

Laser-Induced Phosphor Thermography on Surfaces in Humid Crossflow using Zinc Oxide

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ABSTRACT

The increase of water content of the exhaust gas due to direct injection of water into the combustion chamber or the addition of urea to the exhaust gas promotes contrail formation and makes the water recovery in turbomachinery a potential benefit. In this work, Laser-Induced Phosphor Thermography (LIPT) based on the spectral intensity ratio method is employed to obtain two-dimensional surface temperature distributions on additively manufactured condensation probes exposed to a humid turbulent crossflow. A calibration facility for zinc oxide coatings on surfaces with temperatures between $T_{min} = 283.15$ K and $T_{max} = 298.15$ K was established and successfully put into operation with a temperature uncertainty of $\sigma_T = 0.46$ K. Using this calibration, LIPT measurements were performed on two additively manufactured condensation probe geometries, a basic round geometry and an inward-curving square tube geometry. The resulting two-dimensional surface temperature fields qualitatively reveal consistent features on both probes, in particular a horizontal temperature gradient marking the location of turbulent boundary-layer separation on the basic round geometry. Beyond this qualitative agreement, the comparison between the two geometries demonstrates the enhanced cooling performance of the inward-curving square tube probe: despite a coolant temperature elevated by 15 K, its surface temperature in the inward-curved area remains below that of the basic round sample. This finding is consistent with the design intent of the modified geometry, which was optimized to create zones with increased condensation potential and to enlarge the existing condensation zones of the basic geometry. The presented results highlight the capability of LIPT to resolve subtle differences in the local temperature distribution of complex, additively manufactured surfaces and provide a basis for further optimization of condensation probe geometries and heat transfer analysis.

1. Introduction

Novel aircraft configurations based on jet propulsion systems will rely on fuels that result in water being emitted in gaseous form as part of the exhaust gas flow. This development is associated

with concepts of Cheng & Nelson (2002) and Schmitz et al. (2021), such as direct injection of water into the combustion chamber or the addition of urea to the exhaust gas for chemical reduction. Both concepts increase the water content of the exhaust gas, which promotes contrail formation and thus makes the recovery of water from the exhaust gas more important. One approach to remove water from the exhaust gas is the use of condensation probes placed in the exhaust gas channel downstream of the jet engine's turbine. Investigating condensation, and thus the heat transfer, requires spatially resolved temperature measurements on the surface. For this purpose, thermographic phosphors are utilized on the condensation probes and two-dimensional temperature fields are captured via Laser-Induced Phosphor Thermography (LIPT).

The temperature-dependent luminescence of thermographic phosphors was first utilized for temperature measurements by Neubert (issued 1937 (application in Germany 1932)). Early developments explored the potential of phosphors for thermal mapping, which led to the introduction of phosphor paints in the 1940s. Later, Thureau (1957) introduced the spectral intensity ratio method for temperature determination, utilizing spectral shifts in the emission spectrum of an excited material. Over the following decades, advances in optical technology led to further developments in measurement technology relating to thermographic phosphors. Today, luminescence of various phosphor materials is being applied to a broad spectrum of engineering application fields, whether in heat transfer, combustion research, or fluid dynamics. As shown by Allison & Gillies (1997); Brübach et al. (2013) and Abram et al. (2018), luminescent particles are used in the form of powders, paints, or thin film coatings on surfaces and even in liquid and gas flows of high-pressure reactors, gas turbines, and internal combustion engines.

Despite these advances, the application of LIPT to additively manufactured condensation probes under humid crossflow conditions has not been demonstrated. The present work therefore aims to establish a calibration facility with the corresponding post-processing routine, to demonstrate the applicability on additively manufactured condensation probes, and to compare a basic round probe geometry with a geometry which is optimized to increase condensation potential.

2. Experimental Methods and Setups

This section outlines the experimental methods and setups employed in this study. First, the used phosphor particles are introduced, including their luminescent properties relevant to thermometry. Subsequently, the temperature calibration procedure is described, followed by the additive manufacturing technique applied to fabricate the condensation probes. Finally, the design and working principle of the condensation test rig are presented.

2.1. Laser-Induced Phosphor Thermography

Two principal methods are employed for determination of temperature while using LIPT: the lifetime-based method, which measures the decay time of the material's luminescence after excitation, and the spectral intensity ratio method, which compares the intensity of two spectral emission bands after excitation. The latter is applied in the present study, which represents a time-integrated approach.

The two spectral emission bands, the blue camera channel BC and the red camera channel RC, with various temperature-dependent emission spectra of the phosphor used are schematically depicted in Figure 1. The temperature-dependent intensity ratio $\mathbb{I}$ is calculated by

$$\mathbb{I}(x, y, T, F) = \frac{I_{RC}(x, y, T, F)}{I_{BC}(x, y, T, F)}, \quad (1)$$

with the intensity I_{RC} of the red camera channel (400 nm – 450 nm) and the intensity I_{BC} of the blue camera channel (382 nm – 393 nm).

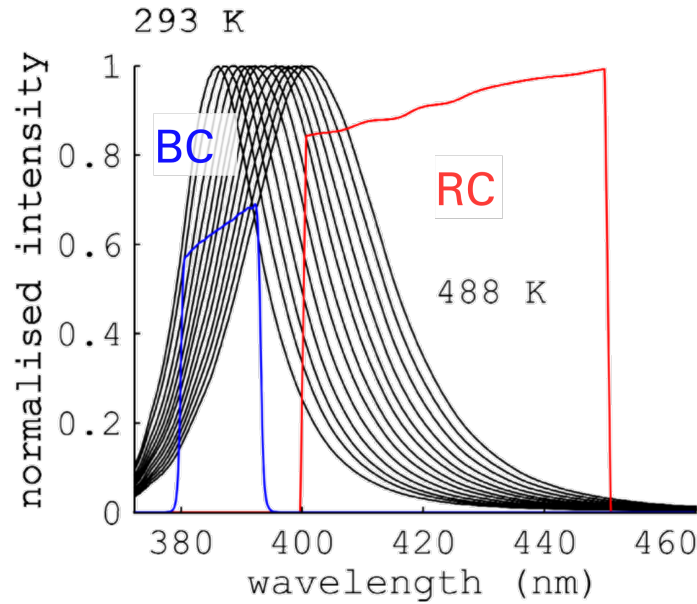


Figure 1. Schematic illustration of temperature-dependent ZnO emission spectra with the corresponding camera channels, BC: blue channel, RC: red channel, adapted from Abram et al. (2018).

Both intensities depend on the measured position in x and y direction, the temperature T , and the laser fluence F . The intensity ratio $\mathbb{I}$ is divided by a reference intensity ratio $\mathbb{I}_{ref}$ at ambient conditions, to eliminate camera errors and irregularities in the laser illumination. This leads to the normalized intensity ratio $\mathbb{I}_{norm}$ with

$$\mathbb{I}_{norm} = \frac{\mathbb{I}}{\mathbb{I}_{ref}}. \quad (2)$$

Following these steps, the normalized intensity ratio $\mathbb{I}_{norm}$ transforms the two intensities I_{RC} and I_{BC} into a temperature-dependent scalar value that offers a robust approach for precise two-dimensional temperature measurement (Brübach et al., 2013).

2.2. Phosphor Particles

An additional key aspect is the choice of thermographic particles that are used. Among available phosphors, zinc oxide (ZnO, Sigma-Aldrich 99.4 % purity) is selected because of a range of advantageous material characteristics. ZnO is a direct wide-bandgap semiconductor with remarkable chemical and thermal stability. Furthermore, the high exciton binding energy of ZnO ensures stable excitonic emission at room temperature, which is beneficial for moderate temperatures as in the present case. Luminescence in ZnO occurs in two distinct spectral bands: a near-band-edge emission band at approximately 385 nm and a broader deep-level emission band at approximately 510 nm (Rodnyi & Khodyuk, 2011).

Heating ZnO causes a temperature-dependent redshift in the emission spectrum. Figure 1 illustrates this behavior, demonstrating that the emission peak shifts towards longer wavelengths with increasing temperature, as shown in Särner et al. (2008). For producing the ZnO coating, ZnO powder was mixed with a bonding agent (HPC binder, ZYP Coatings) and water. A mixing ratio of 1 g of ZnO powder to 15 ml of binder and 5 ml of water is used and the coating was spray painted onto the surface with an air brush.

2.3. Temperature Calibration

The ZnO coating has to be calibrated to match the normalized intensity ratio $\mathbb{I}_{norm}$ with the corresponding temperatures T . The experimental test facility used for calibration can be seen schematically in Figure 2. A copper block is spray-coated with ZnO coating. 30 layers were applied to enhance coating uniformity and each layer was dried before the application of the next. The copper block was temperature-controlled by a cryostat (Unistat 815, Huber Kältemaschinenbau) using denatured ethanol as coolant.

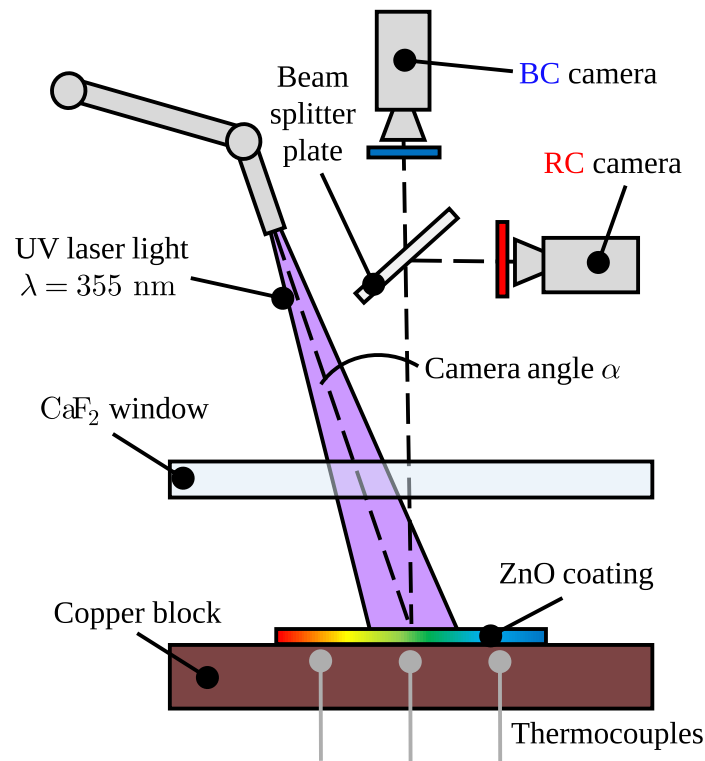


Figure 2. Schematic sideview of the calibration facility.

Once the copper block temperature has reached steady-state conditions, measurements are performed using the spectral intensity ratio method. The ZnO layer on the measuring plane is excited by laser light with a wavelength of $\lambda = 355 \text{ nm}$, which comes from a pulsed Nd:YAG laser (Q-smart 450, Quantel-laser) and is positioned at a certain angle $\alpha = 20^\circ$ relative to the camera axis. A calcium fluoride (CaF_2) window is placed between the cameras and the copper block to replicate the actual experiment as closely as possible. Thermocouples are integrated into the copper block from below to measure the surface temperature directly. A ground glass diffuser (N-BK7, DG10-600, Thorlabs) was utilized, providing a homogeneous light field and expanding the laser beam to a measurement surface with a diameter of $d = 75 \text{ mm}$.

To capture the luminescence of the ZnO coating, two cameras and a beamsplitter plate (46-642, Edmund Optics) are aimed perpendicularly to the coated surface. The cameras are equipped with two bandpass interference filters for the RC channel (86-961, Edmund Optics) and the BC channel (84-110, Edmund Optics).

2.4. Condensation Probes

The reduction of water vapor emissions in the exhaust gas of a jet engine is an important factor influencing the overall contrail formation. One approach involves condensing water vapor

downstream of the turbine to reduce the water content in the exhaust gas, thus mitigating contrail formation. For this purpose a channel flow equipped with condensation probes is used to investigate water condensation in humid airflows.

The channel is a suction mode driven wind tunnel operated by a vacuum pump (WGK 8000, Pfeiffer Vacuum). The intake mass flow rate of ambient air is entering the flow channel through an inlet with appropriate dust filter and is measured by a laminar flow element (LFE50MC02-06, Meriam Instruments). Afterwards, the air stream is heated by an electrical heater (CSB803A, Schniewindt) with a maximum electrical power of $P_{el} = 44$ kW. The hot gas flow is exiting the heater before entering the modular test section with dimensions of a height $H = 60$ mm, a width $W = 90$ mm, and a length of $L = 420$ mm. To monitor boundary conditions, air temperature T_{air} (Sensing Precision) and relative humidity RH (SEK-SHT40I-HD1B, Sensirion) can be measured at the inlet and outlet of the test section. At the channel exit, a water cooled heat exchanger (Kühner) is implemented to cool the main stream temperature back down. Detailed information on the setup of the test rig can be found in Schwab (2024). The condensation probes are mounted perpendicular to the heated air-flow in the center line of the test section and are additively manufactured, enabling complex probe geometries beyond the capabilities of conventional manufacturing methods. Their manufacturing method will be discussed in Section 2.5 in detail. A schematic top view of the test section with the camera and laser setup can be seen in Figure 3.

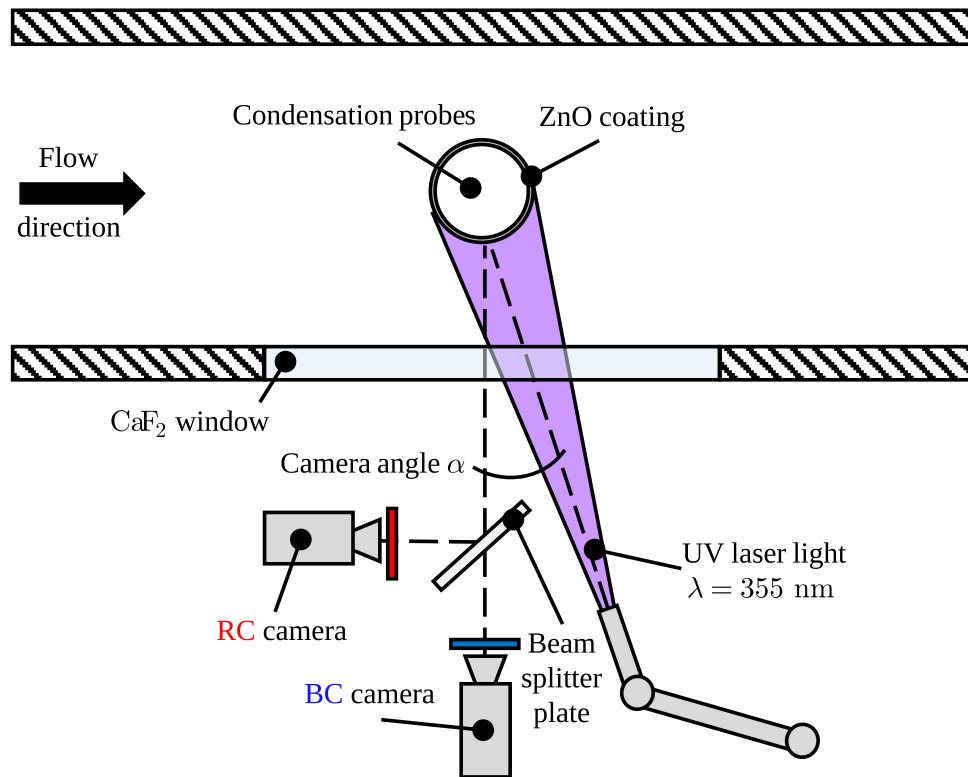


Figure 3. Schematic top view of the condensation probe test section and measurement setup. The ZnO-coated probe is mounted in the center line of the test section.

Figure 4 shows three types of probe geometries examined, installed in the test section: (a) is a basic round tube geometry, (b) represents a straight inward-curving square tube geometry, and (c) follows an inward-curving square tube geometry bent in flow direction on both sides. The two inward-curving square tube geometries (b) and (c) are optimized to create zones with increased condensation potential and to enlarge existing condensation zones of the basic geometry (a). Geometry (c) is introduced here for context but will be investigated in future work. The present study focuses on condensation probe geometries (a) and (b). A cryostat (unistat 815, Huber) is connected to the condensation probes to cool them down. With the described experimental setup it is possible to achieve the specified preliminary target values at the test section like a Mach number of $Ma = 0.25$, a maximum flow temperature of $T = 370$ K, and a mass flow rate of $\dot{m} = 0.5$ kg/s.

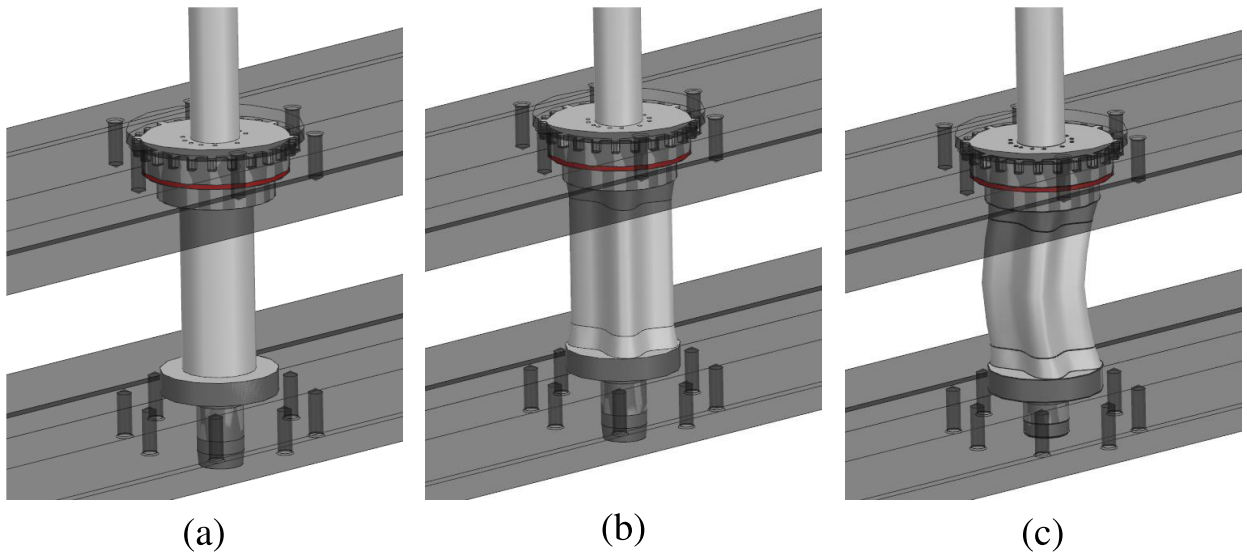


Figure 4. Condensation probe geometries mounted between upper and lower channel wall (black transparent), (a) basic round geometry, (b) straight inward-curving square tube geometry, (c) inward-curved square tube geometry bent in flow direction, flow direction: from left to right.

In addition to the pointwise temperature measurements inside the probes, provided by conventional thermocouples, LIPT enables a spatially resolved temperature field mapping of the probe's surface. Therefore, a surface area on the side of each condensation probe will be spray painted with ZnO coating and illuminated using the experimental camera setup mentioned in Section 2.3.

2.5. Additive Manufacturing

The condensation probes were additively manufactured at the Materials Testing Institute (MPA) University of Stuttgart using laser powder bed fusion (PBF-LB/M) due to the complexity of their geometric design. Fabrication was carried out on a TruPrint 3000 G08 system (TRUMPF SE + Co. KG), equipped with two lasers, each delivering a maximum power of $P_{max} = 700$ W, operating

at a wavelength of $\lambda = 1070$ nm and a beam diameter of $d_B = 0.08$ mm. Inconel 718 powder with a particle size distribution of 15–45 μm (m4p material solutions GmbH) served as feedstock material. To achieve near-net-shape quality and reduced surface roughness of the internal surfaces of the 1.6 mm diameter channels intended for thermocouple insertion, optimized and laser beam-compensated contour parameters were applied. The contour exposure was performed using a laser power of $P_L = 125$ W, a scan speed of $v_S = 400$ mm/s, and a layer thickness of $t_L = 0.03$ mm. Beam compensation was implemented by applying an inward offset of 0.05 mm to the contour. The bulk volume of the specimens was fabricated using a bidirectional (bilinear) hatch pattern with a volumetric energy density of $E_V = 70$ J/mm³. The hatch orientation was rotated by 61° between successive layers. The corresponding process parameters of the bulk volume included a laser power of $P_L = 168$ W, a scan speed of $v_S = 800$ mm/s, and a hatch spacing of $h = 0.1$ mm. Argon (purity grade 4.6) was used as shielding gas, and no preheating of the build plate was applied. The geometry of the test specimen was designed to minimize the need for support structures while ensuring that mechanical finishing is straightforward.

3. Results and Discussions

First, the temperature calibration procedure of the ZnO coating is depicted and the results are discussed. Second, the transfer to an engineering application is shown, such as surface temperature measurements on condensation probes in humid airflow.

3.1. Temperature Calibration

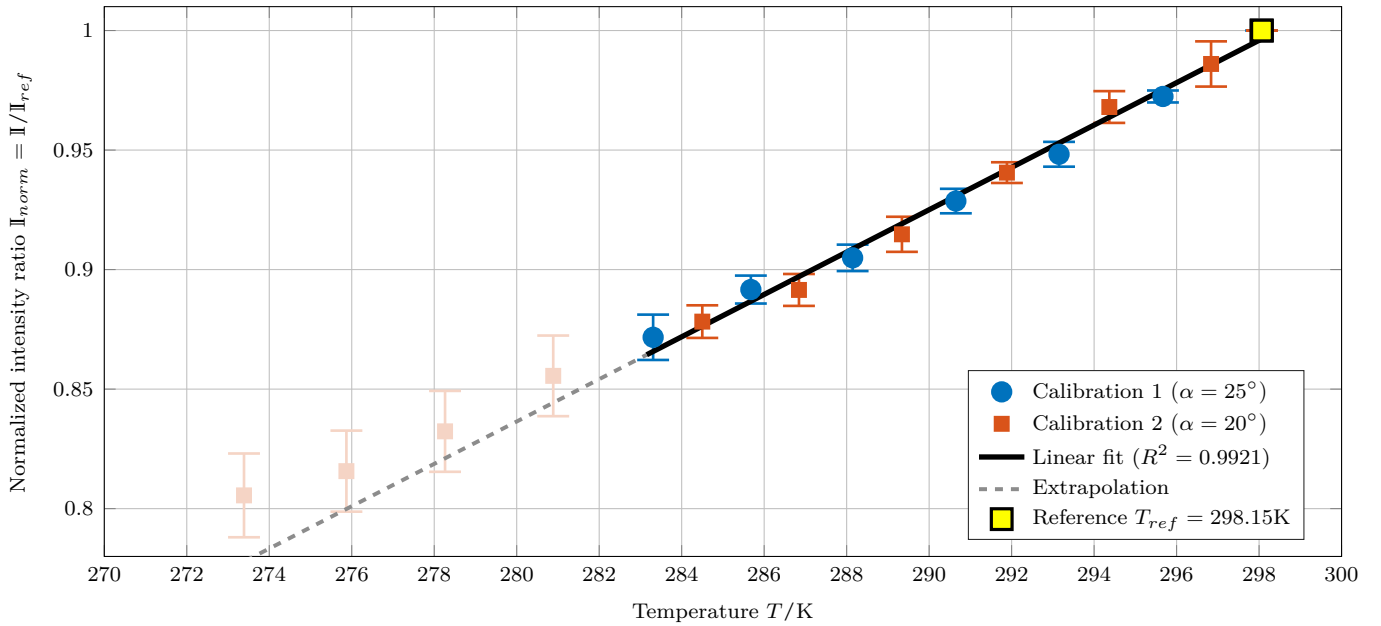
A square area with side length of $L_{cal} = 3.0 \cdot 10^{-2}$ m is examined on the surface illuminated by the laser, corresponding to a total amount of $\approx 3.8 \cdot 10^5$ px. A total of 300 images are captured at a frequency of $f = 10$ Hz which results in a total recording time of $\tau = 30$ s. Every set of calibration images is then time-averaged to compensate for minor fluctuations in laser power. To align the two camera channels RC and BC with pixel precision, a spline interpolation is performed. The aligned and time-averaged calibration images are then evaluated pixel-by-pixel according to Equation (1). A $2 \text{ px} \times 2 \text{ px}$ Gaussian filter is applied to the RC channel and BC channel to smooth the resulting intensity ratios $\mathbb{I}$.

The normalized intensity ratio $\mathbb{I}_{norm}$ is calculated with Equation 2 for a total temperature range from $T_{min} = 283.15$ K to $T_{max} = 298.15$ K. The measurements at nearly ambient conditions ($T_{max} = 298.15$ K) for both campaigns are used as reference cases for each calibration campaign.

Table 1. Ambient conditions recorded during the calibration measurements and angle α between laser and camera axis.

	Ambient temperature T_{amb} / K	Relative humidity RH / %	Angle α / °
Calibration 1	296.31	49.10	25
Calibration 2	296.22	28.06	20

To show that environmental factors such as ambient temperature T_{amb} or ambient relative humidity RH do not influence the measurements, Figure 5 shows two calibration campaigns carried out under different ambient conditions. The angle α between the camera and the laser axis is varied between the experiments to demonstrate that for small changes in angle, the angle of incidence of the UV light does not have an effect on the measurement outcome. This aspect is important for the analysis of curved surfaces, such as those encountered in condensation probes. The boundary conditions are summarized in Table 1.

**Figure 5.** Temperature calibration curve matching normalized intensity ratio I_{norm} with corresponding temperatures T . Linear fit was created using the colored data points. Grayed-out data points were not used for calibration due to condensation.

The linear fit of the temperature calibration curve is created using only the colored data points from T_{min} to T_{max} . This leads to a linear temperature curve equation of the form

$$I_{norm} = aT + b, \quad (3)$$

with a slope $a = 8.633 \cdot 10^{-3} \text{ 1/K}$ and the constant $b = -1.577$.

Equation 3 connects the measured normalized intensity ratios $\mathbb{I}_{norm}$ with the corresponding temperatures T and a corresponding temperature uncertainty σ_T of

$$\sigma_T = \frac{\text{RMSE}}{|a|} = 0.46 \text{ K.} \quad (4)$$

The temperature uncertainty σ_T is quantified by the root-mean-square deviation of the calibration points from the linear fit and expressed in temperature units via the calibration slope a , where the RMSE denotes the residual scatter of the normalized intensity ratio about the fit. This value represents the global accuracy of the calibration over the investigated temperature range. Data points that are grayed-out were not used for calibration because their temperatures lie below the dew point corresponding to the ambient conditions of calibration campaign 2. They exhibit a higher standard deviation as the colored points, and show slightly higher temperatures as the linear temperature curve in Equation 3. This could be due to the fact that condensation occurs below the dew point, which in turn generates heat of condensation directly, and this would result in higher temperatures on the surface. However, this is subject of further investigations on temperature measurements using ZnO during condensation processes.

The calibration is strictly valid only within $T_{min} = 283.15 \text{ K} \leq T \leq T_{max} = 298.15 \text{ K}$, corresponding to the temperature range covered by the calibration measurements. Temperatures outside this interval that appear in the following results are obtained by extrapolating the linear temperature equation 3. This extrapolation is considered admissible for two reasons: first, all observed temperatures remain above the dew point, so that condensation effects on the optical signal can be excluded. Second, it is assumed that the linear relation between the normalized intensity ratio $\mathbb{I}_{norm}$ and the temperature T extends beyond the calibrated area. Under these assumptions, the extrapolated values are treated as valid for the subsequent analysis.

3.2. Condensation Probes

In the next step, the condensation probes introduced in Section 2.4 are prepared. On the sides facing the camera and the laser, the same number of layers of ZnO coating is sprayed as was done during calibration. The layers are also dried again between the coats. Since the configuration and dimensions of the cameras, laser, and the intervening plate are identical to those of the calibration setup, it can be assumed that the same geometrical boundary conditions apply to both the calibration and the actual measurement. The final setup during the actual measurements can be seen in Figure 3. For all subsequent tests, the same boundary conditions were used for the flow onto the condensation probes. For this study, an operation point with an air mass flow of $\dot{m} = 0.3 \text{ kg/s}$, an inlet flow temperature of $T_{air} = 308.15 \text{ K}$ and a relative humidity of $RH_{air}(T_{air}) = 20 \%$ is applied.

Given that steady-state conditions are being considered, a total of 300 images are captured at a frequency of $f = 10 \text{ Hz}$ resulting in a total recording time of $\tau = 30 \text{ s}$. These raw images of both chan-

nels RC and BC are averaged over time, aligned using a spline interpolation, and smoothed using a $2 \text{ px} \times 2 \text{ px}$ Gaussian filter. The intensity ratio $\mathbb{I}$ is then calculated pixel-by-pixel using Equation 1. With the help of a reference measurement for each probe at $T_{ref} = T_{air} = T_{cool} = 298.15 \text{ K}$ and Equation 2 the normalized intensity ratio field $\mathbb{I}_{norm}$ is determined. Pixel-wise outliers in the normalized intensity ratio field were detected and excluded using a median-based criterion. Values deviating by more than three scaled median absolute deviations (MADs) from the field median were replaced by NaN. The MAD was chosen because it remains robust against extreme values, ensuring that the outlier threshold is not biased by the artifacts themselves. In the subsequent temperature fields in Figure 6, these outliers appear as dark spots. Using Equation 3 from the calibration measurement performed in Section 3.1, the normalized intensity ratio field is converted into a temperature field. This temperature field can be seen in Figure 6 for the basic round geometry (a) and the straight inward-curving square tube geometry at two coolant temperatures T_{cool} (b) and (c).

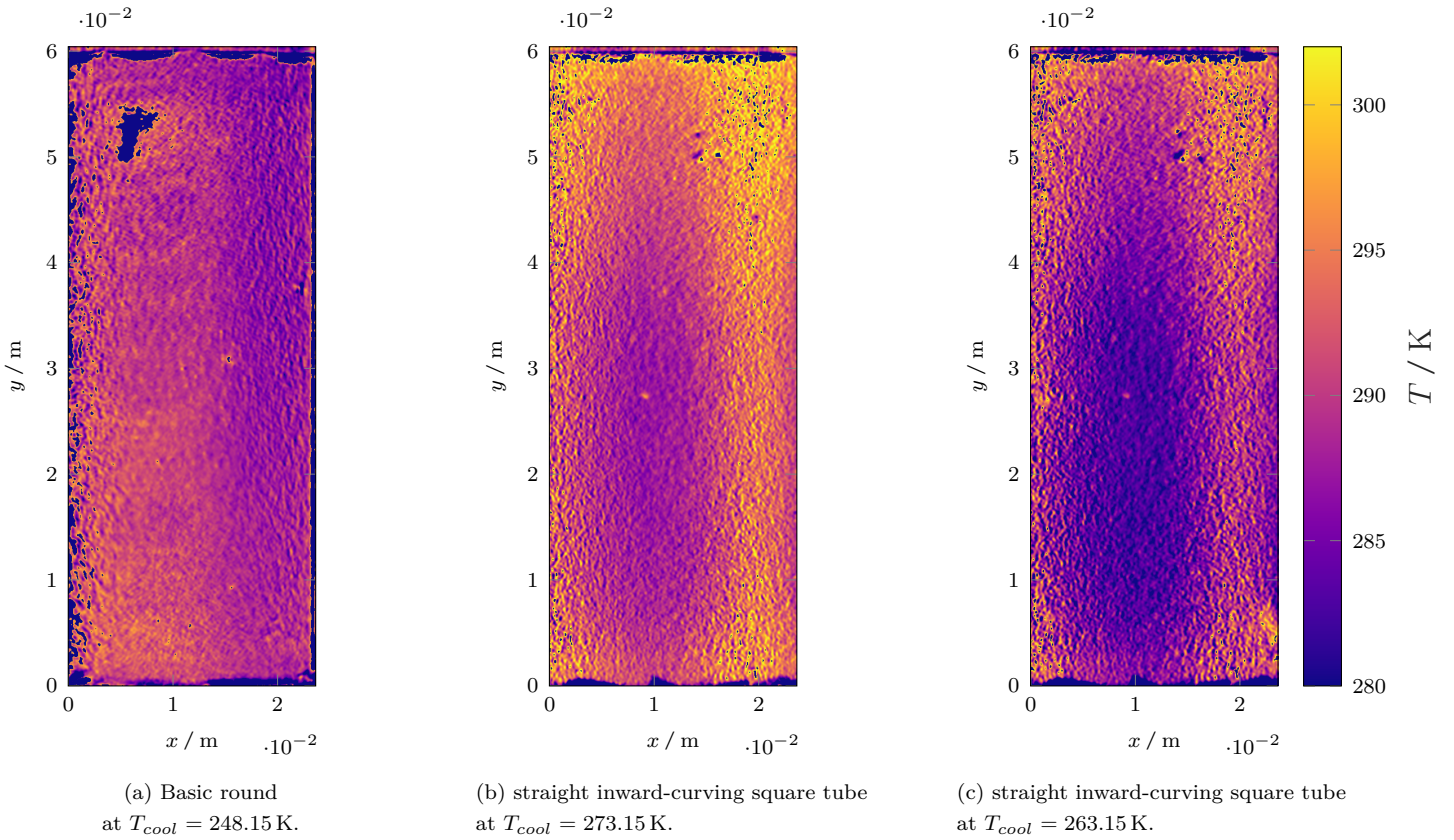


Figure 6. Two-dimensional temperature fields on the sidewalls of the basic round geometry (a) and the straight inward-curving square tube geometry (b) and (c).

The distribution of the temperature field depicted in Figure 6 (a) for the basic round geometry shows the characteristic temperature field for a subcooled circular cylinder mounted perpendicular to a turbulent hot air stream. A horizontal temperature gradient is visible at $x \approx 1.6 \cdot 10^{-2} \text{ m}$ and

indicates the location of the turbulent boundary-layer separation throughout the entire height y of the condensation probe. Downstream of the separation point, the recirculation region significantly reduces the transfer of convective heat from the hot turbulent free flow to the surface, so the surface temperatures decrease there. In contrast, the attached-flow region upstream of the separation point exhibits stronger convective heating, which results in higher surface temperatures in this regime. An artifact visible in the upper left region originates from the detached coating during the reference measurement.

The uniform distribution of the horizontal temperature profile across the height of the condensation probe can also be seen in Figure 7. The temperature profiles correspond to three different heights $y_1 = 4.5 \cdot 10^{-2}$ m, $y_2 = 3.0 \cdot 10^{-2}$ m, and $y_3 = 1.5 \cdot 10^{-2}$ m. All profiles are spatially smoothed with a Savitzky-Golay filter with a window size of $w = 31$ px and a polynomial order of $n = 3$. For better readability, every fifth data point is displayed in Figure 7.

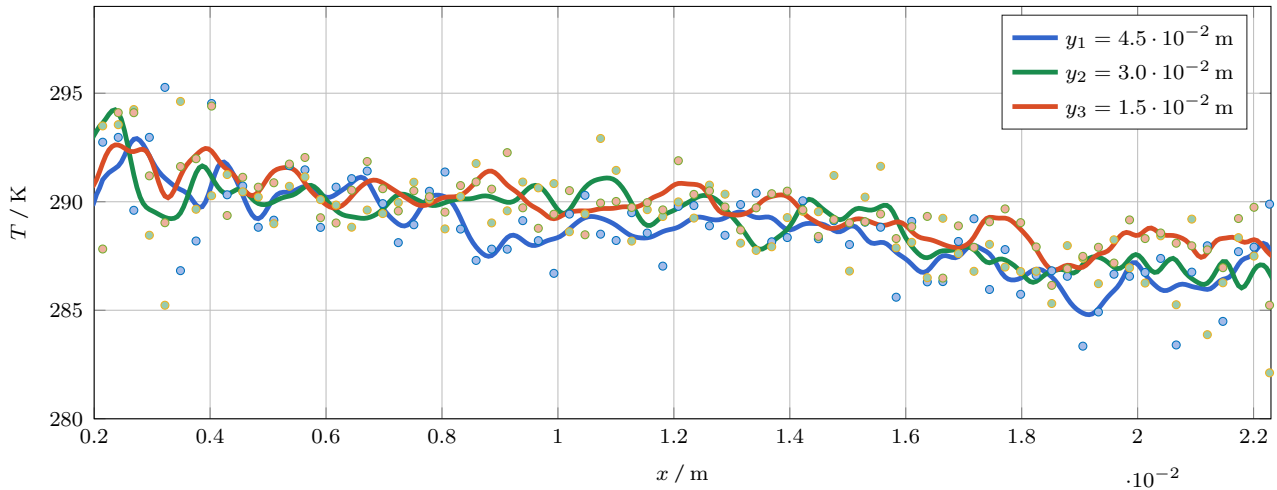


Figure 7. Horizontal temperature profiles $T(x)$ along the basic round probe extracted at three different heights y at $T_{cool} = 248.15$ K. Profiles are spatially smoothed with a Savitzky-Golay filter (window size $w = 31$ px, polynomial order $n = 3$).

All three y positions indicate a decrease in temperature along the x -axis in flow direction. The horizontal temperature gradient is also visible at $x \approx 1.6 \cdot 10^{-2}$ m where the temperature drops by 2 K. Additionally, the temperatures remain constant along the y -axis, which indicates a steady state. The temperature field distribution in Figure 6 (a) and the temperature profiles in Figure 7 indicates that condensation will first occur on the back of the probe, since temperatures there drop below the dew point earlier than on the front side of the condensation probe.

The distribution of the temperature fields depicted in Figure 6 (b) and (c) for the inward-curving square tube geometry show features that are characteristic of the shape of the sample. They only differ in the coolant temperature T_{cool} where the coolant in Figure 6 (b) is 10 K warmer than in Figure 6 (c). On the one hand, higher temperatures can be seen in the areas that protrude furthest

into the turbulent free stream at $x_1 \approx 0.2 \cdot 10^{-2}$ m and $x_2 \approx 2.0 \cdot 10^{-2}$ m. On the other hand, lower temperatures are found in the inward-curved area at $x_1 < x < x_2$ with global minima at $x = 1.0 \cdot 10^{-2}$ m, as can be seen in Figure 8 and Figure 9.

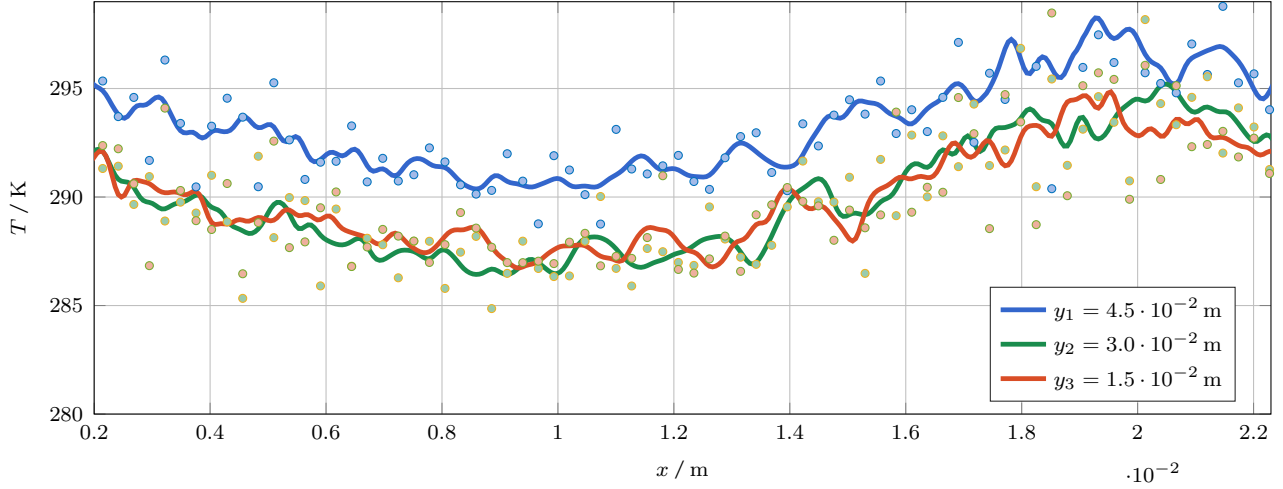


Figure 8. Horizontal temperature profiles $T(x)$ along the straight inward-curving square tube probe extracted at three different heights y at $T_{cool} = 273.15$ K. Profiles are spatially smoothed with a Savitzky-Golay filter (window size $w = 31$ px, polynomial order $n = 3$).

This is further supported by the horizontal temperature profiles at various heights, as depicted in Figure 8 and Figure 9. Although the horizontal temperature distribution remains consistent throughout the height y , an increase in temperature can be found in the upper half of the condensation probe, as indicated by the temperature profile of the height y_1 . This suggests that the sample is cooled at different cooling rates across their height and requires further investigation.

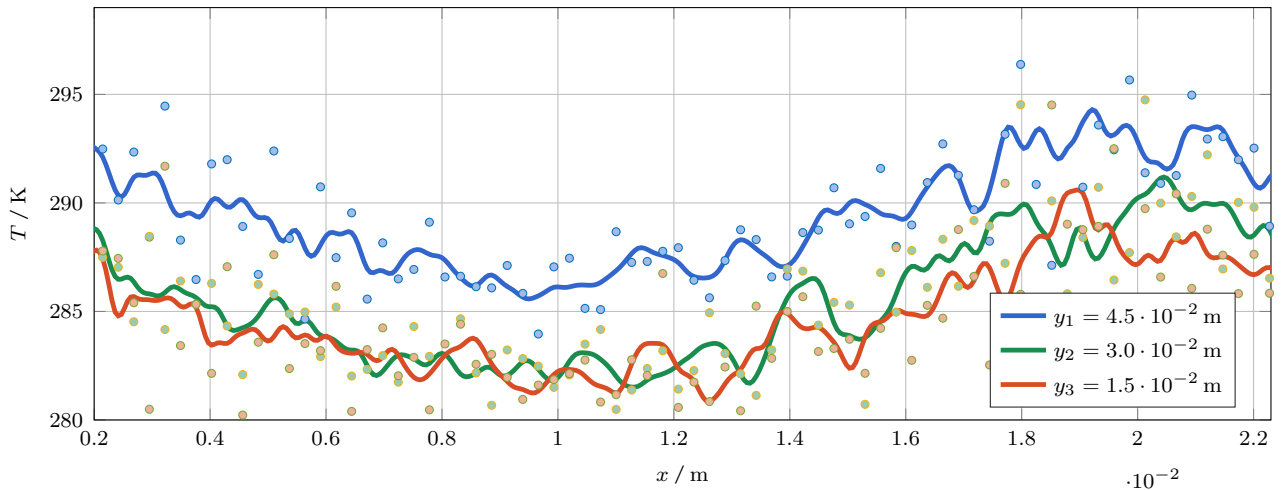


Figure 9. Horizontal temperature profiles $T(x)$ along the straight inward-curving square tube probe extracted at three different heights y at $T_{cool} = 263.15$ K. Profiles are spatially smoothed with a Savitzky-Golay filter (window size $w = 31$ px, polynomial order $n = 3$).

Based on Figure 6 (a) and (c) and the required cooling temperatures T_{cool} , the performance of the two geometries can already be compared. With the straight inward-curving square tube geometry, areas on the side wall of the sample can be cooled more effectively than with the basic round geometry. This is reflected in two observations: despite a 15 K higher coolant temperature, the surface temperature on the modified geometry remains below that of the basic round sample.

4. Conclusions

In this work, a calibration facility for zinc oxide coatings on surfaces using the spectral intensity ratio method was established and has been successfully put into operation. The calibration was carried out in the temperature range from $T_{min} = 283.15$ K to $T_{max} = 298.15$ K and yielded a temperature uncertainty of $\sigma_T = 0.46$ K, demonstrating the suitability of the experimental setup and processing routine for quantitative surface temperature measurements. Using this calibration, LIPT measurements were performed on two condensation probe geometries - a basic round geometry and a straight inward-curved square tube geometry - exposed to a humid turbulent cross-flow. Both probes were manufactured by additive manufacturing, which enabled the realization of novel geometries compared to conventional fabrication methods. The resulting two-dimensional surface temperature fields were evaluated with the calibration and reveal the spatial heat-transfer characteristics of the investigated geometries in detail. Qualitatively, the temperature distributions on both condensation probe geometries show consistent features, in particular the formation of a horizontal temperature gradient that marks the location of flow separation on the basic round geometry. Beyond this qualitative agreement, the comparison between the two geometries demonstrates the enhanced cooling performance of the inward-curving square tube probe: despite a 15 K higher coolant temperature, the surface temperature on this geometry remains below that of the basic round sample. This is consistent with the design intent of the two inward-curving square tube geometries, which were optimized to create zones with increased condensation potential and to enlarge the existing condensation zones of the basic geometry.

The future focus will be on three aspects. First, the calibration range will be extended towards lower temperatures in order to interpret the surface temperatures observed below the dew point, where the local release of heat of condensation is expected to influence the measured temperatures. Second, a more detailed analysis of the interaction between the turbulent free flow and the surfaces on the two considered geometries will be carried out along with a parametric study covering various coolant temperatures and flow conditions. Third, a bent inward-curving square tube geometry will be investigated to further explore the additional formation of condensation on the surface and the removal of condensed water.

Acknowledgements

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Nomenclature

a	Slope [1/K]
b	Constant [-]
d	Diameter [m]
E	Volumetric energy density [J/m ²]
f	Frequency [Hz]
F	Laser fluence [J/m ²]
h	Hatch spacing [m]
H	Height [m]
I	Intensity [counts]
$\mathbb{I}$	Intensity ratio [-]
L	Length [m]
$\dot{m}$	Mass flow rate [kg/s]
Ma	Mach number [-]
n	Polynomial order [-]
P	Power [W]
RH	Relative humidity [%]
t_L	Layer thickness [m]
T	Temperature [K]
v	Velocity [m]
w	Window size [px]
W	Width [m]
x	Horizontal direction [m]
y	Vertical direction [m]
α	Laser angle [°]
λ	Wavelength [nm]
σ_T	Temperature uncertainty [-]
τ	Recording time [s]

References

- Abram, C., Fond, B., & Beyrau, F. (2018). Temperature measurement techniques for gas and liquid flows using thermographic phosphor tracer particles. *Progress in Energy and Combustion Science*, 64, 93-156. doi: 10.1016/j.pecs.2017.09.001
- Allison, S. W., & Gillies, G. T. (1997, 07). Remote thermometry with thermographic phosphors: Instrumentation and applications. *Review of Scientific Instruments*, 68(7), 2615-2650. doi: 10.1063/1.1148174
- Brübach, J., Pflitsch, C., Dreizler, A., & Atakan, B. (2013). On surface temperature measurements with thermographic phosphors: A review. *Progress in Energy and Combustion Science*, 39(1), 37-60. doi: 10.1016/j.pecs.2012.06.001
- Cheng, D. Y., & Nelson, A. L. C. (2002, 06). The chronological development of the cheng cycle steam injected gas turbine during the past 25 years. *Proceedings of the ASME Turbo Expo 2002, Volume 2: Turbo Expo 2002, Parts A and B*, 421-428. doi: 10.1115/GT2002-30119
- Neubert, P. (issued 1937 (application in Germany 1932)). Device for indicating the temperature distribution of hot bodies. *US Patent Specification*(2,071,471).
- Rodnyi, P. A., & Khodyuk, I. V. (2011). Optical and luminescence properties of zinc oxide (review). *Optics and Spectroscopy*, 111, 776-785. doi: 10.1134/S0030400X11120216
- Schmitz, O., Klingels, H., & Kufner, P. (2021, 01). Aero engine concepts beyond 2030: Part 1—the steam injecting and recovering aero engine. *Journal of Engineering for Gas Turbines and Power*, 143(2), 021001. doi: 10.1115/1.4048985
- Schwab, A. (2024). *A contribution to transpiration cooling for rocket combustion chambers in a stacked transpiration cooling arrangement* (Published doctoral dissertation). University of Stuttgart.
- Särner, G., Richter, M., & Aldén, M. (2008, oct). Investigations of blue emitting phosphors for thermometry. *Measurement Science and Technology*, 19(12), 125304. doi: 10.1088/0957-0233/19/12/125304
- Thureau, P. (1957). Une nouvelle methode de mesure des temperatures utilisant la thermosensibilite des fluorescence. *Publications Scientifiques et Techniques du Ministere de l'air*, 73, 147-52.