Evaluation of Droplet Evaporation in Gasoline Sprays by Differential Infrared Thermography

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Abstract This work examines gasoline direct injection and related sprays inside a heated pressure chamber with Differential Infrared Thermography (DIT). In contrast to conventional thermography, the emissivity of a fuel spray is assumed to be variable and not known a priori. Both 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 for averaged images. The results from DIT are compared to CFD simulations carried out with AVL Fire. Data from Fire is post-processed using a Mie scattering code and a MATLAB based infrared ray tracing algorithm. In this way, the contributions from the evaporated fuel (which emits and absorbs radiation in the infrared and thus contributes significantly to the images) and the liquid droplets can be determined. Based on this information, an infrared image of the simulated spray is calculated. This makes a direct comparison of experiment and simulation possible. The influence of several parameters such as fuel temperature and evaporation models are evaluated and matched up against to the experimental results. **Keywords:** Differential Infrared Thermography, Gasoline Direct Injection, Spray

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 (GDI) system. However, GDI provides additional degrees of freedom which increase the overall complexity of the engine. Furthermore, the exact properties of the spray have a much higher influence on the subsequent combustion process. Engine development thus 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, which is quite important not only for the internal cooling of the engine but also for the distribution of fuel vapour and remaining liquid droplets. Thus, 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 evaporation of fuel droplets.

The aim of this paper is to generate synthetic differential infrared thermography (DIT) images of a gasoline spray from a fluid dynamic simulation and subsequent ray tracing. These images are then compared to available experimental images. The simulation allows to perform parametric variations and thus to assess these parameters' influences on an actual DIT experiment. Additionally, it is assessed whether it is possible to falsify any of the implementations of the evaporation models used for the simulations.

2 Theory

The theoretical foundation of this paper can be divided into three parts: transport phenomena of light in dense media, simulation of sprays and differential infrared thermography. While all three parts are relatively well established individually, it is a novel approach to combine them and to use the resulting information to establish both the capabilities and the limitations of DIT and spray simulations.

Differential Infrared Thermography (DIT) DIT is a method for evaluating the temperature of a semitransparent object with unknown emissivity ε . As the name suggests, the method relies on infrared radiation and the difference between several measurements to determine a temperature: Every object emits radiation according to its temperature (Planck's law) and its ability to absorb and emit radiation (Kirchhoff's law). If a semi-transparent thin slab of thickness *d* is observed in front of a temperature-controlled black body, there is extinction of background light (intensity I_0), scattering of ambient light ($I_{ambient}$) onto the detector and thermal emission (I_{self}) of the observed object. According to Kirchhoff's law, the probability of spontaneous emission is equal to the probability of absorption. Throughout this paper, absorption is considered to be the net difference of two concurrent processes: the induced absorption of photons and the stimulated emission of photons.

$$I = (-I_0 \sigma_{\text{ext}} + I_{\text{ambient}} \sigma_{\text{sca}} + I_{\text{self}} \sigma_{\text{abs}}) nd$$
(1)

The cross sections σ give the scattering (index "sca"), absorption ("abs") and extinction ("ext" sum of scattering and absorption) probabilities of the molecules with number density *n*. In the case of vanishing scattering this problem can be solved analytically. The solution for a non-scattering object with arbitrary number density in front of an ideal black body at temperature T_{bg} is given by an apparent emissivity ε and an apparent temperature T_{app} of the observed object (for details see [1]):

$$\Delta I = -\varepsilon I_{\rm bb} \left(T_{\rm bg} \right) + \varepsilon I_{\rm bb} \left(T_{\rm app} \right) \tag{2}$$

Here, ΔI is the intensity difference between the signals of the lone black body and of the object in front of the black body. I_{bb} is the intensity that would be detected from a perfect black body with an emissivity of unity. The apparent temperature T_{app} is given by a weighted mean along the path of light. By taking $I_{bb}(T_{bg})$ as a dependent variable and measuring ΔI for different background temperatures with an infrared camera, a simple linear fit yields the emissivity ε and $I_{bb}(T_{app})$. The temperature T_{app} is then obtained by an inversion of I_{bb} . For sufficiently smooth temperature distributions, the apparent temperature is approximately given by the temperature at an optical depth of unity (extinction by 1/e).

The same algorithm can be applied to the case of a scattering object. However, care has to be taken in the evaluation of the results. Assuming that all scattering of background light is directed away from the detector, the first part of Eq. (2) remains correct assuming an extinction of the background signal with the overall extinction power ε . The second part should be replaced by two terms: The emission of light according to the absorption power and the scattering of ambient light according to the scattering power. However, the latter two cannot be separated. The sum of absorption and scattering has to be the extinction for energy to be conserved. So the term $\varepsilon I_{bb} (T_{app})$ is not replaced but simply reinterpreted as an apparent temperature due to the temperature of the surrounding environment (scattering) and the object temperature (thermal emission). As the DIT algorithm cannot deduce the amount of scattered light, it is inherently difficult to obtain reliable temperature information in a fuel spray. It is one of the aims of this publication to address the nature of the apparent DIT temperature in terms of the boundary conditions.

A typical experimental set-up used for DIT is shown in Fig. 1. A temperature stabilized black body with specified emissivity serves as a background light source. The fuel spray is injected with an eight-hole Bosch injector into a chamber that is filled with heated and pressurised nitrogen. In order to maintain the temperature, the chamber is constantly flushed with heated nitrogen at a rate of the order of 10 g s^{-1} . The injection chamber is equipped with CaF₂ windows that are transparent in the relevant parts of the infrared spectrum (given by the sensitivity of the camera, approximately 2 to 5 µm). The algorithm for DIT is a bit more complicated in the presence of windows and a background with an emissivity of less than unity, but the general idea of Eq. (2) remains. Details can be found in [1].

In a realistic fuel spray environment, liquid droplets of constantly changing number density and size distribution are surrounded by a cloud of evaporated fuel of constantly changing partial pressure. Depending on the wavelength interval chosen for the observation, the vapour phase may be clearly or barely visible. Due to scattering, the droplets are always visible. For the apparent temperature from DIT to be close to the droplet temperature, the liquid has to have a high imaginary value of the refractive index – otherwise no radiation is emitted from the droplets. The apparent temperature is nearly equal to the temperature of the surroundings in



Fig. 1 The experimental set-up used for the DIT measurements. Adapted from [1].

the case of vanishing absorption. Ideally, a wavelength should be chosen for droplet temperature measurements where the vapour phase is translucent and the liquid phase is opaque. However for conventional fuels, the two are correlated which limits the evaluation of droplet temperatures. For molecules which have a different 3D structure in liquid and vapour phase, a pure droplet temperature determination could be achievable.

Scattering can be excluded if gaseous injections are considered. Figure 2 shows the temperature distribution of a methane injection in false colours. The saturation of the pixels is given by their apparent emissivity. As methane has an emissivity with distinct peaks and valleys that reach nearly zero within the wavelength interval of the camera, the maximum emissivity is not unity, but approximately 0.3. Some part of the spectrum is absorbed while the rest is transmitted without any losses. For more complex alkanes, the individual absorption lines will be broadened and thus overlap. Accordingly, the observed maximum emissivity is very close to unity in sufficiently dense n-heptane vapour regions.

The injector in Fig. 2 has one large central hole and six smaller holes that are oriented in a ring around the central hole. This multi-jet structure is clearly visible in the temperature distribution just below the nozzle. A vertical cut through the central axis of the large central jet is shown in Fig. 2b. The apparent emissivity shows the formation of equally spaced Mach discs below the injector (the injection is a choked and supercritical nozzle flow with a subsequent free expansion). The apparent temperature is very low initially due to the strong cooling caused by the fast expansion of the methane jet. The increase of the CH_4 temperature due to mixing with hot



(a) 2D visualisation for three time steps.

(b) Vertical cut through the central axis of the gas jet at 900 µs.

Fig. 2 Temperature distribution in a methane jet with a small cross flow of heated nitrogen (white arrow). Scaled to a maximum emissivity of 0.3. $p_{\text{fuel}} = 15 \text{ MPa}$, ambient conditions 0.4 MPa and 520 K, N₂ flow 11 g s⁻¹, integration time 300 µs, CH-filter (at 3.4 µm). Injection times are given relative to the start of energization of the injector.

nitrogen is visible as well. More than 80 mm downstream from the injector the emissivity is very low, thus the temperature precision is low as well and the signal appears quite noisy. The observed temperatures can reach values above the pressure vessel temperature of 520 K as the injected nitrogen is pre-heated to 650 K to maintain the equilibrium temperature within the pressure vessel.

Lorenz-Mie Scattering The transport of electromagnetic waves can be calculated with different methods according to the problem in question. Beginning with quantum electrodynamics and ending with geometrical optics, a wide range of toolboxes is available. As image formation in DIT of sprays is governed by the transport of light in a heterogeneous medium of varying density, a formalism which can handle scattering and absorption should be chosen.

The scattering and absorption of a planar wave of light at a spherical particle with complex refractive index is a well-known problem in the literature and can be solved analytically with Maxwell's equations. The far-field solution of the problem is commonly called (Lorenz-) Mie scattering. The incoming plane wave is attenuated and its energy is redistributed into all solid angles. For a volume with thickness *d* and a homogeneous number density *n*, the transmitted intensity *I* of an incoming wave I_0 is given by the Beer-Lambert law:

$$\frac{I}{I_0} = \exp\left(-\sigma_{\text{ext}}nd\right) \tag{3}$$

The extinction cross section σ_{ext} is of the same order of magnitude as the geometric cross section of the scatterers. In a classical analogy, the extinction cross section is the geometric cross section of a hypothetical hard sphere hit with small bullets that has the same effect as the scatterer in question.

The conservation of energy requires that the extinction cross section is the sum of absorption and scattering:

$$\sigma_{\rm ext} = \sigma_{\rm abs} + \sigma_{\rm sca} \tag{4}$$

The scattering of electromagnetic waves by a spherical particle is in general not isotropic and is given by the differential scattering cross section. All these cross sections are given by Lorenz-Mie scattering and are computed with a code from [3]. For n-heptane in air interacting with light at $3.4 \,\mu$ m, the ratio of the three total cross sections to the geometric cross section of the droplets is shown in Fig. 3b. It is a well-known phenomenon that the total extinction cross section is twice the geometric cross section for large droplets. However, as scattering by large particles is mostly forward directed this effect is usually not observable. Especially for droplet radii in the order of magnitude of the wavelength of the light, there are distinct resonances of the



(b) Mie cross sections normalized to the geometric cross section at a wavelength of 3.4 μm.

Fig. 3 Index of refraction and Mie scattering of n-heptane.

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cross section ratio. The ratio of scattering to absorption is influenced by the refractive index of the liquid phase. Accordingly, it is important to choose a region with a high imaginary part of the refractive index so that scattering is minimal relative to absorption. A plot of the refractive index of n-heptane is shown in Fig. 3a. The shown camera filter is adjusted so that it covers most parts of the absorption band of C-H-bonds.

Spray Simulation Spray simulations can be performed with different levels of complexity. As the aims of this paper are to show the feasibility of the method and to assess the capabilities of DIT, a relatively simple model of a multi-hole injector is simulated in AVL Fire. The model is loosely based on [4]. It does not consider any droplet breakup models but is sufficiently correct to predict the main influence factors for infrared images: Liquid penetration lengths and the approximate distribution of evaporated fuel. Essentially, real primary break-up is skipped. The result of a primary break-up model - a droplet size distribution - is entered a priori and used to initialize the remaining calculations. For the resulting droplets, the aerodynamic Weber number is mostly below ten (except for some droplets very close to the nozzle outlet). As a consequence, these droplets are stable and no substantial further aerodynamic break-up occurs.

The droplets are not modelled individually but in packages which typically represent about 10^4 actual droplets. The direction of the spray plumes and their opening angles are taken from the injector design and established geometry correlations. The spray is initialized with a normalized Nukiyama-Tanasawa droplet distribution function according to [5]. The probability density *f* is given by a three parameter *m*, *n*, *p* function:

$$f(D) = \frac{nD^p}{m^{p+1}\Gamma\left(\frac{p+1}{n}\right)} \exp\left(-\left(\frac{D}{m}\right)^n\right)$$
(5)

Given the three parameters a Sauter mean diameter D_{32} can be calculated:

$$D_{32} = m \frac{\Gamma\left(\frac{p+4}{n}\right)}{\Gamma\left(\frac{p+3}{n}\right)} \tag{6}$$

PDA-measurements have shown that the Sauter and count mean diameter should be approximately $9 \mu m$ and $6 \mu m$ respectively, so three sets of different parameters for the droplet distribution are chosen as shown in Fig. 4. The parameters of the first distribution are tweaked so that the count mean diameter is $6 \mu m$ and that *n* and *p* are integer numbers. The second distribution uses the more conventional value p = 2, has nearly the same count mean diameter and is generally a bit wider. However, the difference between the first two distributions is



(a) Graphical representation of the droplet distributions. The delta distribution is not shown.

m (µm)	n	р	$D_{10} (\mu m)$	D ₃₂ (µm)
1.5	1	3	6.00	9.00
3.21	1.29	2	5.97	9.00
1.5	0.864	1	4.11	9.00
-	-	-	9.00	9.00

(b) Parameters of the four droplet distributions. The last row is a monodisperse δ -distribution at 9 µm. D_{10} is the resulting count mean diameter and D_{32} is the resulting Sauter mean diameter.

Fig. 4 The droplet distributions compared within this publication.

very small. The third distribution is the most extreme and is heavily skewed towards small droplets with a large tail of large droplets to maintain a Sauter mean diameter of 9 μ m. Additionally, a δ -distribution fixed at 9 μ m is also tested.

All simulations and experiments are performed with n-heptane as a surrogate fuel to circumvent problems with unreliable physical parameters such as the refractive index. Especially evaporating gasoline droplets show a continuous change of their physical parameters due to the different boiling points of the constituents. Additionally, simulation models are more reliable for single component fuels.

Ray Tracing To assess the influence of parameters that cannot easily be changed in the experiment, an inverse ray tracing algorithm is used to generate synthetic DIT images from the fluid dynamics simulation results. The algorithm traces rays from the camera backwards to the respective source as the forward problem is quite computation time intensive in the infrared where every object is a source of light.

Before the actual algorithm is used, the Fire data is used to generate an octree according to [6]: An initial cube with 20 cm edge length around the simulated spray is checked for droplet and vapour content. If the corresponding optical density of the gas is greater than 1×10^{-5} or if there are any droplets present it is subdivided into eight smaller cubes. This process is repeated for each child cube until the cube in question is either empty or has an edge length below 0.5 mm. For each volume element the average absorption due to the gas phase and the absorption and extinction due to droplets are saved to memory. The averaged temperatures are saved as well and are used together with the absorption strength for the calculation of the emission.

Using a hypothetic pinhole camera geometry 1 m from the spray, 1000×1000 light rays are initialised that cover an area of $16 \text{ cm} \times 16 \text{ cm}$ (resulting in a full opening angle of 9°). Each ray is traced from the camera chip in a straight line until it hits a cell that either absorbs or scatters light. Refraction is not taken into account. The optical density and temperature of the gas in the cell is then used to assess the influence on the detected intensity on the camera pixel. The same procedure is used for the absorption and emission due to droplets. In the case of vanishing scattering, the ray is attenuated according to the overall optical density and traced to the next volume element where the process is repeated until the ray is attenuated to 10^{-4} of its original value or until it hits the boundaries of the largest cube and hence the walls of the simulation volume. It is distinguished whether the light ray hits the circular background which is used for DIT or the other walls of the boundary. In the case of scattering, the attenuation due to scattering is calculated and then random rays (isotropic distribution) are started from within random positions in the scattering volume. The number of rays depends on the attenuation due to scattering and is given by the product of the attenuation and 1000, but does not exceed 100. The assumption of isotropic scattering is not strictly correct, but neither is the spatial droplet distribution within Fire (droplets are modelled as large packages) – so a correct simulation regarding scattering is not possible. For a scattering distribution with an angular dependency, the number of scattered rays required for an adequate simulation would also be considerably higher.

The contribution to the intensity of the light rays is calculated from the remaining strength of the light (after all previous attenuation), the optical density of the volume in question and Planck's law of radiation for photons. While in principle variable wavelengths could be calculated and tested, all results shown are based on a wavelength of 3.4 µm. This is approximately the central wavelength of the CH-filter in the IR-camera. Planck's law of radiation is integrated over the full width at half maximum of the filter assuming an idealized rectangular filter. As it is sufficient to calculate a value that is proportional to the camera intensity, the sensitivity of the camera is not considered. The resulting signal on the camera chip is independent of the distance to the object and its inclination, accordingly both are not considered in the calculation. Strictly speaking this assumption is only valid if the image of the observed area on the camera sensor is larger than a single pixel. Accordingly, gradients in the simulation may appear sharper than in the experimental data and high spatial frequencies cam be down converted into lower frequencies (spatial beat patterns).

3 Visualisation

The general trends of the simulation are verified with visible light Mie scattering visualisations. A high speed camera observes the injector from below with 67 500 fps while a metal halide lamp provides illumination from



Fig. 5 Top row: High speed images of visible light Mie scattering averaged over 15-20 injections at different ambient conditions, 1.5 ms after optical start of injection. Bottom row: Accumulated droplet mass of simulated spray plumes. $p_{fuel} = 20 \text{ MPa}$

the side. The droplets have a high scattering cross section and are thus quite clearly visible while the black background and the vapour cause a very weak signal and are thus nearly invisible. The used eight hole injector has different inclination angles for each of the holes. Accordingly, it is expected that the projected penetration visible from below is different for each spray plume. A simultaneous plot of the spray images and simulated liquid mass results is shown in Fig. 5. The asymmetry of the injector accommodates for the proximity of the spark plug in a real engine. The trend that the penetration decreases with increasing pressure and temperature is visible quite clearly, both in simulation and experiment. The simulated spray plumes show a slightly larger projected penetration but have a slightly lower cone opening angle. Overall the expectations from the injector design agree with the experimental data.

A similar comparison can be performed with infrared images. However a view from the side is chosen for all infrared images, as temperature controlled background, spray and camera have to be aligned in a straight line for DIT to work reliably. An exemplary image as it is recorded by the camera ($640 \times 512 \text{ px}$, integration time 25 µs, CH-filter around 3.4 µm) is shown in false colour in Figs. 6a and 6b. Cold fuel is injected into a hot environment with a background at intermediate temperatures. Accordingly, the spray appears to emit few



Fig. 6 Exemplary experimental and simulated IR images. Camera images have a resolution of 640x512. Ambient pressure 0.4 MPa, 300 μ s after start of injection, $T_{Wall} = 415$ K, $T_{BG} = 443$ K, $T_{fuel} = 370$ K.

photons (low intensity) right below the injector and a high number of photons further downstream, especially at the edges of the spray plumes. There is a region where background and spray are not discernible because they radiate with the same intensity. Ideally, this would directly be the region where the apparent spray temperature is equal to the background temperature. However, in the case of a background with an emissivity lower than unity that is located outside of the pressure chamber (i. e. with windows), the temperature determination requires to take account the transmissivity of the windows and the emissivity of the black body. Details can be found in [1].

The same image can be generated from simulation results with the ray tracing algorithm discussed in Section 2. The original ray tracing result is an image with a resolution of 1000×1000 px which is cropped to show a similar region as the IR camera images. The general trend of the intensity is quite similar in experiment and simulation. Probably, turbulence and air motion that are generated by the injection cause the gas distribution to be wider in the experiment than in the simulation. The distribution and intensity of the gas starting 15 mm below the injector changes noticeably from injection to injection while the simulation is only capable of calculating average values. The wide distribution of fuel vapour in the experiment is expected and can be confirmed with a Schlieren set-up [7]. The large influence of the initial turbulence on the vapour penetration length is a known problem in simulations of Diesel pressure chamber experiments [8]. Vapour and liquid phase cannot be clearly distinguished in a DIT image. However, for the operating conditions presented, visible light Mie scattering experiments and broadband DIT images are available; they essentially show only the liquid phase of the fuel.

The injection is performed into different ambient conditions. Typical operating conditions are chosen for the visualisations in Fig. 7. Pressure and temperature correspond to typical values during the compression cycle of an Otto engine. The images are created with a DIT algorithm that is used with single images at five to seven background temperatures. Each pixel is calculated in an HSV colour space. The pixel hue (H) is set by the apparent temperature and the pixel saturation (S) is calculated from the emissivity. Unless noted otherwise black corresponds to an emissivity of zero and bright colours are equal to an emissivity of one. The HSV value (V) is always maximal. The colour code of the hue is given by the respective colour bar.

Figure 7 shows a good correspondence between simulation and experiment. The reduction of the penetration with increasing temperature and pressure and the final temperatures detected at the spray tips are very



Fig. 7 Comparison of DIT images and infrared ray tracing at different ambient conditions. $T_{\text{fuel}} = 370 \text{ K}$, $p_{\text{fuel}} = 20 \text{ MPa}$

similar in experiment and simulation. As seen in the single images in Fig. 6, the vapour distribution is larger in the experiment than in the simulation. The temperature just below the injector is usually lower in the experiment than in the simulation. The reason is possibly that the pressure chamber is equipped with three windows, two of which are made out of CaF_2 . These windows transmit radiation from the 295 K warm laboratory into the pressure chamber, thus reducing the effective wall temperature compared to the temperature measurements of the pressure vessel's walls that were used to initialize the simulation. Due to a background subtraction, the wall temperature is not visible in the final experimental data while it is visible in the simulation where no background subtraction is necessary. The images in Fig. 7 are scaled to show the same region. The reference point at 0.9 MPa and 620 K could not be visualised with DIT as there were doubts on the ability of the CaF_2 windows to withstand these high gas temperatures and pressures.

It is also worth noting that the experimental set-up is not capable of measuring temperatures below 340 K. During the integration time of $25 \,\mu\text{s}$ the amount of photons emitted is not high enough to see a difference in the intensity. As a direct consequence, the accuracy of the temperature measurement is quite poor at such low temperatures: It relies on the derivative of the intensity with respect to temperature.

The signal intensity can be increased if the images are taken without a wavelength filter, i. e. if the whole sensitive wavelength interval of the sensor (approximately 2 to $5 \,\mu$ m) is used. Exemplary images and a simulation at 3.4 µm are displayed in Fig. 8. It is worth noting that the increased temperature below the injector is clearly visible in the image with filter while it is hardly discernible in images taken without the filter. Additionally the left and right edges of the spray appear smoothed out without a wavelength filter. This effect is caused by the lower absorption power of the fuel in the wider wavelength band whereas the absorption is quite high within the region of the filter at 3.4 µm. The temperature far away from the injector seems to be predicted better by the experiment without a filter. However, this is merely an effect of the scattering of the droplets: Rather than detecting the fuel temperature, the wall temperature has a large influence on the measurement result. The same result was seen for higher gas temperatures in [1]. As the case presented in Fig. 8 has equal gas and wall temperature, the resulting apparent spray temperature seems to be correct. The signal intensity with filter is quite low which leads to a very "grainy" image impression.

4 Sensitivity Analysis

The apparent temperature reconstructed with a DIT algorithm is a mean temperature over the path of a light ray. Accordingly, it is important to assess the sensitivity of the apparent temperature on the relevant parameters. The list of possible influences is numerous, but the most important ones shall be addressed in this section. To begin with, there are parameters of the surroundings, for example the wall temperature. Then there are parameters of the spray such as droplet size distribution and its evaporation. Additionally, there is also a dependence on the refractive index of the fluid and the absorption power of the gas.



Fig. 8 Comparison of DIT images with and without wavelength filter and infrared ray tracing at $3.4 \,\mu\text{m}$. $T_{\text{fuel}} = 370 \,\text{K}$, $p_{\text{gas}} = 0.15 \,\text{MPa}$, $T_{\text{gas}} = 300 \,\text{K}$, $T_{\text{wall}} = 300 \,\text{K}$, $300 \,\mu\text{s}$ after start of injection, averaged over five background temperatures with 19 injections each.



Fig. 9 Influence of the scattering order on the apparent temperature at different times after the start of the injection. All panels show the difference to triple scattering $T_n - T_3$. Gas conditions are 0.6 MPa and 570 K, $T_{\text{fuel}} = 370$ K, $p_{\text{fuel}} = 20$ MPa.

Before any of these parameters can be discussed it is vital to evaluate the influence of the maximum scattering order that is calculated in the ray tracing programme. In reverse ray tracing, the scattering order is the maximum number of times that a photon can be reflected by droplets. Hence, a scattering order of zero means that no scattering is considered at all. If a light ray is scattered more often than the maximum scattering order, its intensity is set to the wall intensity. For practical reasons the scattering cannot be extended to arbitrarily high orders: Already at a value of two, the computation of a single image takes a few hours on a CPU with 3.6 GHz. The computation time increases exponentially with each scattering order as each scattering event starts approximately 100 new light rays. The change in apparent temperature relative to a scattering order of three is shown in Fig. 9.

As expected, the influence of the maximal scattering order is highest where evaporation is lowest: At early time steps after the start of the injection, very close to the injector and at the tips of the individual spray plumes. In the experiment, the tips of the plumes are surrounded by a large cloud of gas. However, as Fire simulates droplets in large packages, larger droplets start to accumulate at the tips of the spray plumes. At 950 µs after the start of injection, the difference between no scattering and single scattering is below 5 K and between single and triple scattering, the difference is smaller than 1 K. Accordingly, all ray traced images within this paper are performed with a maximal scattering order of one unless noted otherwise. As the wall temperature is 115 K lower than the gas temperature, the spray appears colder for higher scattering orders.

Wall Temperature A very interesting test is to change the temperature of the pressure chamber's walls. Unfortunately, this cannot be done experimentally: The wall is heated up by the gas inside the chamber, but its temperature is not stabilised. However, it reaches a stable state well before the two hours required for a DIT image acquisition. This final temperature is largely dominated by the gas temperature. The influence on a single infrared image has been demonstrated in [1], the change of the detected intensity due to the change of wall temperature is approximately as significant as expected for droplets with a scattering-to-extinction ratio of 0.5.

Figure 10 illustrates the influence of the wall temperature. The first panel shows a hypothetical case where the temperature controlled background extends all the way around the spray. Accordingly, scattering from the walls of the pressure chamber towards the camera is interpreted as an increased transmission and the apparent emissivity of the spray is well below unity right at the injector tip. Further downstream where most of the fuel is gaseous, the emissivity of the spray is close to unity and the apparent temperature is mostly equal to the vapour temperature. An extrapolation of the Antoine equation of n-heptane to 0.6 MPa yields a boiling temperature of approximately 450 K [9]. The droplets start at approximately 370 K and have a wet bulb temperature in the

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Fig. 10 Influence of the wall temperature on the apparent temperature at 0.950 ms after start of injection, gas conditions are 0.6 MPa and 570 K, $T_{\text{fuel}} = 370$ K, $p_{\text{fuel}} = 20$ MPa.

simulation that is approximately 380 K – with the exception of droplets at the tip of the spray which can become significantly warmer. Neither case in Fig. 10 is able to reproduce droplet temperatures near 380 K. In fact the apparent temperature is very close to the gas temperature. The fuel vapour temperature depends on the mixing with the surrounding air. The simulated vapour around the spray plumes has a temperature very close to the nitrogen temperature. This temperature is reproduced in all ray traced images and in the experiment.

Panels two to five of Fig. 10 show the influence of a wall temperature that is constant during the DIT measurement. Especially the near-nozzle region is quite sensitive to the wall temperature, because of the high influence of the scattered radiation. It should be noted that even a hypothetical wall temperature of absolute zero is not able to reproduce the droplet temperature. The reason is quite obvious: Scattering reduces the amount of light passing through the spray but not its emissivity. Accordingly, the inversion of the calibration curve uses an intensity that is too low. Using Planck's law for the expected intensity and assuming a droplet with a scattering to absorption ratio of unity, the expected apparent temperature can be calculated. Using a wall temperature of 300 K and a single droplet at 400 K, the resulting apparent temperature is 6 % lower than the droplet temperature. This general trend is visible in the apparent DIT temperatures of panels two to five in Fig. 10: While a low wall temperature means a slightly lower apparent temperature than in the reference case (first panel), a high wall temperature increases the apparent temperature at the root of the spray dramatically. So as a rule of thumb, the wall temperature should be set a few Kelvin below the temperature of interest if it cannot be set to the background temperature.

Droplet Distribution The scattering cross section depends largely on the droplet size, see Fig. 3b. Accordingly, sprays based on different droplet size distributions (see Fig. 4) have been simulated with Fire. The resulting apparent temperature maps are shown in Fig. 11. Since D_{32} is equal for all distributions, the results



Fig. 11 Influence of the droplet distribution on the apparent temperature at 0.950 ms after start of injection, gas conditions are 0.6 MPa and 570 K. The droplet distributions of Fig. 4 are used for the initialization, D_{32} is fixed to 9.0 µm. $T_{\text{fuel}} = 370 \text{ K}, p_{\text{fuel}} = 20 \text{ MPa}, T_{\text{wall}} = 450 \text{ K}.$

look astonishingly similar. In a direct comparison, very slight differences in spray penetration are seen. However, no general trend towards higher or lower temperatures can be extrapolated from the simulations. There are of course temperature differences which are in the range ± 10 K. Since Fire simulates droplets in packages of a few thousands, a lot of these differences are possibly due to the initial droplet initialization and thus noise introduced by the random number generator. One general trend can be observed though: Larger droplets have a longer lifetime and thus the tips of the spray plumes appear colder when the droplet distribution is changed to larger droplet diameters. However because of the slightly different penetration, a subtraction of evaluated temperatures as in Fig. 9 is not a suitable way to compare the results. Considering spray simulations, it is a reassuring fact that there is no clear dependence of the apparent temperature on the exact droplet distribution as long as D_{32} remains constant.

Refractive Index A complete simulation of the physical scattering problem posed by the thermography of a fuel spray would of course include an integration of simulated images over the relevant wavelength range (i. e. as determined by the filter in front of the camera chip). There is a wavelength dependence in three main parameters that has to be evaluated: The sensitivity curve of the camera, the refractive index of the liquid (which influences absorption and scattering of the droplets) and the absorption power of the vapour phase. Especially the latter two are inherently incorrect as those values are typically not available for the temperature ranges present in a fuel spray. For simplicity, the sensitivity of the camera in the simulation is restricted to a narrow wavelength interval around $3.4 \,\mu$ m. The second derivative of the photon distribution of a black body with respect to wavelength is sufficiently small to not have an influence on the resulting temperature sensitivity. However, the exact refractive index at this wavelength will play a role in the apparent temperature, especially since the imaginary and real part of the refractive index change rapidly across the absorption band of CH-bonds.

For four exemplary refractive indices, the difference of the apparent temperature compared to the reference case with n = 1.338 and k = 0.0341 is shown in Fig. 12. Each pair of n and k is chosen from Fig. 3a. The two values are not varied independently as n is calculated from k using the Kramers–Kronig relations. Generally, a reduction of the k-value results in less absorption and an increase in the n-value results in higher reflectivity at gas-liquid boundaries. The trend is clearly visible for the imaginary part of the refractive index in Fig. 12: A low value of k corresponds to a high apparent temperature while a high value corresponds to a low apparent temperature below the injector. This is of course caused by the fact that cold fuel is injected into a hot atmosphere with hot walls. Accordingly, a reduction in absorption (which usually corresponds to a slight increase in scattering) causes more radiation from hot walls to be visible in the images and the spray appears warmer. The regions of the spray which contain a significant amount of fuel vapour around the liquid core do not show any influence as the apparent temperature is dominated by the vapour phase. The real part of the refractive index does not have a very strong influence as can be seen in the third panel of Fig. 12. This case has the highest difference in the real part of the refractive index while having a similar imaginary part compared to the standard case. Since the relative change of the real part is very small when compared to the relative change of



Fig. 12 Influence of the index of refraction on the apparent temperature at 0.950 ms after start of injection, gas conditions are 0.6 MPa and 570 K. $T_{\text{fuel}} = 370 \text{ K}$, $p_{\text{fuel}} = 20 \text{ MPa}$, $T_{\text{wall}} = 450 \text{ K}$. All panels show the difference in temperature $T_n - T_0$ to the standard case at 3.4 µm with n = 1.338 and k = 0.0341. For details on the index of refraction see Fig. 3a.



Fig. 13 Influence of the absorption in the gas phase on the apparent temperature at 0.950 ms after start of injection, gas conditions are 0.6 MPa and 570 K. $T_{\text{fuel}} = 370 \text{ K}$, $p_{\text{fuel}} = 20 \text{ MPa}$, $T_{\text{wall}} = 450 \text{ K}$. All panels show the difference in temperature $T_n - T_0$ to the standard case with $\sigma = 5 \times 10^5 \text{ cm}^2 \text{ mol}^{-1}$.

the imaginary part this is not unexpected – even when considering that the important aspect is the difference of the real part to the surrounding medium which is assumed to be an optical vacuum ($n = 1, \varepsilon = 0$).

Vapour Absorption Similar influences can be found for the light absorption in the vapour phase. Figure 13 shows different absorption cross sections compared to the reference case with an accumulated cross section of $5 \times 10^5 \text{ cm}^2 \text{ mol}^{-1}$ [10]. The influence of a 10% change in absorption cross section is quite dramatic, both in absolute apparent temperature deviation and in the affected region of the spray. Every light ray that interacts with vapour and droplets shows a significant influence on the apparent temperature: the differences are approximately $\pm 10 \text{ K}$. The only rays that appear unaffected are those that do not interact with droplets. These are seen as a yellow halo in Fig. 13. Without droplets, the emissivity correction of the DIT algorithm is able to reproduce the correct temperature while error appear if scattering from the droplets becomes more prominent. Usually,



Fig. 14 Influence of the evaporation models 0.950 ms after start of injection, gas conditions are marked. $T_{\text{fuel}} = 370 \text{ K}$, $p_{\text{fuel}} = 20 \text{ MPa}$. All panels show the difference in temperature $T_n - T_0$ to the standard case with the Abramzon model.

gas and liquid absorption are strongly correlated unless the three-dimensional structure of the molecule changes during the phase transition. Accordingly, absolute temperatures should be evaluated only if any influence of droplets can be excluded.

Evaporation Models Originally, this study was started with a special interest on the influence of the evaporation models in Fire. For the implementation of Dukowicz' [11], Frolov's [12] and Spalding's [13] evaporation models, the difference of the apparent temperature to the reference case with Abramzon's model [14] is shown in Fig. 14. The implementation of Spalding's model does not work for temperatures above the boiling temperature at atmospheric conditions. Without going into the details of the different models, a comparison at ambient conditions of 0.15 MPa and 300 K shows that the differences for the evaporation models are below 10 K. Droplets that are on the outside of the spray plumes show the most influence on their apparent temperature. A comparison with Fig. 8 reveals that the sensitivity of the camera is not high enough to allow any experimental falsification of any of the four models at 300 K. For higher gas temperatures, the evaporation starts to play a more significant role. This is clearly visible at the spray tips which appear warmer for Dukowicz' model and colder for Frolov's model. Also the apparent temperature below the injector is significantly lower for Frolov's model. However, a large part of the deviation in the high temperature cases is probably caused by initialization of the droplets and should not be overestimated. In conclusion, the trends are similar to those observed by changing the droplet size distribution slightly and cannot be used to falsify any of the evaporation models. This is especially true since the overall vapour distribution is much larger in the experiment than in the simulation, so a correct modelling of turbulence should be a much stronger priority than any dispute on the correct approximation of the droplet evaporation.

Fuel temperature As a last step, the influence of the fuel temperature before injection is assessed. While this parameter cannot be changed directly experimentally, the injector is temperature stabilised and this stabilisation temperature can be reduced from 370 K to 330 K. To see this effect more clearly, images were averaged nineteen times at every one of the six background temperatures. The general trend shown in Fig. 15 is as expected: The temperature difference is in the order of 30 K and the visible structures follow the spray plumes. Since the evaporated fuel reaches the same end temperature in both cases, the difference becomes smaller while the fuel propagates in the hot ambient gas and heats up. The simulation shows a general temperature difference in the same order of magnitude as the experiment.



Fig. 15 Difference between an injection with an injector temperature of 370 K and 330 K. The experimental data is averaged over two data sets with six background temperatures and 19 injections at each temperature. $p_{\text{fuel}} = 20 \text{ MPa}$, gas conditions 0.6 MPa and 570 K, 300 µs after optical start of injection, $T_{\text{wall}} = 450 \text{ K}$.

5 Conclusion

It is shown that a ray traced 3D fluid dynamic simulation is able to reproduce apparent temperatures detected experimentally by DIT with a multi-hole gasoline injector. Depending on the wavelength range of the camera, the images either show mainly the liquid droplets or the combination of droplets and vapour. A variety of parameters are recognized to influence the apparent temperature of the spray when mapped with differential infrared thermography. Most importantly, the gas phase has a significant influence on the apparent temperature and scattering by droplets causes large deviations of the measured temperature from the combined droplet vapour temperature in simulation – even in the case of a hypothetical enclosure at 0 K. As a rule of thumb, it can be stated that DIT of a spray with large temperature gradients in a vessel with fixed wall temperature measures either vapour temperatures or is somewhat inaccurate. Nevertheless, DIT is an excellent tool to observe trends in apparent spray temperatures when certain parameters such as the ambient temperature are changed.

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