

Film temperature and thickness measurements of an impinging oil jet for cooling of electric components based on two-color laser-induced fluorescence

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ABSTRACT

A fluorescence based two-color detection scheme is used to characterize a jet impingement cooling process relevant for electric and electronic applications. The presented technique enables a simultaneous determination of film temperature and film thickness. The fluorescence signal was generated by the temperature-sensitive fluorescence tracer nile red, which was added to Marlotherm LH, a commercially available heat transfer oil. Suitable band pass filters enable accurate temperature measurements.

A preliminary spectral study investigates the influence of dye concentration, temperature and film thickness. At high dye concentrations (up to 37.5 mg/L) reabsorption effects takes place and lead to a spectral shift towards higher wavelengths with increasing film thickness. Low dye concentrations (0.59 mg/L) exhibit no film thickness dependent spectral shift. A film temperature investigation at low dye concentration showed no bias of the intensity ratio due to film thickness, i.e. no additional spectral shift towards lower wavelengths was observed. The investigations on the jet impingement setup revealed an increasing film temperature and decreasing film thickness with increasing solid temperature. The average film temperature increases with increasing solid temperature from 298 K (solid temperature 298 K) to 308 K (solid temperature 398 K). At higher solid temperatures, the film temperature increases with distance to the stagnation zone. The average film thickness decreases with increasing solid temperature from 0.24 mm to 0.17 mm. At high solid temperatures, the film temperature increased with radial distance to the stagnation zone. This behavior is caused by the increasing temperature gradient with increasing solid temperature and decreasing viscosity with increasing film temperature.

1. Introduction

Nowadays electric and electronic devices are ubiquitous in our lives, since they are present in various sectors (industrial, aerospace, automotive, energy, etc.). An optimization of those systems take place in a way that the systems become more and more compact in combination with increased performance. This is only achievable by highly complicated thermal management solutions, which could enable high heat flux dissipation rates in combination with a homogenous temperature distribution. Large heat flux dissipation rates of electric and electronic devices were often realized by immersion cooling (Pambudi et al., 2022; Roe et al., 2022), heat pipes (Abdelkareem et al., 2022; Pandey & Kumar Gupta, 2022) and impingement cooling (Celata et al., 2009; Labergue et al., 2015).

Jet or spray impingement cooling is a very efficient cooling method paired with an economic liquid consumption and is described for this reason in more detail (Labergue et al., 2015). The technique is based on an intact jet or otherwise small atomized droplets impacting the hot surface, forming a liquid film and leading to high dissipation flux. The spray impingement is governed by its sub-processes. An optimization requires the improvement of these sub-processes, where a deep understanding is indispensable. Besides the atomization process, the film temperature and the film thickness determine the dissipated heat flux and the required volume flow of the cooling fluid.

Until now, only a few investigations deal with simultaneous detection of the film thickness and temperature. Schagen et al. studied the film thickness and temperature in a laminar, wavy film of water doped with biacetyl. The developed technique is based on the fact that biacetyl emits fluorescence as well as phosphorescence when illuminated under UV light (Schagen et al., 2006). The local film thickness is determined by the fluorescence, while the film temperature is determined by the phosphorescence. Borgetto et al. investigated the film temperature and thickness of a liquid heptane film along a wall with a low-coherence interferometry technique. The presented technique show some limitations, such as the minimum possible thickness, which is restricted by the coherence length of the light source ($20\text{ }\mu\text{m}$ @ 1310 nm) and the influence of surface waves on the measurement results (Borgetto et al., 2013). Huang et al. investigated the temperature profile and thickness of a lubricant film during machining based on laser-induced fluorescence (LIF). They utilized a combination of a temperature-insensitive probe (fluorescence pink) and temperature sensitive probe (europium 3 thenoyltrifluoroacetate (EuTTA) (Huang et al., 2014). Wu et al. investigated the film thickness and temperature of water on a metal plate with diode laser absorption spectroscopy. Their results are in good agreement with thermocouple

(temperature deviation: 2.0 %) and ultrasonic pulse-echo method (film thickness deviation: 3.3 %) measurements (Wu et al., 2021). Collignon et al. investigated thin liquid films flowing down a heated and inclined plane based on a two-color LIF technique. They determined film temperature and film thickness of water simultaneously and quantified the heat transfer coefficient (Collignon et al., 2022). Similar measurements in heat transfer oil films are not reported in the literature so far. The present study focuses on film thickness and temperature measurements of a jet impingement cooling process of a cylindrical geometry based on a two-color detection technique developed in an earlier study of the group (Koegl, Delwig, et al., 2022). For this purpose, Nile red was dissolved in the heat transfer oil Marlotherm LH (Koegl, Delwig, et al., 2022). The present publication gives an overview of calibration data and planar LIF measurements in the jet impingement setup, while a detailed description is given in [Koegl EXIF 2024]. The paper is structured as follows: First, tracer concentration dependent spectral measurements are carried out for various film thicknesses in a special calibration setup enabling various liquid film thicknesses and temperatures. Second, temperature dependent measurements for various film thicknesses at a constant tracer concentration were performed spectrally and by using the imaging setup. Third, temperature and liquid film thickness were determined using a jet impingement driven film cooling setup for various solid body temperatures. Finally, a brief conclusion and an outlook is provided.

2. Experimental setup

Two fluorescence setups were designed for the calibration of temperature and liquid film thickness (1) as well as the jet impingement measurements themselves (2). The experimental setups are shown in Figure 1 and Figure 2. A cw laser (model: LSR532F-2500, 532 nm, 2.5 W, Lasever, China) is used to illuminate the probe region in both setups. A remote-controlled external shutter enables a probe illumination only during measurements and possible photo-dissociation effects were kept as low as possible. A beam expander just after the laser exit is used to expand the beam by the factor of 8. A glass plate was applied to monitor the laser fluence simultaneously (model: S425C coupled to PM10D, Thorlabs, USA). The transmitted expanded beam hits the probe region under a 75° angle. This illumination angle allows a perpendicular signal detection of the liquid film. A fiber coupled spectrometer (model: Maya 2000-Pro, Ocean Optics, USA, wavelength range: 200.5-1120.4 nm, pixels 2048, slit size 25 μm , integration time 100 ms, 20 subsequent spectra were averaged for each measurement) with a detection optic and a camera system (for more details see (Koegl et al., 2024)) are used for signal detection. The detection optic is placed 100 mm above the

probe region and collects the fluorescence signal of an area of 10 mm^2 in the center of the liquid film (see Figure 1).

2.1 Fluorescence film calibration setup

The calibration of the liquid film thickness was conducted as follows: In order to generate the liquid films with various thickness, heated inserts with various slot depths (0.3 mm- 2 mm) were produced. The inserts are made of the same material as the cylindrical surface (aluminum 7075, same charge) described in the subsequent paragraph with the same sandblasted surface treatment to ensure comparability. The coolant-tracer mixture is placed with a syringe in the cavity, a cover glass (thickness 0.16 mm) in combination with a metal ring ensures accurately adjusted film thickness. A small thermocouple (type K, diameter: 0.25 mm, tc-direct, Kitzingen, Germany; accuracy $\pm 0.3 \text{ K}$) in the liquid volume ensures constant measurement conditions. The temperature of the liquid film is adjusted and kept constant with a modified soldering iron (model WT 1010H, Weller, Besigheim, Germany).

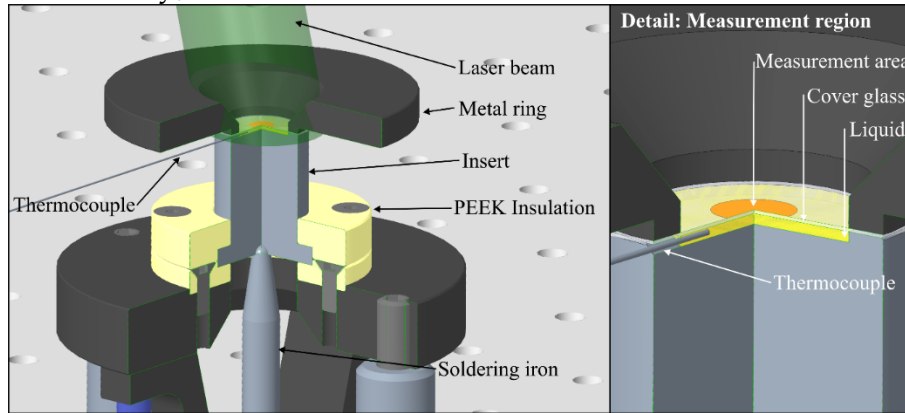


Figure 1: Optical setup for the spectral measurements.

2.2 Jet impingement cooling setup

The optical setup for the jet impingement measurements is shown in Figure 2. The illumination of the probe region remains the same as already described in the previous section. Instead of the spectrometer, a specially designed camera system, which is equipped with a long-distance microscope (Infinity, Distamax K2, Centennial, CO, USA) is used. The two detection bands of the LIF signals were recorded simultaneously. A geometric calibration (mapping) is performed in Matlab® to ensure proper alignment of the two detection channels. The LIF signal bands are detected by using appropriate filters (Edmund optics: filter1: 568 nm (#65-221), filter2: 632 nm (#65-166); 10 FWHM), which were selected in a previous study (Koegl, Delwig, et al., 2022). The

coolant-tracer mixture is pumped in a closed loop (2000 ml liquid volume) with an adjustable modified gear pump (model: UP3, Marco s.p.a., Castenedolo, Italy). The fluid went via an adjustable bypass through a seamlessly drawn stainless steel tube (1mm inner diameter, nozzle velocity: 2.03 m/s) and hits the heated cylindrical surface (diameter 15 mm) perpendicular in the center. The surface (aluminum 7075) is heated with a heating cartridge (model: RS PRO 200W, RS-Components, Frankfurt am Main Germany) driven by a laboratory controller (model: LR 316, Jumo, Fulda, Germany). The Reynolds and Prandtl numbers at 293 K are calculated at the nozzle outlet to be $Re = 508$ and $Pr = 48.7$, respectively. Fluid properties are also provided in table 1.

The solid temperature T_s of the cylinder is measured 1 mm below the surface with a thermocouple (type K, tc-direct GmbH, Kitzingen, Germany; accuracy ± 0.3 K). The surface is sandblasted to achieve a homogeneous surface without any manufacturing traces and ensure a homogeneous reflection behavior. The temperature of the coolant circuit is kept constant by a counterflow heat exchanger driven by a recirculating thermostat (model: CP50, Thermo Fisher Scientific, Waltham, MA, USA). Multiple thermocouples (type K, tc-direct GmbH, Kitzingen, Germany) at the nozzle outlet, before the pump and after the cooler ensure constant measurement conditions.

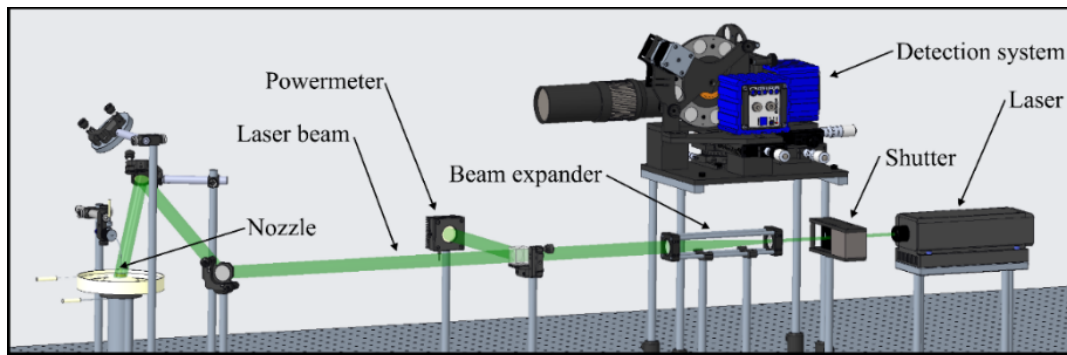


Figure 2: Optical setup for the fluorescence measurements

2.3 Coolant and tracer used

In the present study, the emission signal of the heat transfer fluid Marlotherm LH (Sasol Germany GmbH, Hamburg, Germany) in combination with the fluorescence tracer Nile red were investigated. The chemical and physical properties of Marlotherm LH are shown in Table 1.

Table 1: Physical properties of Marlotherm LH (Eastman chemical company, 2022; McClintock, 2003).

Property	Unit	Marlotherm LH
Density	g/cm^3	9.960 (293 K)
Heat conductivity	$\text{W/(m}\cdot\text{K)}$	0.132 (293 K)
Kinematic viscosity	mm^2/s	4.00 (293 K)

Specific heat capacity	kJ/(kg·K)	1.614 (293 K)
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Nile red is soluble in alkanes and real-world fuels (multi component fuels) (Durst et al., 2018). A minimum of 3.75 mg of Nile red was weighted with a high-precision analytical scale (Mettler Toledo XS 205, proofed repeatability 0.05 mg). The tracer was completely dissolved in the investigated heat transfer oil. Nile red has a melting point of 476 K – 479 K (Roth, 2019), but this temperature is above the maximum tested temperature in the current setup. For the present study, tracer concentrations of 0.59 mg/L – 37.5 mg/L were investigated. The various investigated tracer concentrations were generated by diluting the initial oil–tracer mixtures.

2.4 2-color detection scheme for temperature determination

The temperature of the liquid-dye mixture can be determined with the intensity ratio r of the two detection channels CH1 and CH2, respectively. After the determination of the local temperature, the film thickness can be determined by the intensity ratio r and the intensity of either CH1 (used in this study) or CH2. In a preliminary spectral study, we determined the intensity ratios for the dye in different oils for a dye concentration of 9.38 mg/L. The fit parameters and the corresponding coefficient of determination can be found in (Koegl, Delwig, et al., 2022). However, in the present study, the dye concentration is much lower (0.59 mg/L) resulting in a significantly reduced fluorescence reabsorption. Additionally, a different detection system is applied as in the previous work, so that the fit parameters have to be calculated again. The ratio r can be determined using the ratio of the two products of the transmission curves τ of the respective filters and the spectral fluorescence emissions I_{CH1} and I_{CH2} : (when other efficiencies of the optical setup (e.g., cameras) are neglected):

$$r = \frac{\sum \tau_{Filter_568nm} \cdot I_{LIF}}{\sum \tau_{Filter_632nm} \cdot I_{LIF}} = \frac{I_{CH1}}{I_{CH2}} \quad (1)$$

3. Results

This section is structured as follows. First tracer concentration dependent spectral measurements were carried out for various film thicknesses at constant temperature. Here, the influence of the film thickness on the spectra due to reabsorption effects were studied. Second, temperature and film thickness were calibrated spectrally and by imaging at a constant optimal tracer concentration. Afterwards, a jet impingement cooling process is investigated and the film

temperature and film thickness are determined at various liquid volume flows. All spectral results are presented in the visible wavelength range (380 nm-780 nm), which is most relevant for the absorption and emission of nile red (Koegl et al., 2019).

3.1 Spectral measurements

3.1.1 Film thickness variation

The emission spectra of nile red at various concentrations dissolved in Marlotherm LH for various film thicknesses are shown in Figure 3.

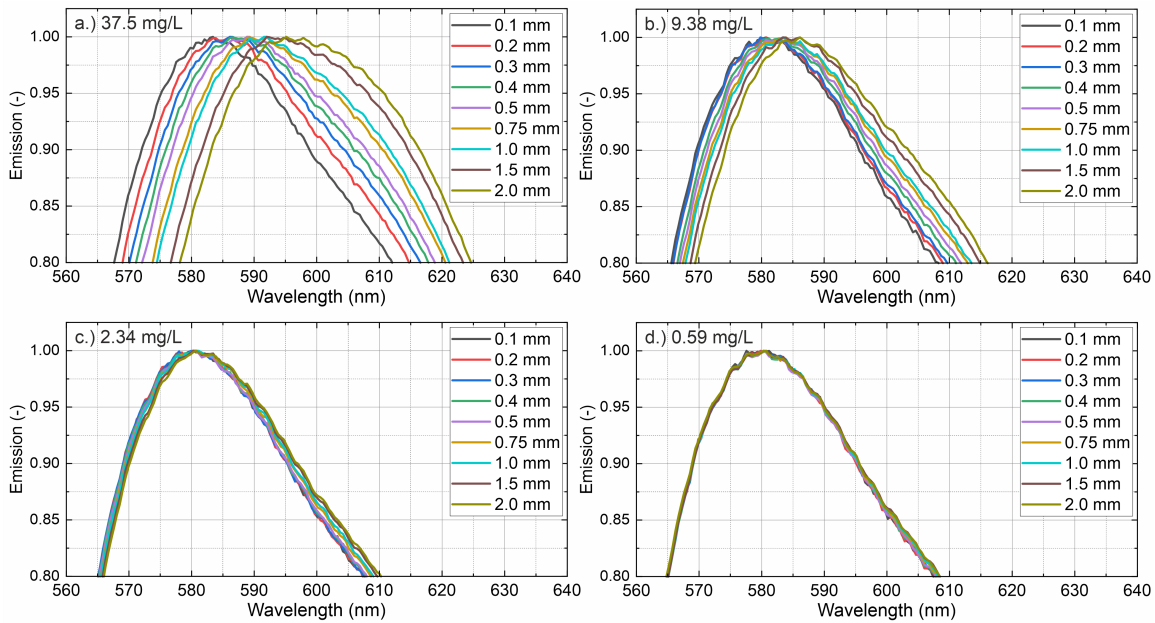


Figure 3: Normalized emission spectra of nile red at various concentrations and film thicknesses, 298 K.

Here, the peak regions are magnified, since an occurring spectral shift is important for the measurement uncertainty of the applied technique. The measurements revealed a spectral shift of the maxima and both flanks towards larger wavelengths with increasing film thickness. This behavior is caused by reabsorption effects, since the fluorescence at lower wavelengths is in the absorption band and may lead to an excitation of the tracer. An investigation on the absorption (and fluorescence) of the used tracer-oil mixture was already performed in a previous paper of the group (Koegl, Delwig, et al., 2022). A decrease of the tracer concentration leads to a decrease of the film thickness dependent spectral shift, since the reabsorption effect is reduced with lower tracer concentration. A 2-color ratio technique for the determination of the temperature is only applicable, when the temperature dependent spectral shift is not affected by a variation in film thickness.

On the other hand, a sufficient signal to noise ratio (and thus large tracer concentrations in principle) is indispensable for reliable measurements. To achieve a good signal to noise ratio, a high laser fluence would be beneficial. However, this could be problematic as tracer dissociation may occur. Thus, cw lasers (continuous wave) and LEDs are advantageous compared to pumped laser systems. These illumination systems enable a longer exposure time (here 100 ms), while pumped lasers illuminate usually between 6 ns to 8 ns. CW-lasers feature a very narrow spectral emission (down to 1 nm FWHM for Raman spectroscopy) compared to LEDs (30 nm FWHM and larger). Previous investigations with the same tracer-oil mixture in a larger volume revealed no photo-dissociation effects within 20 min at constant laser illumination with an pulsed Nd:YAG laser (Koegl, Delwig, et al., 2022). The cw-laser in the current setup in combination with the high radiant power, long illumination duration and low film thicknesses of the spectral setup (see Figure 1) lead to significant photo-dissociation effects, which have to be taken into account (i.e. by changing the tracer-liquid mixture after each measurement). The photo-dissociation effect for the impingement cooling setup is neglectable, since the volume (2000 mL) for the operating time is large enough. The spectral shift within the investigated thickness interval (0.1 mm – 2.0 mm) for various dye concentrations is shown in Table 2. The spectral shift of 13.6 nm (@ 37.5 mg/L) decreased to 0.1 nm (@ 0.59 mg/L) with decreasing tracer concentration. For the following investigations a concentration of 0.59 mg/L is used.

Table 2: Film thickness dependent spectral shift of the emission peak for various dye concentrations.

Concentration (mg/L)	Spectral shift (nm)
37.5	13.6
9.38	5.5
2.34	1.4
0.59	0.1

3.1.2 Temperature study

The temperature dependent film thickness is measured spectrally and by imaging. The planar measurements were conducted with a detection system (see imaging setup Figure 2) with respective band pass filters. For the 2D measurements, the fluorescence intensities within a region of interest (ROI, see Figure 1) are summed up and the ratio is determined. The emission spectra of Nile red dissolved in Marlotherm LH for various temperatures and at a film thickness of 0.5 mm are shown in Figure 4. Here, the peaks are magnified again, since the spectral shift is important for the measurement uncertainty of the applied technique. The measurements revealed a spectral shift

of 6.3 nm of the maxima and both flanks towards lower wavelengths with temperature. A variation of the film thickness does not affect the spectra, since the dye concentration is low enough (see previous section).

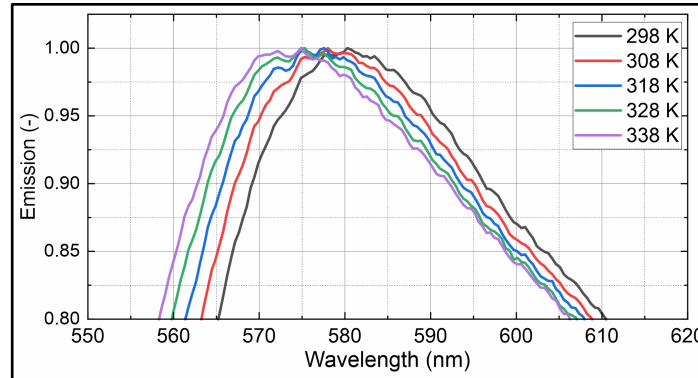


Figure 4: Normalized emission spectra of Nile red at various temperatures at a film thickness of 0.5 mm, 0.59 mg/L.

3.2 Imaging measurements

For the following measurements a dye concentration of 0.59 mg/L was used as discussed above. The camera-based detection system has a different efficiency (filters, lenses, mirrors and quantum efficiency of the sCMOS, etc.) in comparison to the spectroscopic setup. The temperature and film thickness dependent measurements at a fixed dye concentration have to be repeated, to ensure an adequate calibration of the setup. The results can be found in (Koegl et al., 2024).

The impingement heat transfer takes mainly place in the stagnation zone and the wall-jet zone of the impinging jet (Liu et al., 2014). For the experiments, only the wall-jet zone can be evaluated, since so called morphologic dependent resonances, MDRs (or whispering gallery modes) are present from the hydraulic jump radially outwards. These effects emit signal at larger wavelengths and thus may cause significant measurement uncertainties (Koegl, Dai, et al., 2022). However, the temperature of the wall jet region is the scope of the present paper, since it governs the heat transfer and no MDRs were observed there. The temperature and film thickness are determined by the calibration curves derived from the fluorescence film calibration setup (see Figure 1).

The temperature and film thickness dependent intensity ratio and the respective spatial standard deviations in the ROI are shown in Figure 5. Since the intensity ratio is not dependent on the film thickness for low tracer concentrations (see **Error! Reference source not found.**), an average for the determination of the fit equation was applied.

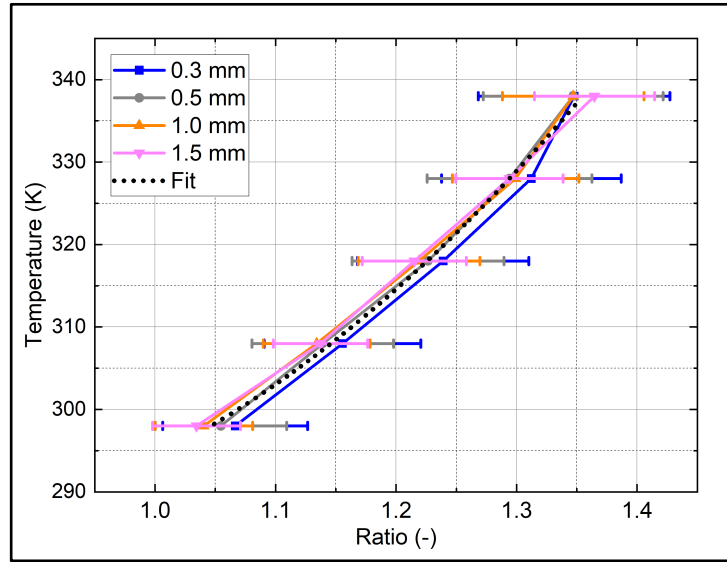


Figure 5: Calibration of film temperature and film thickness dependent intensity ratio determined by using the imaging setup. Error bars refer to the spatial precision (standard deviation) in the ROI.

This polynomial fit of the regression function gave the best value of the coefficient of determination R^2 , which is 0.99851. The spatial standard deviations of the intensity ratio are between 0.0365 - 0.0795, which corresponds to a COV between 3.4 % - 5.9 %. The temperature sensitivity decreases almost linearly from 1.02 at 298 K to 0.51 at 338 K.

The film thickness t_{Film} is dependent on the signal intensity I_{CH1} and the temperature T_{Film} (see Figure 4). Since the measurements revealed a film thickness and film temperature of the operating points (impinging jet) in the interval of [298 K – 318 K] and [0.2 mm – 0.5 mm] a fit of the mean values for the signal intensity of CH1 is sufficient. The measurement points, the corresponding fit and standard deviations are shown in Figure 6. The nonlinear increase of film thickness with signal intensity is caused by extinction effects, which reduce the average illumination fluence in the liquid film and signal re-absorption.

It should be noted that the calibration process is conducted by using a cover glass, while the actual film measurements are conducted in an uncovered film. This introduces differences in signal intensities between calibration and film measurements. The thickness of the cover glass used is 0.16 mm. The transmission at 532 nm is in the range of 0.92. However, reflexion effects of the uncovered film surface will also reduce the laser fluence. This has only an impact on the film thickness determination and can be corrected in the wall film measurements by adopting the laser fluence. Fluorescence scattering effects in the calibration cell may occur as well, but this is more distinct in the side wall region (visible in form of the bright rings, but this is outside the ROI of the

calibration). The temperature determination is a ratio-based method, which is less affected by variations in laser fluence.

The spatial variation (COV) of 3.4 % - 4.7% are mainly introduced by inhomogeneities in laser illumination. For complex curved geometries (such as wavy liquid films) a uniform illumination is usually not possible. Non-uniform illumination will only cause measurement uncertainties for the determination of the film thickness (and not for the thermometry), since it is based on the intensity of one detection channel only.

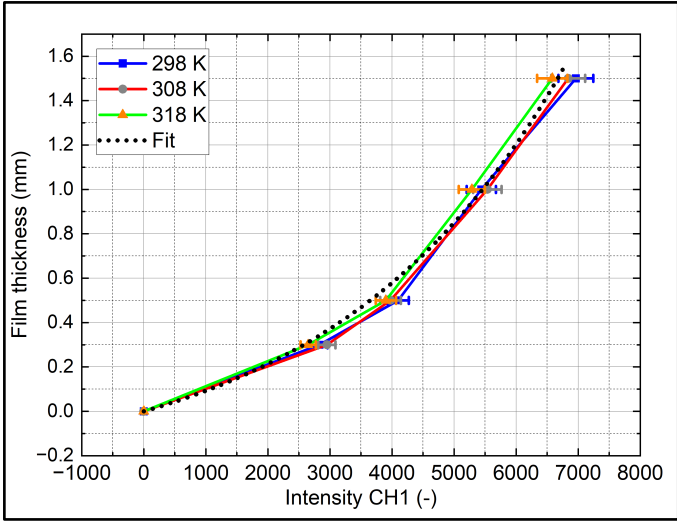


Figure 6: Fit for film thickness as a function of the temperature and the signal intensity I_{CH1} . Error bars refer to the spatial precision (standard deviation) in the ROI

The intensities of the intensity ratio, the temperature and the film thickness fields at various solid temperatures are shown in Figure 7. The corresponding solid and initial jet temperatures are shown in Table 3.

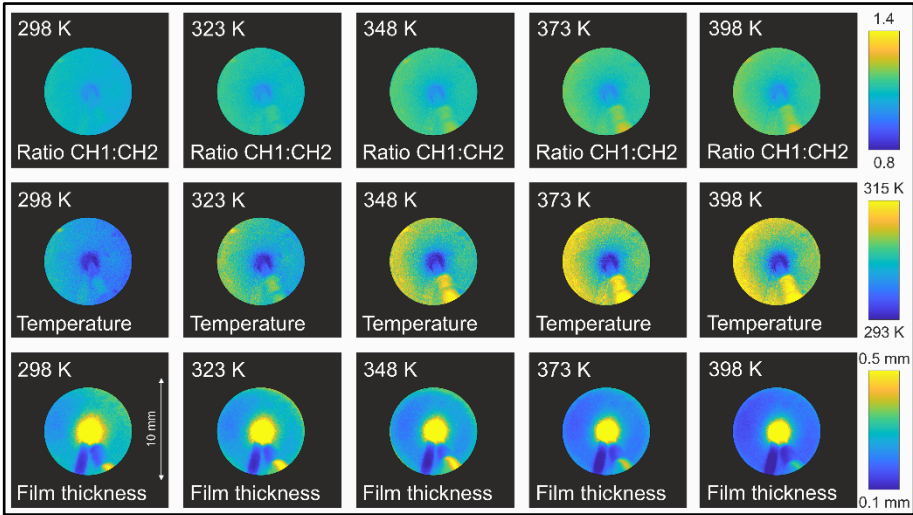


Figure 7: Signal ratio (top), temperature (center) and film thickness (bottom) fields for various solid temperatures.

The signal intensities of both detection channels are in the same range at low temperature. The intensity ratio increases with solid temperature, since the emission spectra were shifted towards lower wavelengths (see Figure 4). Since the wall-jet zone is not completely symmetric (orientation of the jet nozzle and disturbed flow field caused by elbow in the nozzle pipe), the film thickness on the left side is smaller in comparison to the right side. This leads to slightly higher film temperatures on the left in comparison to the right side. (The spatially averaged film temperature increases with increasing solid temperature from 298 K to 308 K. The temperature difference between the left and the right side for elevated temperatures (≥ 348 K) is approximately 4 K.

The solid temperature was measured on the top of the cylinder (see **Error! Reference source not found.**), thus the heat transfer process leads to a varying temperature field over the cylindrical surface. At higher solid temperatures, the film temperature increases with distance to the stagnation zone. This behavior is caused by the increasing temperature gradient with increasing solid temperature and decreasing viscosity with increasing film temperature. The average film thickness decreases with increasing solid temperature from 0.3 mm to 0.2 mm. This behavior is again caused by the reduced viscosity at higher temperatures and obviously larger flow velocity generated at the heated wall.

Table 3: Solid and initial jet temperatures (solid temperatures ± 0.3 K) measured by thermo couples.

Solid temperature (K)	298	323	348	373	398
Jet temperature (K)	295.4	295.9	295.6	295.9	295.9

It should be noted that the thermal boundary layer at the bottom of the film might influence the measurement results. Only spatially averaged temperatures can be provided and no information with the film thickness are available. If the film thickness is smaller than the theoretical thermal boundary layer, this will affect the temperature measurements. This effect could be included also in the resulting fit curve for the intensity ratio of the calibration, which is averaged for different film thicknesses.

4. Conclusions and future work

Film thickness and film temperature of a jet impingement cooling process of a simplified heated cylindrical geometry were investigated based on a two-color LIF technique. The LIF signal was created by admixture of the fluorescent dye nile red to Marlotherm LH. A spectral investigation

revealed a dye concentration dependence of the emission spectra for various film thicknesses. At high dye concentrations (up to 37.5 mg/L) reabsorption effects lead to a spectral shift towards higher wavelengths with increasing film thickness. Low dye concentrations (0.59 mg/L) show no film thickness dependent spectral shift. A film temperature investigation at low dye concentration showed a spectral shift towards lower wavelength with increasing temperature.

The investigations on the jet impingement setup revealed an increasing film temperature and decreasing film thickness with increasing solid temperature. The average film temperature increases with increasing solid temperature from 298 K (solid temperature 298 K) to 308 K (solid temperature 398 K). At higher solid temperatures, the film temperature increases with distance to the stagnation zone. The average film thickness decreases with increasing solid temperature from 0.24 mm to 0.17 mm. At high solid temperatures, the film temperature increased with radial distance to the stagnation zone. This behavior is caused by the increasing temperature gradient with increasing solid temperature and decreasing viscosity with increasing film temperature.

The temperature sensitivity of the intensity ratio was 0.51 % / K – 1.02 % / K, the spatial temperature precision was 3.4 % - 5.9 % and the spatial thickness precision 3.4 % - 4.7%. The presented technique works well on the simplified cylindrical geometry. The application of planar diagnostics for jet and spray measurements on real geometries (heat sinks and other complex geometries) is part of future work.

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