

Differential Infrared Thermography System and Optical Calibration for Transcritical Spray Analysis

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ABSTRACT

A Differential Infrared Thermography (DIT) system and an optical calibration methodology were established for quantitative analysis of transcritical fuel sprays in high-pressure nitrogen environments. A calibration procedure was developed for high-pressure, high-temperature conditions in a chamber using cyclopentane as a surrogate fuel and preheated nitrogen to precisely control chamber conditions. The infrared camera signal was calibrated with a gray-body source to relate measured intensity to black-body temperature, and the combined noise from the camera and the optically accessible chamber (with two opposing sapphire windows) was systematically characterized. The effects of chamber pressure and temperature on recorded infrared intensities were evaluated to ensure robust calibration across transcritical conditions. Spray temperature fields were obtained under transcritical operation using the DIT technique with a slab-spray assumption and two independently controlled background temperatures, enabling spatially resolved, quantitative evaluation of spray temperature. However, the system yielded overestimated temperatures in the dense core region due to high optical depth and associated radiative transfer effects. Overall, the proposed DIT system and calibration framework offer a viable tool for investigating transcritical phase change and heat transfer, but the results highlight that improving accuracy in optically thick regions will require deconvolution-based analysis to better account for path-integrated emission and attenuation.

1. Introduction

Understanding the transcritical phase transition and mixing mechanisms of fuel sprays in high-pressure nitrogen environments is essential for optimizing modern combustion systems (Liu et al., 2017; Oschwald et al., 2006; Son et al., 2025). At these elevated pressures, the classical liquid-vapor interface vanishes and the fluid has continuous diffusive mixing characteristics (Crua et al., 2017). Under transcritical conditions, intrusive measurement of the quantitative characteristics is challenging, therefore, a non-intrusive measurement technique is necessary.

Infrared (IR) thermography offers a non-intrusive method to map these temperature fields. However, quantitative interpretation remains a challenge due to the difficulty in determining local spray emissivity and signal attenuation through chamber windows. In this study, we implement a Differential Infrared Thermography (DIT), which can provide emissivity information and evaluate the spray temperature. (Lamanna et al., 2013; Golzke et al., 2016).

This study focuses primarily on the preparation phase, specifically the calibration of the IR camera and the assessment of the noise generated by the two opposing sapphire windows of the injection chamber. Accordingly, the DIT procedure is defined and applied to the specific case of a transcritical spray to determine the spray temperature.

2. Experimental Concept and Theoretical Background

A test facility for transcritical spray research, the Multi-diagnostic Spray Investigation Chamber (MuSIC), as shown in Fig. 1, is operated by the Institute of Thermodynamics, the University of the Bundeswehr Munich.

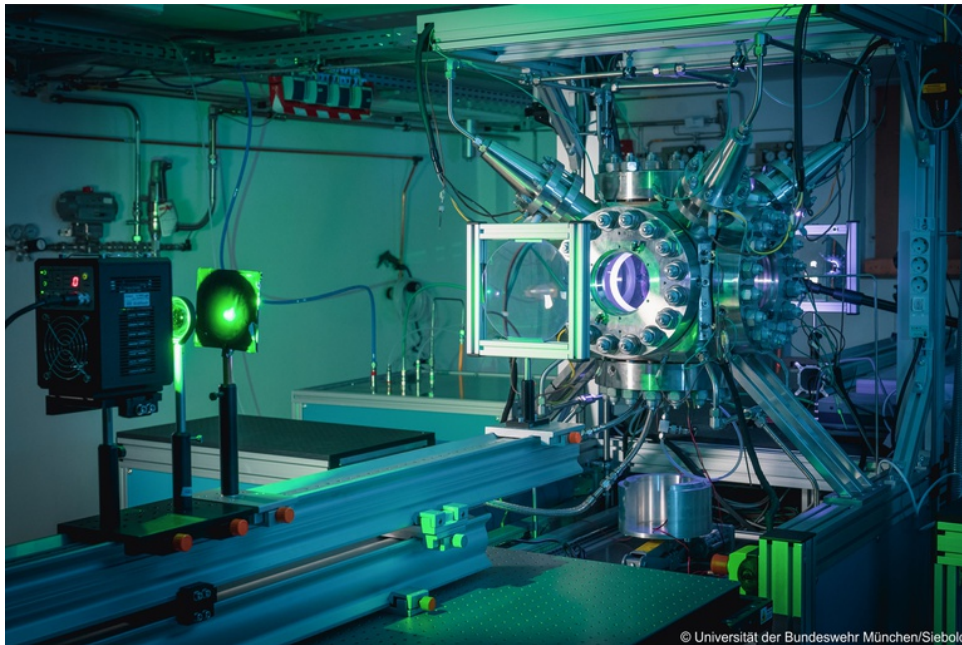


Figure 1. Multi-diagnostic Spray Investigation Chamber (MuSIC).

The experimental concept is to measure the radiance of the sprays in a high-pressure and high-temperature environment to obtain the spray temperature. The line of sight of an infrared camera consists of background, spray, and two identical sapphire windows (w_1 and w_2), as shown in Fig. 2.

The measured IR intensity $I_{\text{meas}}(x)$ along the lateral coordinate x is modeled by integrating local emissions and background radiation along the line-of-sight z , as illustrated in Fig. 3.

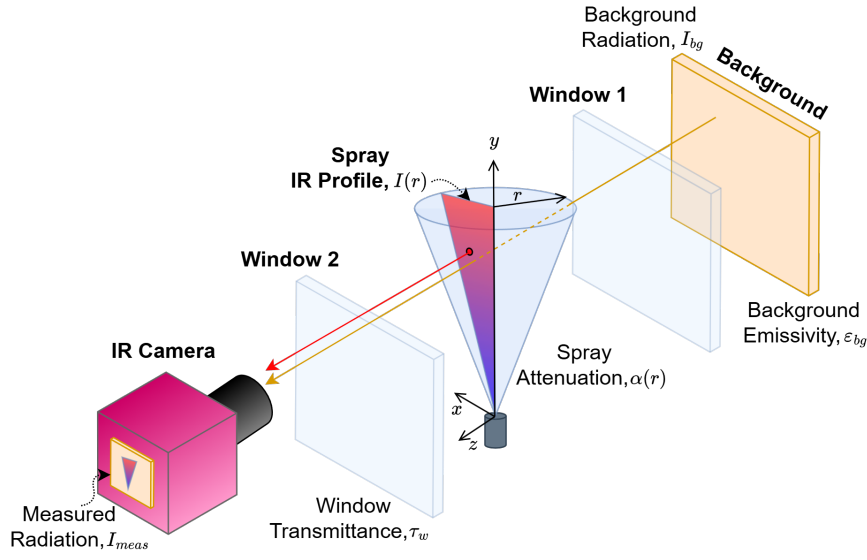


Figure 2. Schematic of the experimental setup.

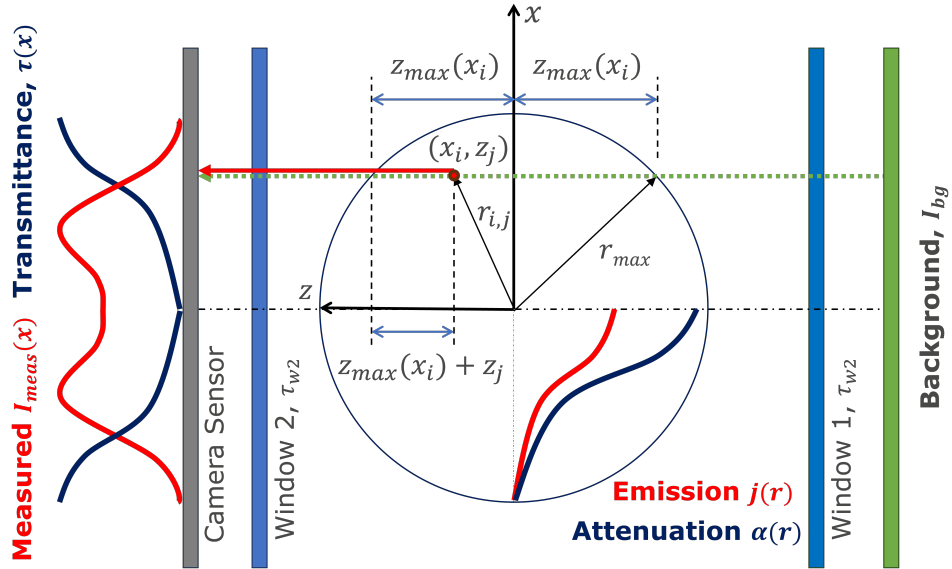


Figure 3. Diagram of emission and attenuation along the line of sight.

The measured radiation can be expressed using a radiative transfer equation (RTE) as shown in Eq. 1, where $I_{N, \text{cam}}$ is the cam noise from the IR camera itself and $I_{N, \text{ch}}$ is the additional noise associated with the chamber.

$$I_{\text{meas}}(x) = \tau_{w,2} \left[I_{bg}(x) \cdot \tau_{w,1} e^{-\sigma_{\text{max}}(x)} + \int_{-z_{\text{max}}(x)}^{z_{\text{max}}(x)} j(r) \cdot e^{-\sigma(x,z)} dz \right] + I_{N,\text{cam}} + I_{N,\text{ch}}(x) \quad (1)$$

Since the local optical depth $\sigma(x, z)$ is obtained by integrating the radial extinction coefficient $\alpha(r)$ as given in Eq. 2, the term $e^{-\sigma_{\text{max}}(x)}$ represents the total attenuation across the maximum spray

depth.

$$\sigma(x_i, z_j) = \int_{z_j}^{z_{\max}(x_i)} \alpha \left(\sqrt{x_i^2 + \zeta^2} \right) d\zeta \quad (2)$$

Assuming that both windows have the same transmittance τ_w and that the calibrator radiance $I_{\text{bg}}(x)$ consists of the effective black-body radiance $I_{\text{bb}}(x)$ with an emissivity in the filtered range ε_{bg} , the RTE can be rewritten as shown in Eq. 3.

$$I_{\text{meas}}(x) = \tau_w^2 \varepsilon_{\text{bg}} I_{\text{bb}}(x) \cdot e^{-\sigma_{\max}(x)} + \tau_w \int_{-z_{\max}(x)}^{z_{\max}(x)} j(r) \cdot e^{-\sigma(x,z)} dz + I_{\text{N,cam}} + I_{\text{N,ch}}(x) \quad (3)$$

On the right hand side of Eq. 3, the first term represents the background radiance attenuated by the two opposite windows and the entire spray depth, $z_{\max}(x)$. The integral term represents the local source function $j(r)$ weighted by the cumulative optical depth $\sigma(x, z)$ from the emission point to the exit boundary of the spray. Assuming an axisymmetric spray where $r = \sqrt{x^2 + z^2}$, the maximum optical path along the x-axis, $z_{\max}(x)$, is defined as Eq. 4.

$$z_{\max}(x) = \sqrt{r_{\max}^2 - x^2} \quad (4)$$

3. Calibration

Calibration was conducted using a wide-area gray-body calibrator (Fluke 4181) to determine the temperature according to the intensity of the camera signal, and to evaluate the effective transmittance of the dual-window chamber. A high-resolution IR camera (InfraTec ImageIR® 9480 hp) with a focal length of 500 mm was used, providing a full spatial resolution of 64 mm × 51 mm. To measure the properties of hydrocarbon fuel sprays ignoring ambient nitrogen (>98 %) radiation, a band-pass filter with a range of $3.410 \pm 0.040 \mu\text{m}$ was installed within the camera body. An integration time of 40 μs was maintained to capture spray snapshots.

The radiance from the calibrator, positioned at the same distance from the camera as in the chamber configuration, is measured in open air without the chamber, as indicated by the black solid line with the square symbol in Figure 4. The raw camera signal comprises effective black-body radiation multiplied by the emissivity in the filtered range, plus a constant camera noise term, as described in Eq. 5. Here, $\varepsilon_{\text{bg}} = 0.958$ was applied as measured by Goltzke et al. (2016).

$$I_{\text{meas},0} = \varepsilon_{\text{bg}} I_{\text{bb}} + I_{\text{N,cam}} \quad (5)$$

Because the IR camera sensor is cooled to 90 K, the dark noise $I_{\text{N,cam}}$ is obtained by extrapolating the raw signal to 90 K, as indicated by the dashed line at the raw value of 17978 in Figure 4. Consequently, the quantity I_{bb} is then specified in Eq. 6, where $I_{\text{corr},0} = I_{\text{meas},0} - I_{\text{N,cam}}$.

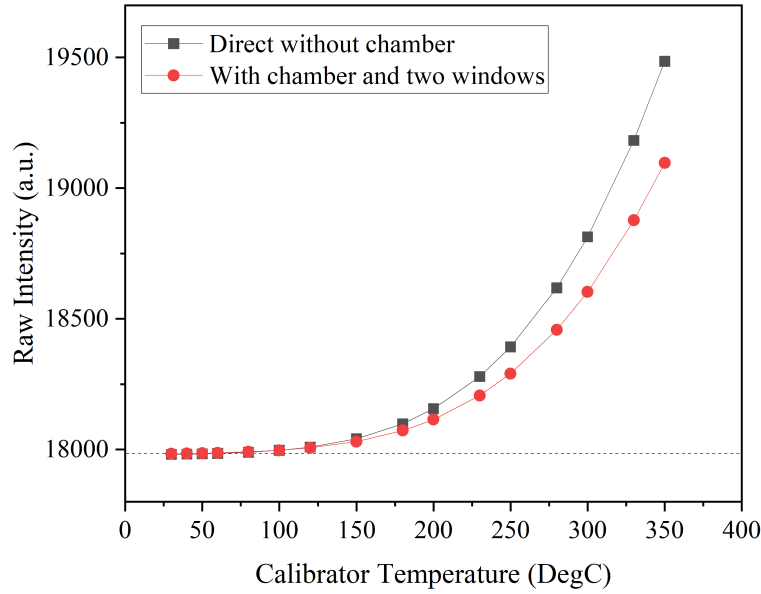


Figure 4. Raw intensities with the band-pass filter according to calibrator temperatures.

$$I_{bb} = \frac{I_{corr,0}}{\varepsilon_{bg}} \quad (6)$$

Accordingly, the effective black-body radiance $I_{bb}(T)$ can be referenced to the calibrator temperature without chamber configuration, as illustrated in Figure 4. Because the cold spray undergoes a phase change in the hot nitrogen environment, the camera was calibrated over a wide temperature interval from 30 °C to 350 °C. The relationships between I_{bb} and the calibrator set temperature T_{cal} are represented by nonlinear piecewise regressions in the form of Eq. 7, where a , b , and c are constants specific to each temperature subrange, as summarized in Table 1.

$$I_{bb} = a \cdot e^{(T_{cal}/c)} + b \quad (7)$$

Table 1. Constants for piecewise calibration curves.

Temperature Range	a	b	c
$303 \text{ K} \leq T_{cal} < 363 \text{ K}$	1.010×10^{-3}	-1.087×10^{-2}	3.783×10^1
$363 \text{ K} \leq T_{cal} < 469 \text{ K}$	2.644×10^{-2}	-1.004×10^1	5.309×10^1
$469 \text{ K} \leq T_{cal} \leq 623 \text{ K}$	2.764×10^0	-1.867×10^2	9.644×10^1

To determine the effective transmittance of the dual-window chamber setup ($\tau_{total} = \tau_w^2$), the effective transmittance through the two windows was evaluated by measuring the calibrator radiation with and without the chamber. When the chamber with two windows is located between the camera and the calibrator, the radiation is attenuated twice by the windows, and the additional noise from the windows and chamber is considered.

$$I_{\text{meas},2w} = \tau_w^2 \cdot \varepsilon_{\text{bg}} I_{\text{bb}} + I_{\text{N,cam}} + I_{\text{N,ch},2w} \quad (8)$$

By combining Eqs. 6 and 8, the relationship between the corrected intensities for the cases without and with chamber is given in Eq. 9, where $I_{\text{corr},2w} = I_{\text{meas},2w} - I_{\text{N,cam}}$.

$$I_{\text{corr},2w} = \tau_w^2 \cdot I_{\text{corr},0} + I_{\text{N,ch},2w} \quad (9)$$

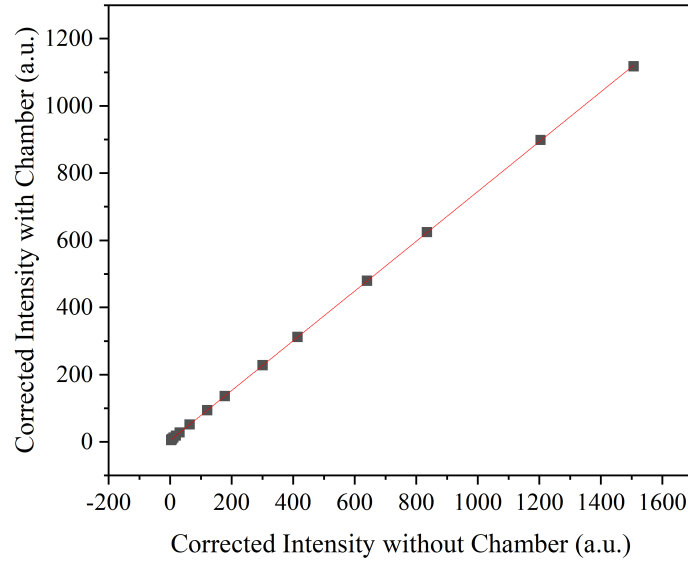


Figure 5. Relationship between corrected intensity values obtained with and without the chamber.

The corrected intensity measured through the chamber varies linearly with the corrected intensity measured without the chamber, as illustrated in Figure 5; the intercept corresponds to the noise of the chamber, and the slope corresponds to the square of the transmittance of the window. Although the raw camera intensities show a pronounced nonlinear increase with temperature, similar to band-integrated Planck radiation, the relationship between the effective radiance obtained with and without the chamber remained strictly linear ($R^2 > 0.99$). From the slope of this linear regression, a total transmittance (τ_w^2) of 0.741 was obtained for the filtered spectral range of $3.410 \pm 0.040 \mu\text{m}$, then a transmittance of 0.861 for a single window (τ_w) can be derived.

In addition, the influence of chamber pressure and temperature on camera intensity was evaluated. The chamber pressure was set to 20, 40 and 60 bar, and at each pressure the temperature was adjusted to 25, 100, 200 and 300 °C. As shown in Fig. 6, this noise presented a weak nonlinear dependence on chamber pressure, while showing a negligible sensitivity to chamber temperature. Nevertheless, this noise will be accounted for in the RTE at each measurement and will subsequently be considered with other noises in the analysis.

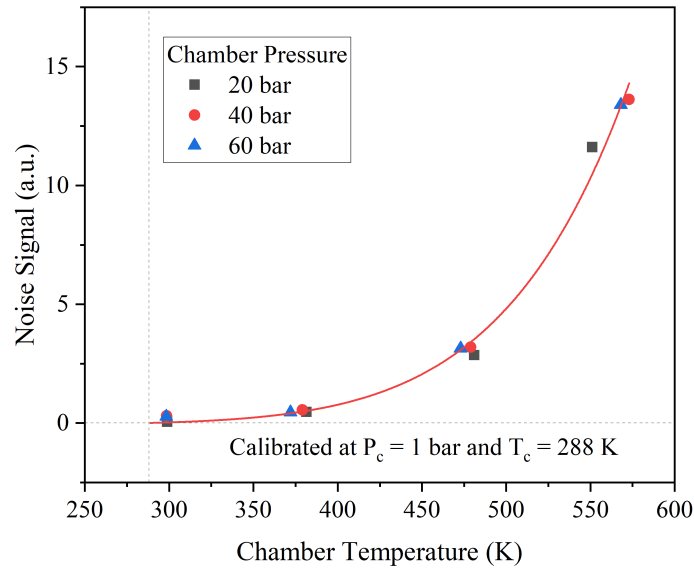


Figure 6. Noise sensitivity at various chamber conditions.

4. Differential Infrared Thermography of Transcritical Sprays

The key challenge in solving the RTE is evaluating the integral term to determine the spray temperature. The spray temperature can be obtained using the differential infrared thermography (DIT) method (Sharkov, 2003), which employs two distinct background temperatures while maintaining identical spray conditions. Note that the DIT temperature does not always reflect the true temperature distribution. However, in some cases, the DIT temperature can be regarded as the spray temperature with approximately a maximum error of 16% in the worst scenario with the scattering albedo of 0.99 (Lamanna et al., 2013).

In this study, liquid cyclopentane is injected into a supercritical nitrogen environment, and the DIT method, together with calibration measurements, is used to determine the temperature of transcritical sprays. The MuSIC facility is operated at 55 bar and 290 °C (563 K) with preheated nitrogen, corresponding to case 3 of the previous investigation (Son et al., 2025). Cyclopentane is injected upward from the bottom of the chamber through a single-hole injector with a nozzle diameter of 0.2 mm, at injection temperature of 25 °C (298 K) and injection pressure of 105 bar.

When the spray is modeled as a thin slab rather than as a three-dimensional volumetric conical cloud, the integral term is simplified as given in Eq. 10, where $\varepsilon_{\text{spray}}$ denotes the emissivity of the spray slab and I_{spray} represents the radiance of the spray slab.

$$\int_{-z_{\max}(x)}^{z_{\max}(x)} j(r) \cdot e^{-\sigma(x,z)} dz = \varepsilon_{\text{spray}}(x) \cdot I_{\text{spray}}(x) \quad (10)$$

From the definition of transmittance, the slab spray emissivity $\varepsilon_{\text{spray}}$ can be reduced to the form of

Eq. 11, ignoring the scattering effect.

$$e^{-\sigma_{\max}(x)} = 1 - \varepsilon_{\text{spray}}(x) \quad (11)$$

Figure 7 presents the recorded spray images at two different background temperatures. The spray is captured in steady-state conditions after injection and the average image of 20 individual shots is used for analysis.

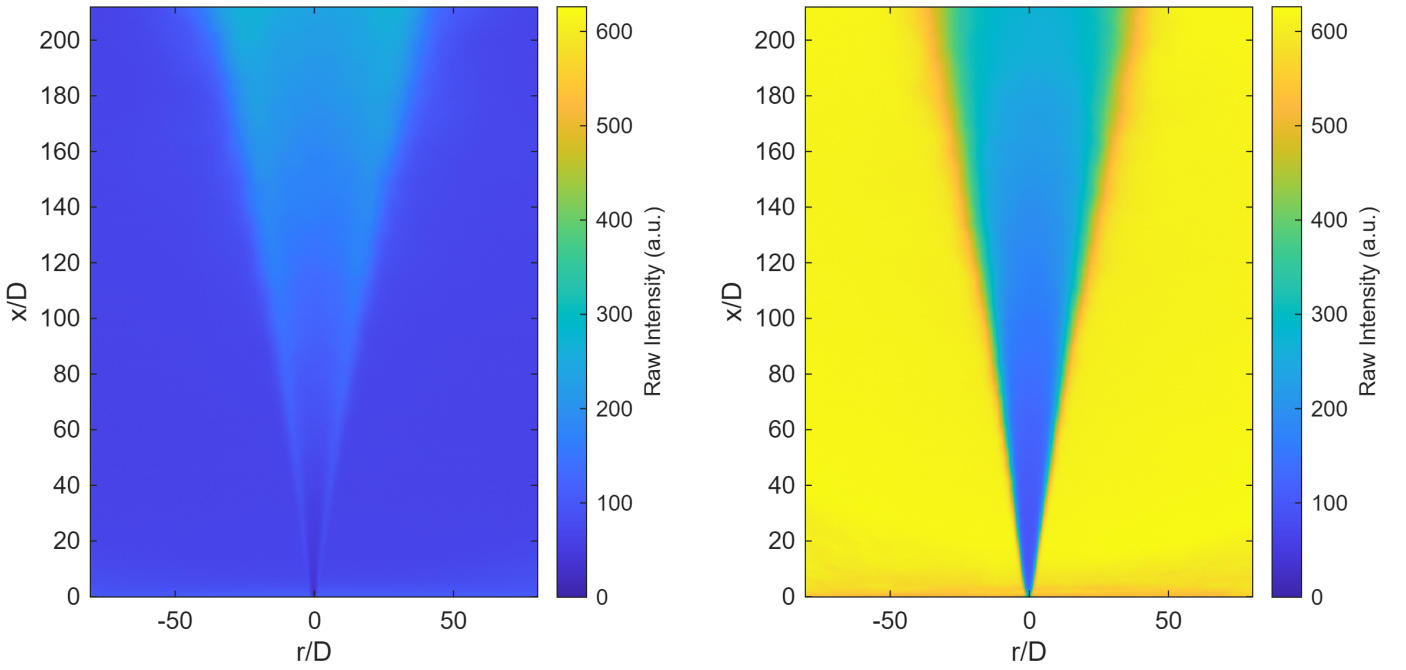


Figure 7. Averaged IR spray images captured at two background temperatures; (left) 150 °C and (right) 300 °C.

Under this assumption, the radiation detected by the IR camera at the two background temperatures can be expressed in the simplified forms given in Eqs. 12a and 12b, whereas the measurements without spray correspond to Eqs. 13a and 13b.

$$I_{\text{meas},1}(x) = \tau_w^2 \varepsilon_{\text{bg}} I_{\text{bb},1} \cdot (1 - \varepsilon_{\text{spray}}(x)) + \tau_w \cdot \varepsilon_{\text{spray}}(x) I_{\text{spray}}(x) + I_{\text{N,cam}} + I_{\text{N,ch},1}(x) \quad (12a)$$

$$I_{\text{meas},2}(x) = \tau_w^2 \varepsilon_{\text{bg}} I_{\text{bb},2} \cdot (1 - \varepsilon_{\text{spray}}(x)) + \tau_w \cdot \varepsilon_{\text{spray}}(x) I_{\text{spray}}(x) + I_{\text{N,cam}} + I_{\text{N,ch},2}(x) \quad (12b)$$

$$I_{\text{bg,meas},1} = \tau_w^2 \varepsilon_{\text{bg}} I_{\text{bb},1} + I_{\text{N,cam}} + I_{\text{N,ch},1} \quad (13a)$$

$$I_{\text{bg,meas},2} = \tau_w^2 \varepsilon_{\text{bg}} I_{\text{bb},2} + I_{\text{N,cam}} + I_{\text{N,ch},2} \quad (13b)$$

To eliminate the extra noise introduced by the chamber and the windows during measurement campaigns, uniform black-body backgrounds $I_{bb,1}$ and $I_{bb,2}$ are generated as reference signals from the calibration data. Using these references, the measurement noises are then determined according to Eqs. 14a and 14b.

$$I_{N,ch,1} = I_{bg,meas,1} - \tau_w^2 \varepsilon_{bg} I_{bb,1} - I_{N,cam} \quad (14a)$$

$$I_{N,ch,2} = I_{bg,meas,2} - \tau_w^2 \varepsilon_{bg} I_{bb,2} - I_{N,cam} \quad (14b)$$

Then, the emissivity of the slab spray, $\varepsilon_{spray}(x)$, can be obtained from Eq. 15, as all the required terms are already known. Based on this equation, the emissivity is obtained, as shown in Fig. 8, using two spray averaged images and two background images.

$$\varepsilon_{spray} = 1 - \frac{(I_{meas,2} - I_{N,ch,2}) - (I_{meas,1} - I_{N,ch,1})}{(I_{bg,meas,2} - I_{N,ch,2}) - (I_{bg,meas,1} - I_{N,ch,1})} \quad (15)$$

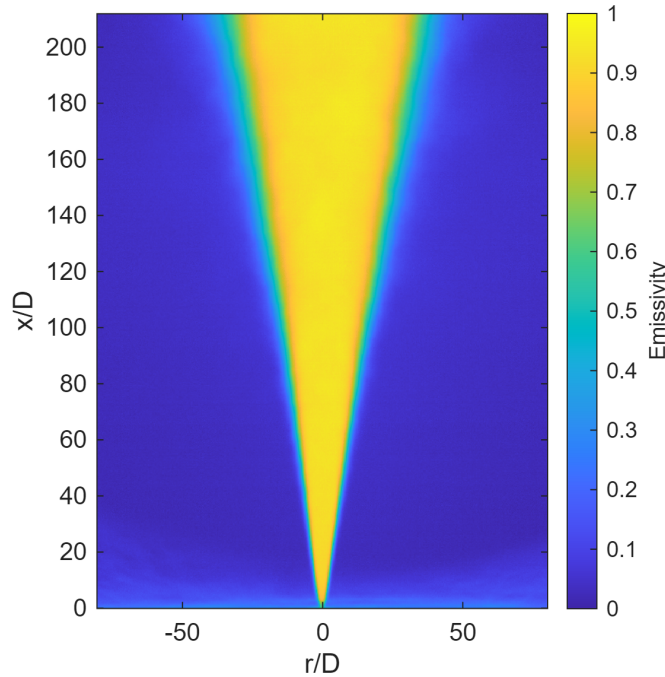


Figure 8. Estimated emissivity of the slab spray using the averaged spray images.

Consequently, the slab spray radiance is obtained using Eq. 16, and the radiance is then converted into temperature using the calibration curves, as shown in Fig. 9.

$$I_{spray} = \frac{I_{meas,1} - \tau_w^2 \varepsilon_{bg} I_{bb,1} \cdot (1 - \varepsilon_{spray}) - I_{N,cam} - I_{N,ch}}{\tau_w \varepsilon_{spray}} \quad (16)$$

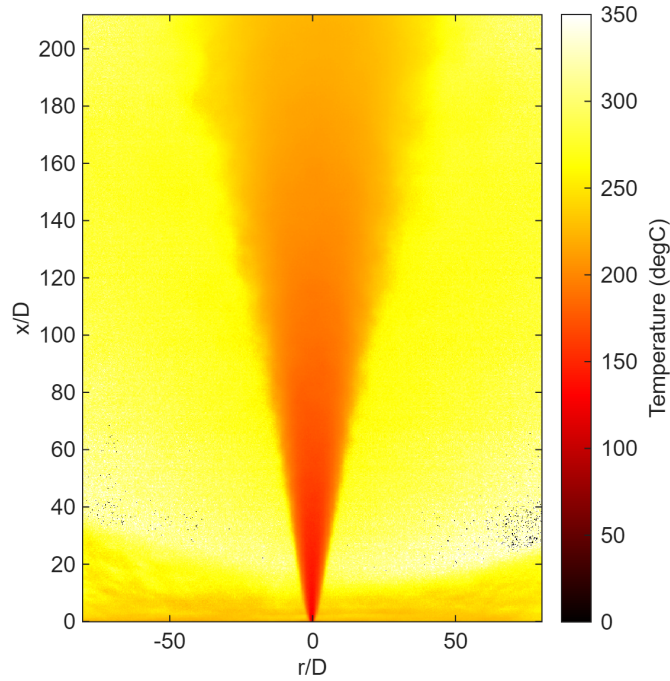


Figure 9. Spray temperature evaluated by DIT using the averaged spray images.

5. Discussion

Using the DIT technique, the averaged spray temperature can be successfully evaluated. However, the axial temperature distribution shows values higher than expected at the beginning of injection, as shown in Fig. 10. Near the nozzle, the temperature should be close to the injection temperature, but the measured values are elevated. Because the injector nozzle was cooled with a cooling jacket to keep the injection temperature constant, the DIT-based temperature appears to be overestimated.

This overestimation was observed by Golzke et al. for DIT-based temperature measurements of evaporating sprays. When the spray is optically thick, i.e., the cumulative optical depth ($\sigma_{\max}$) exceeds 1.0, the DIT temperature represents the true spray temperature at the position of $\sigma_{\max} \approx 1.0$ (Golzke et al., 2016). This behavior is consistent with the temperature measurement approach used for planetary atmospheres based on the Eddington–Barbier approximation (Crivellari et al., 2020), as a consequence of self-absorption.

As shown in Fig. 11, most of the spray core has a higher cumulative optical depth. Consequently, DIT in the core region effectively captures only the front view of the spray where $\sigma_{\max} = 1.0$, and thus the measured value represents an apparent temperature.

On the other hand, in the spray boundary region where $\sigma_{\max} < 1.0$, the temperature can be considered relatively reliable. This is because the temperature gradient along the line-of-sight near the spray edge is smaller than that at the spray centerline. As a result, the mean temperature at

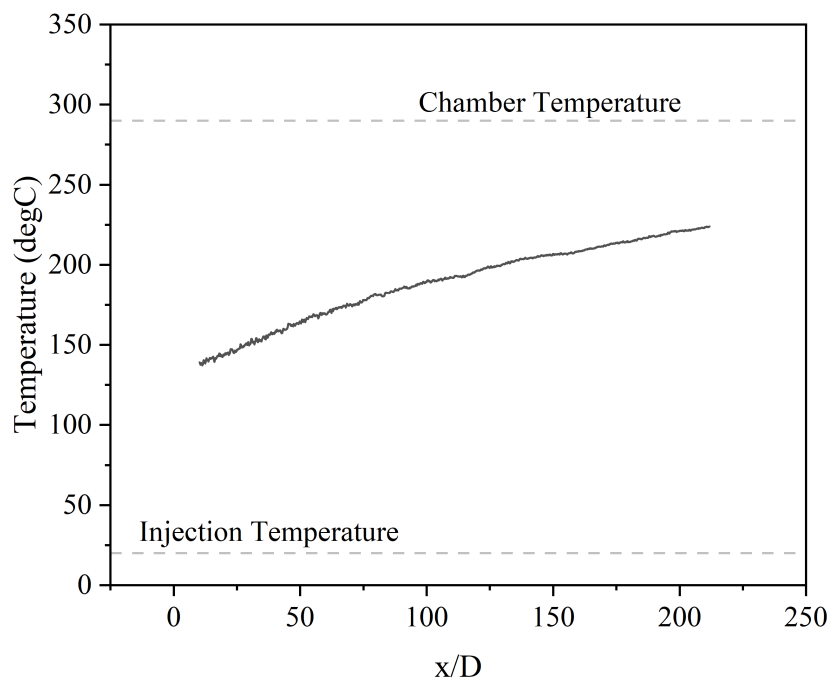


Figure 10. Axial distribution of the DIT temperature.

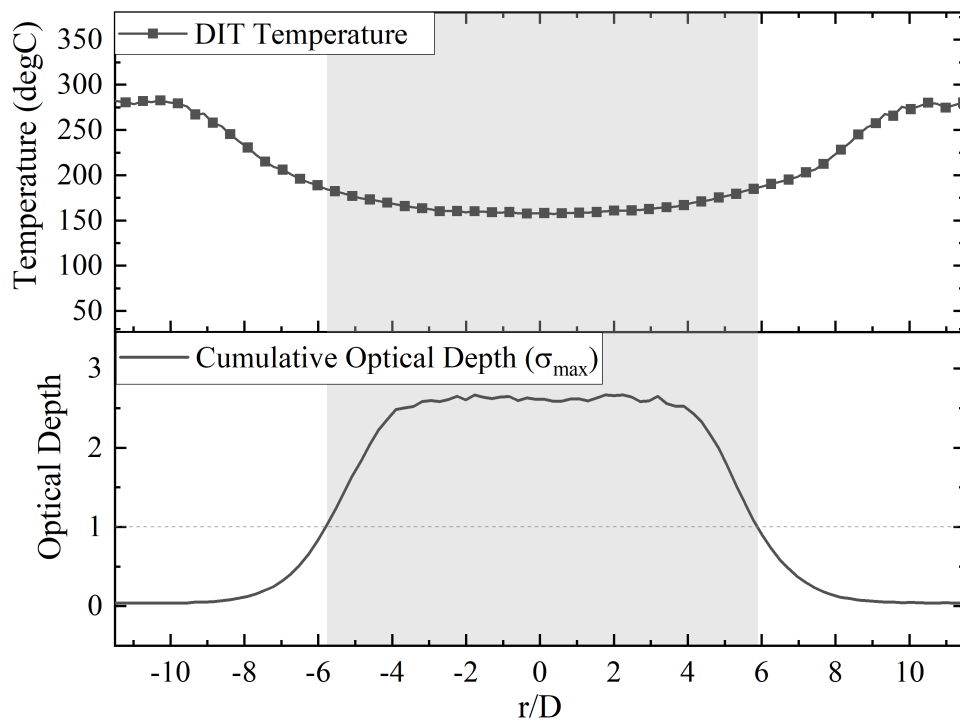


Figure 11. Radial distribution of the DIT temperature and the cumulative optical depth ($\sigma_{\max}$) at $x/D = 40$.

the end of the spray boundary ($r/D \approx 9$ at $x/D = 40$) reaches a temperature close to the chamber condition, 290°C . Note that even at the lower value of $\sigma_{\max}$, the DIT temperature remains biased toward the hotter and denser regions along the line of sight, since the integration is weighted and

the relationship between temperature and intensity is non-linear.

In addition, although the outer DIT temperature is close to the chamber temperature, the far-field temperature cannot be considered fully reliable. In principle, the temperature in the far field without spray cannot be measured due to weak emission and absorption, but some residual vapor still emits radiation, so the optical depth approaches nearly zero (but not zero) outside the spray, as shown in Fig. 11. Consequently, even small variations in the concentration of these residues can lead to comparatively large errors in temperature measurement.

6. Conclusion

In this study, a calibration procedure was performed to measure the spray temperature under high-pressure and high-temperature conditions. Cyclopentane was used as the surrogate injectant and preheated nitrogen was supplied to maintain the chamber environment. The intensity of the IR camera was calibrated using a gray-body calibrator to establish the calibration curve between the camera intensity and the corresponding black-body temperature. The noise from the IR camera and the spray chamber with two opposing sapphire windows was then quantified, while the influence of chamber conditions on the measured intensities was investigated.

The spray temperature under transcritical conditions was determined using the DIT technique on the basis of the slab-spray assumption. Using two different background temperatures, the spray temperature was successfully evaluated. However, due to the high optical depth of the sprays, the DIT method overestimated the temperature in the core region. This approach allows for a comprehensive quantitative analysis of the transcritical phase change, although the potential for improving the measurement technique remains doubtful. The findings indicate that a deconvolution analysis is necessary to evaluate more precise spray temperature.

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