stefan-Boltzmann T<sup>4</sup> fit.



Fig. 5: The intensity difference I<sub>1</sub>-I<sub>0</sub> plotted against the background intensity. A linear fit according to Eq. (17) is shown in red. The background temperatures used to obtain the data points are from left to right: 373, 403, 433, 463, 498 and 533 K. The negative slope is used to obtain the emissivity (0.71 in this case) and the value where the fitted line crosses the horizontal axis can be used to determine the spray's temperature (here 449 K).

The uncertainty of the calibration points in Fig. 4 increases with temperature due to inhomogeneities of the camera's chip and the vignetting of the objective which cause a different sensitivity for every pixel.

The advantage of the method presented in this publication compared to previous works [4, 5] is that more than two background settings can contribute to the temperature determination. Furthermore, the signal to noise ratio can be increased twofold: images can be averaged at a fixed background temperature and images can be recorded at many different background temperatures. Since the object's temperature is determined from the offset *b*, considering more than two background temperatures leads to a significant advantage for objects with a wide range of different temperatures. Additionally, there is no need for optimisation to a single temperature as was the case for example in [5]. The full temperature range is made accessible by interpolation between all the background temperatures where data is available. Of course, the accuracy increases with the number of data points which means that the images at a given background temperature do not have to be averaged by themselves (though it still might be a good idea, depending on the shot-to-shot fluctuations). Exemplary data and a linear fit according to Eq. (17) are shown in Fig. 5. This is a typical example with six different background temperatures. Each data point is the average of 49 images with spray and 49 without.

If an estimation of the errors on the single data points is possible, these errors should be treated according to standard error propagation combined with Eq. (17) and then used as weights for the linear fit. Generally, in this way some of the problems due to the linearization of the fit can be circumvented. Nonlinear transformations combined with linear fits generally change the relative importance of individual data points. A nonlinear fit according to Eq. (17) which varies  $T_{\text{eff}}$  was evaluated as well. However, it was considered to be too slow as the calculation time dramatically increases with the complexity of the fit.

A map of the obtained emissivity and temperature is displayed in Fig. 6. The eight spray cones can be clearly differentiated in the temperature distribution and the measured temperature range corresponds to the range between the



Fig. 6: The emissivity (left panel) and the effective spray temperature (right panel) of an eight-hole injector calculated according to Eq. (17). The injection conditions are 200 bar rail pressure, 110°C fuel temperature, 4.0 bar absolute gas pressure and 250°C gas temperature. The fuel is n-heptane.

injection and gas temperature. The image quality can be further increased by setting thresholds for minimal emissivity and maximal statistical error of emissivity and temperature. The motion blur due to the integration time of  $25 \,\mu s$  is approximately 10 pixels in the vicinity of the injector.

It has been observed in the evaluation of recent data that it is not wise to derive the calibration intensity  $I_{cal}$  from the images or theoretical predictions directly. The reason for this is that the filter is not specified precisely enough to carry out the integration required for Eq. (9) directly and that the gathered data is usually quite noisy. The accuracy of the temperature determination according to Eq. (17) depends on the inversion of  $I_{cal}$ . Hence it is advisable to measure the calibration function precisely which is a time consuming process.

One possible solution would be to use a single, pre-recorded standard calibration curve. However, this is not possible because of long term drifts and variations from day to day. A combined method is proposed to decrease measurement time: A standard calibration curve  $I_{cal,0}$  is obtained for a wide and finely resolved temperature range using the same optics with a high number of averages for each calibration temperature. The actual measurements are then carried out with a limited but current calibration  $I_{cal}(T)$  that is then mapped to the standard calibration curve using another linear fit. Thus, the accuracy of the temperature determination is not dominated by the inversion of  $I_{cal}$ , but by the accuracy of the linear fit which has only two degrees of freedom. The uncertainty of the fitted variables can be decreased by averaging  $I_0$  at two or more background temperatures which is achieved rapidly. Additionally, slight changes in the integration time of the camera can be easily accounted for.

If the spray's emissivity  $\varepsilon$  including its statistical and systematic uncertainty is not too close to unity, Eq. (7) can be inversed to obtain a map of the integrated absorption or emissivity coefficient. Assuming cylindrical symmetry, the line integral can be converted to the absorption power  $\alpha$  using the Fourier transform based Abel inversion given in [6]. The inversion relies on the spray being at least partially translucent. However, this condition is neither fulfilled for the observed hollow cone sprays nor for the completely evaporated fuel after the injection. Exemplary reconstructions were performed but are not shown here for reasons of brevity and because the errors were disproportionally high.

## 5 Simulation

The challenges in thermography of fuel sprays are the droplet's high speeds combined with their partial translucency. In order to interpret the experimental results, realistic simulations of the infrared radiation interacting with the spray are helpful, especially if the local absorption and extinction are unknown or if it is not known whether the observed signal originates from droplets or vapour. In the scope of this contribution two techniques are used: Inverse Ray Tracing and Mie scattering calculations.

To understand the images and to evaluate the contributions of scattering, absorption and thermal radiation a MATLAB based ray tracing tool is employed. Since infrared light can be emitted by each point in space, light rays are traced back from the detector towards their respective source. At every node there are multiple possibilities: the beam can change its direction (scattering, refraction, reflection) or change its intensity (absorption, emission). Usually a combination of all effects has to be taken into account. Using the respective scattering, absorption and emission coefficients obtained from Mie theory, the infrared image of a given spray can be simulated.

Mie theory is the far field solution of the Maxwell equations for the scattering of electromagnetic waves by spherical particles. For all calculations presented here such as Fig. 2, the original FORTRAN code from [7] is used. For several reasons the simulation results should be evaluated carefully: Mie theory does not hold in the case of high droplet densities due to its far field nature, for performance reasons the angular distribution of the scattering is currently not taken into account, scattering and absorption cross sections depend on the local refractive index of the surrounding gas



Fig. 7: Both panels show a ray traced infrared image of a spray from an eight-hole injector simulated with AVL Fire. The fuel (353 K) is injected into hot and dense atmosphere (573 K, 6 bar). The left panel shows an image of the spray in front of a cold background (400 K). The right panel shows the same spray with a hot background (500 K).

which is for simplicity assumed to be nitrogen (e.g.  $n \approx 1$ ) and geometrical optics does not hold in the case of absorbing media [8].

The spray is simulated with AVL Fire [9] using the same boundary conditions as in the experiment. According to [10] an Octree based ray tracing algorithm is implemented using the droplet distribution obtained from the Fire simulation for the volume generation. A volume element is subdivided until there is neither gaseous nor liquid fuel present or the minimal length is reached. Equation (4) is then used to determine the influence of every volume element on the light ray. Rays are traced back until their accumulated emissivity  $\varepsilon$  defined by Eq. (7) is close to unity. Scattering is implemented by creating new light rays starting from random origins within the scattering volume element and with randomised directions. An exemplary simulation of the expected infrared images is shown in Fig. 7. The camera's intensity is assumed to be proportional to the number of photons per second. Especially near the leading edge of the spray vapour is visible. As in the experiment, there is high absorption where droplet density is high. Thus the spray is opaque in these regions. Similar to the experimental results, the intensity and hence the temperature near the injector is quite low.

#### 6 Results

Experiments with two injectors at ambient pressure and temperature and at an elevated pressure of 4 bar with a gas temperature of 250°C are presented in this publication. Furthermore, the effects of scattering of ambient light, fuel properties, the influence of the wavelength filter and the number of images in the averages are investigated.

A major disadvantage of the limitation to the small wavelength band around 3.4 µm can be seen in Fig. 4: At low temperatures the slope of the intensity is quite low which limits the overall performance of the algorithm. However, when the complete wavelength interval of the camera is used, the calculated temperatures are considerably closer to the temperature of the chamber – temperature differences of more than 20 K were not uncommon between the measurements with and without band-pass filter. This is as expected from the theoretical considerations of Sec. 2.

Several types of fuels have been used for the measurements. A comparison is shown in Fig. 8. As there is no complete calculation of the path of light for every experiment yet, the interpretation of the results must be done with care: It is unclear whether the signal is caused by the droplets or the evaporated fuel. Hence, evaporation models should not yet be ranked according to the results shown here. However, there are several indicators which suggest that the gas phase plays an important role. First, there is a considerable difference in the spatial distribution of the spray obtained with and without the C-H filter. Second, the residual gas can be seen quite clearly for a very long time in the chamber – even though it is constantly flushed with pure nitrogen. For n-hexadecane much less evaporative cooling is seen than for the other fuels with lower boiling temperatures (n-hexadecane has a boiling point of 579 K at 1.5 bar [11]). For further evaluation of this effect the ray tracing code will be used.

Two trends are clearly visible in Fig. 8: With the filter the spray appears larger and the measured temperature of

n-hexadecane, 370 K, no filter n-hexadecane, 370 K, with filter n-hexadecane, 400 K, no filter n-hexadecane, 400 K, with filter







Fig. 9: The left panel shows an injection of n-heptane at 370 K in front of a background at 363 K. The gas is conditioned to 520 K and 4.0 bar. The chamber temperature is 400 K. After the chamber temperature increases to 420 K another image set taken under otherwise identical spray conditions. The intensity difference is shown in the right panel. The panels are averages of 19 images with and without spray respectively.

the spray is increased. The reason for this effect is that the environment is significantly colder than the spray; a detailed discussion is given in Sec. 2. The shape of the spray changes from image to image because the injector can never be oriented in exactly the same direction when the fuel is exchanged. The apparent slight differences in spray shape are thus not an effect of the type of fuel used. In all experiments it is observed that the measured temperature and the spatial distribution of E10 and n-heptane are quite similar. Hence, n-heptane seems to be a good surrogate fuel for simulations where one component fuels are needed. n-Hexadecane evaporates only very slowly so that the single cones remain visibly separated throughout the injection event, and the lack of evaporative cooling also allows the liquid to remain at high temperature.

Generally, the emissivity of the sprays is close to unity which means that not much information from the inside of the spray cones can be obtained. Even in the vapour phase the (optical) density is high enough to seriously attenuate transmission of radiation from the background. This also results in a minimum delay between two injections of at least 15 s as residual vapour otherwise attenuates the infrared light in the chamber even though the pressure chamber is flushed with a constant 1.2 kg/min stream of heated nitrogen.

There has not yet been any systematic comparison of the data with simulations. But the general trend is as expected: The injected fuel enters the chamber approximately at the temperature of the injector. As it progresses through the heated nitrogen it heats up. After about 1 ms the final temperature of the evaporated fuel is – regardless of its molecular composition – within 20 K of the ambient temperature.

To evaluate the influence of scattering the same images are taken twice with a different chamber temperature. It can be seen that an increase of the wall temperature from 400 K to 420 K results in an increase of the intensity by about



Fig. 10: These panels show the influence of using multiple images at the same background temperature. The reference uses five different background temperatures with 19 images with and without spray (190 images in total). The panels show the difference in the temperature compared to 19 images per background temperature when the algorithm is limited to 18, 14, 10, 3, 2 or 1 image per background temperature. The number in the top right corner of each panel is the root mean square of the temperature deviation to reference case.

5 counts in the space occupied by the spray, as is displayed in Fig. 9. This is a bit less than half the value expected from a perfect mirror and the values shown in Fig. 4. However, considering the scattering to extinction ratio given in Fig. 2, this result is not too surprising even if the evaporated fuel partly compensates for the large expected scattering cross sections. In Fig. 9, the left side of the spray appears to be warmer than the right. This is the case because the emissivity of the chamber is not completely equal between left and right. Also the heated nitrogen flows towards the left side of the chamber. For a detailed analysis of the errors due to scattering the ray tracing tool will be used more extensively in the future.

To evaluate the shot-to-shot fluctuations of the injection, the number of averages at each background temperature used for the evaluation of the temperature was changed. A full set of 19 images at each background temperature was recorded, but image processing can be limited to a given subset to investigate the influence of the considered number of images. Generally, it can be observed that the temperature map converges when the number of averages increases. As shown in Fig. 10, the influence of a pair of frames (with and without spray) is around 0.4 K for a typical injection. Due to shot-to-shot variations, the difference from the reference is quite high when the algorithm is limited to one or two sets of images per background temperature. This deviation decreases with increasing number of averages. The algorithm performs quite poorly for two and three averages since the standard deviation which is used as a weight in the fit of Fig. 5 is not yet reliable. Without any averages (bottom right panel) the algorithm falls back to a linear fit without weights. The deviation is essentially not an effect of camera noise but of shot-to-shot fluctuations of the injection itself since there is a clear structure in the temperature difference.

Effects from motion blur and optical resolution have not been considered so far but they were discussed in detail in [4]. There is no indication yet that these effects seriously affect the calculated temperatures or emissivities. On one side, care has to be taken close to the injector where the temperature gradients are usually quite large. On the other side, the temperature distribution at a given distance from the injector does not change very quickly with time. This would seriously limit the interpretation of the data. For most of the injection processes presented in this paper, temperature map videos with a frame rate of apparent 20,000 fps were generated from multiple injections. Temporal gradients can be observed; however they are small in the developed region where the emissivity is also nearly constant. When the emissivity changes rapidly, a sudden change of the temperature is generally also seen. This occurs for example at the beginning and end of the injection and near the spray tip – these regions can be identified easily in visible light or infrared images.

### 7 Conclusion

Considerable improvements are made in the Differential Infrared Thermography (DIT) of fuel sprays. The use of the camera's digital counts instead of its temperature readings, the employment of wavelength filters and the evaluation of the data with a linear fit method leads to more accurate and robust results than a  $T^4$ -approach based on two background temperatures. On one hand, DIT is not limited to a small temperature range anymore. On the other hand, the use of a band pass filter increases the overall accuracy of DIT. The general trends that are expected can be reproduced: Depending on the gas temperature the droplets heat up or cool down and eventually reach the gas temperature. Due to the wavelength filter the vapour has a strong influence on the detected temperature and can be identified.

A very important step forward in the evaluation of the DIT images will be reached once a systematic analysis has been carried out combining the ray traced CFD simulations with experimental results.

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