5th International Conference on Experimental Fluid Mechanics – ICEFM 2018 Munich
Munich, Germany, July 2-4, 2018

Accessing quantitative heat transfer with Temperature Decline Thermography

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Abstract

Analyzing local heat transfer on complex components in fluid flows is crucial for the optimization of modern aerodynamical systems. Many flow situations like in gas turbines, are difficult to access and require fast measurement techniques which offer two-dimensional information with negligible impact on flow conditions. Therefore, a transient measurement technique based on infrared thermography is investigated to access local heat transfer coefficients without contact by means of a calibration. A flat plate in a free-jet is used as a calibration vehicle where results are compared to the flat plate Nußelt correlation in laminar flow. To transfer the observed linear calibration relation to different flow conditions, a turbulent boundary layer is generated and results are compared to the turbulent Nußelt correlation. Good agreement of converted measurement data and theory is obtained. Temperature Decline Thermography (TDT) was introduced by the authors to qualitatively measure laminar-turbulent transition. In this work TDT is extended to access quantitative heat transfer coefficients.

1 Introduction

For the design of modern aerodynamical systems with highest possible efficiencies, it is desirable to gain detailed knowledge about laminar-turbulent transition and heat transfer distribution of flows around complex aerodynamical components. Many available measurement techniques, like for example surface hot films, access this information with great effort of instrumentation and calibration. For fast rotating devices like turbines, most techniques are impractical which is why a method based on infrared thermography was introduced recently by the authors (von Hoesslin et al., 2017, Stadlbauer et al., Patentnr. WO2014198251 A1, 2014). It was shown that Temperature Decline Thermography (TDT) can be used to qualitatively visualize laminar-turbulent transition in boundary layers. This work investigates the possibility to quantitatively derive heat transfer coefficients from TDT data.
In literature, a classification of techniques for measuring convective heat transfer is given (Carlomagno et al., 2014, Astarita and Carlomagno, 2013). The present TDT method can be correlated to a class of techniques know as thin skin calorimeter. Thin skin sensors consist of a thermally thin slab exposed to convective flow. Since a constant temperature over its thickness is assumed, local heat transfer is evaluated from the temporal change in slab surface temperature (Boutafar and Hammand, 2005, Bougeard, 2007). By using infrared thermography, no temperature sensors have to be included into the slab, since surface temperature is measured in two spatial dimensions by the IR sensor.
A particular feature of the TDT method is that it uses a pulsed light source for heating up the slab material within nanoseconds. The decay of thermal energy is measured during short periods of time ranging

between 10 to 50 ms. This allows the application of the technique in setups even when convective conditions are only stable for short durations. Due to short integration times of the camera down to a few microseconds and short heating pulses of the laser (few nanoseconds), periodic flow conditions, like on rotating turbine blades can be examined. Furthermore, heat losses due to a non-ideal isolation of the slab and radiative heat transfer, as well as errors due to reflections on the surface under test, are effectively corrected by a reference measurement without forced convection.
In this paper, heat transfer coefficients are derived from TDT data and compared to theory. This can be done by developing a model of the heat transfer processes in the slab material and calculate heat transfer coefficients by knowing the specific thermo-physical constants. However, determining those constants can be error-prone and sometimes not possible. This is bypassed in this work by conducting a calibration measurement which converts TDT data into heat transfer coefficients.
In the following heat conduction processes in the slab material are analyzed to derive a calibration relation theoretically. The relation is confirmed by measurements using Nußelt correlations. It is shown that the calibration relation recorded under specific conditions can be applied to other flow situations and geometries.

2 Measurement principle and theory

2.1 Description of thermodynamic processes during a TDT measurement

The TDT method requires a surface coating with high emissivity which is isolated by a low thermal conductivity layer against the underlying material. By radiating the coated surface with a single-pulsed laser, the topmost layers of the coating are heated up by several degrees.

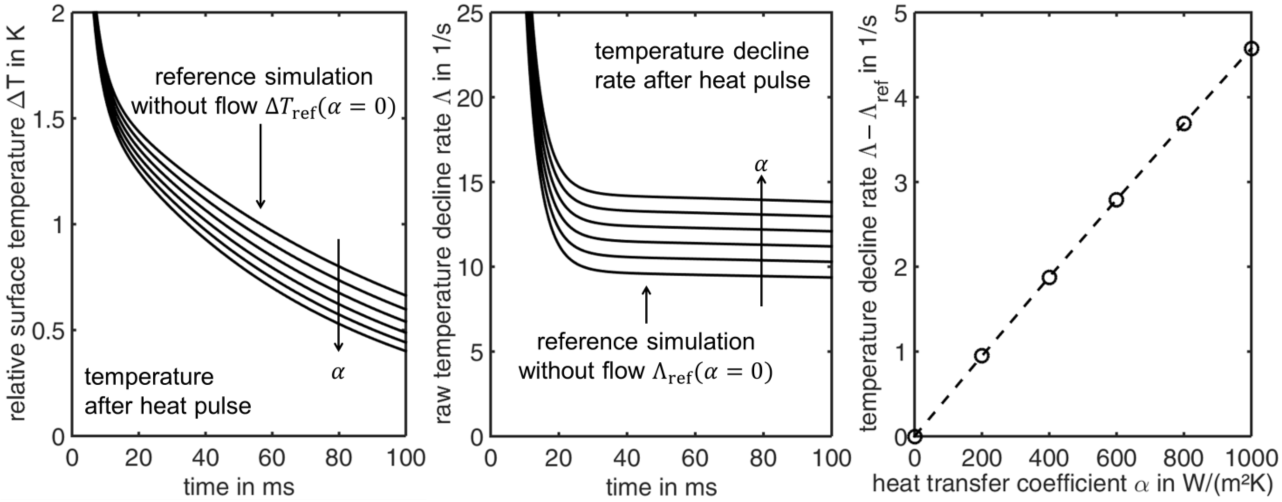

Fig. 1 Left Simulation of the temporal temperature behavior for different heat transfer coefficients $\alpha \in [0{,}1000]$ W/(m²K). **Center** Calculated raw temperature decline rate Λ for the same heat transfer coefficients. The temperature decline rate without air flow ($\alpha = 0$) is defined as Λ_{ref}. **Right** Extraction of the temperature decline $\Lambda - \Lambda_{\mathrm{ref}}$ from the quasi-constant time regime at 80 ms from the left-hand plot. A linear relation between TDT data and heat transfer coefficient is predicted.

Right after the pulse, the temperature of the surface declines due to conduction into the material, radiation and convection into the flow. The integral effect of these heat transfer mechanisms is recorded by a high-speed IR camera to determine the dynamics of the temperature decline. A post-processing algorithm is used to calculate the temperature decline rate for every pixel, to achieve a two-dimensional map of quantities proportional to the heat transfer coefficient.

To understand the dynamics of the temperature decline shortly after the heat pulse, a one-dimensional numerical simulation was developed by the authors which was outlined in von Hoesslin et al. (2017). It analyses the heat conduction in a multi-layer system under a constant convection condition. For the present case the above mentioned two-layer system with aluminum substrate material was simulated. The left-hand side of Fig. 1 shows the temporal behavior of the temperature right after the heat pulse. The simulation was performed for different convection conditions with heat transfer coefficient α varying from 0 – 1000 W/(m²K). The temperature decline rate Λ is calculated from the temporal temperature behavior (Fig. 1, center). Shortly after the heat pulse at t = 0 ms, the heat is conducted from the uppermost molecule layers of the high emissivity coating into the material. This fast process results in a rapid decrease of Λ until the isolation layer strongly reduces further conduction into the underlying aluminum substrate. The heat inside the coating layer now serves as a heat reservoir for the ongoing convection into the flow. A quasi-stationary Λ develops for several milliseconds. By plotting Λ in this time range against the corresponding α (Fig. 1, right-hand side), a linear relation is observed where TDT data can be correlated to quantitative heat transfer coefficients.

In the measurements described in this paper this linear relation was confirmed. To motivate the linear relation theoretically, the quasi-stationary state of Λ serves as a necessary prerequisite which is described in the following.

2.2 Theoretical derivation of the calibration relation

In the previous paper, a theory was developed to describe the temperature decline after the heat pulse by assuming the isolation layer beneath the slab material to be ideal and radiative losses to be negligible (von Hoesslin et al., 2017). The present paper extents this theory by additionally considering the heat conduction into the substrate material and the heat flux due to radiative heat transfer. The assumptions made for this theory lead to a calibration relation which is in agreement with numerical simulations.

After the heat pulse, the temperature decline on the surface takes place due to a combination of heat fluxes including convection into the flow $\dot{q}_{\mathrm{conv}}$, conduction into the material $\dot{q}_{\mathrm{cond}}$ and radiation $\dot{q}_{\mathrm{rad}}$

(1) $\dot{q} = \dot{q}_{\mathrm{conv}} + \dot{q}_{\mathrm{cond}} + \dot{q}_{\mathrm{rad}}$.

When quasi-stationary conditions are present, the spatial slab temperature will be almost constant and the surface temperature rise $\Delta T = T - T_\infty$ is proportional to the pulse energy q_{pulse} according to the first law of thermodynamics

(2) $\Delta T_0 = \frac{q_{\mathrm{pulse}}}{C}$.

Here, $C = c_e \rho_e h$ is a proportionality constant containing the effective specific heat of coating and isolation layer and their effective density, while h corresponds to the penetration depth of the thermal wave within the layers. Using Newton's law of cooling, the resulting differential equation can then be written as

(3) $\Delta\dot{T} = \frac{1}{C}(\alpha \Delta T + \dot{q}_{\mathrm{cond}} + \dot{q}_{\mathrm{rad}})$,

with α being the convective heat transfer coefficient

(4) $\alpha = C\frac{\Delta\dot{T}}{\Delta T} - \frac{\dot{q}_{\mathrm{cond}} + \dot{q}_{\mathrm{rad}}}{\Delta T}$.

The term $\Lambda = \Delta\dot{T}/\Delta T$ represents the temperature decline rate which can be extracted from the measured temperature behavior using the numerical representation of $\Delta\dot{T}$.

By setting α to zero, for example by performing a reference measurement without any airflow, $\Lambda_{\mathrm{ref}} = \Lambda_{\alpha=0} = (\dot{q}_{\mathrm{cond}} + \dot{q}_{\mathrm{rad}})/(C\Delta T)$ can be determined. The reference measurement is used as a correction for the measurement with flow to determine the heat transfer coefficient with negligible errors due to conduction and radiation losses

$$(5) \quad \alpha = C(\Lambda - \Lambda_{\mathrm{ref}}), \quad C > 0\,.$$

Equation (5) represents the calibration equation which will be used to convert TDT decline rates $\Lambda - \Lambda_{\mathrm{ref}}$ into heat transfer coefficients α.

2.3 Nußelt correlations used for calibration

For a calibration measurement both, $\Lambda - \Lambda_{\mathrm{ref}}$ and α must be determined to estimate the proportionality constant C. $\Lambda - \Lambda_{\mathrm{ref}}$ is measured by TDT, α is calculated using Nußelt correlations. The valid use of a Nußelt correlation requires a calibration vehicle with defined properties. For this study a flat plate with negligible pressure gradient was used for which the Nußelt correlation of laminar flow (Incropera and De Witt, 1985) takes the form

$$(6) \quad \alpha_{\mathrm{lam}}(x) = Nu_{x,\mathrm{lam}} \cdot \frac{x}{k} = 0.453 \cdot Re_x^{\frac{1}{2}} \cdot Pr^{\frac{1}{3}} \cdot \frac{k}{x}\,,$$

where x is the distance from the leading edge of the flat plate, $Nu_{x,\mathrm{lam}}$ the local Nußelt number in laminar flow, k the thermal conductivity of the fluid, Re_x the local Reynolds number and Pr the Prandtl number. For turbulent flow an empirical correlation is given (Incropera and De Witt, 1985)

$$(7) \quad \alpha_{\mathrm{tur}}(x) = Nu_{x,\mathrm{tur}} \cdot \frac{x}{k} = 0.0318 \cdot Re_x^{\frac{4}{5}} \cdot Pr^{\frac{1}{3}} \cdot \frac{k}{x}\,.$$

Since the heat flux can be considered as quasi-stationary during two time frames of a TDT measurement, the Nußelt correlation for constant heat flux was used.

3 Calibration setup

The calibration measurements were performed on a flat plate at zero angle of attack in a free jet facility. The aluminum plate was laminated with a Kapton isolation foil with a low thermal conductivity of 0.12 W/(mK) according to Dupond (2017). The foil is coated with Nextel-Velvet-Coating 811-21 which offers a high emissivity of around 0.97 in the spectral range of 2 – 6 µm, see Batuello et al. (1999). The leading edge of the plate has an asymmetrical profile which was derived from a numerical optimization which minimizes the pressure gradient around the leading edge (Hanson et al., 2012). The plate was positioned in the center of an exit nozzle of the free jet facility with 160 mm diameter at Mach numbers varying from Ma = 0 – 0.15.

For the TDT measurement, a high-energy Nd-YAG laser with 5 J pulse energy heats up the coating and 35 ns pulse length at 1064nm wavelength. The laser beam is expanded by an engineered diffusor, resulting in a homogeneously heated measurement area of about 50 mm×50 mm. A high-speed infrared camera with InSb detector (Infratec IR9300) is used to record the temperature decline with 200 Hz frame rate within a wavelength range of 2 – 5.7 µm. Both laser and camera were triggered externally to ensure synchronized measurements. The camera acquires 150 frames beginning directly after the heat pulse generated by the laser.

For the calibration, a measurement with flow and a reference measurement without flow were conducted with exactly the same geometry and equipment settings. The data reduction was performed following the steps described in von Hoesslin et al. (2017).

Since heat transfer coefficients are equal perpendicular to the flow direction, the resulting image was spatially averaged over 300 pixels to gain the mean profile section of $\Lambda - \Lambda_{\mathrm{ref}}$ along the chord of the plate. This profile section was compared to heat transfer coefficients $\alpha(x)$ from the Nußelt correlation by calculating the corresponding x and Re_x for each pixel along the chord line and applying Eq. (6) and Eq. (7) to derive $\alpha(x)$.

4 Results and discussion

4.1 Calibration measurements

For the calibration measurements, the free-jet was set to three different flow velocities, 17m/s, 33m/s and 51m/s resulting in different Re_x ranges along the plate. A laminar boundary layer developed within the first centimeters of the flat plate. The measurement area started at the leading edge of the plate within the laminar region. For this measurement area and free-jet velocities, a local Reynold's number range of $Re_x \in [0.32 \cdot 10^3, 155 \cdot 10^3]$ was achieved for calibration. By using the local Nußelt correlation for laminar flow Eq. (6), heat transfer coefficients $\alpha(x)$ were calculated along the plate.

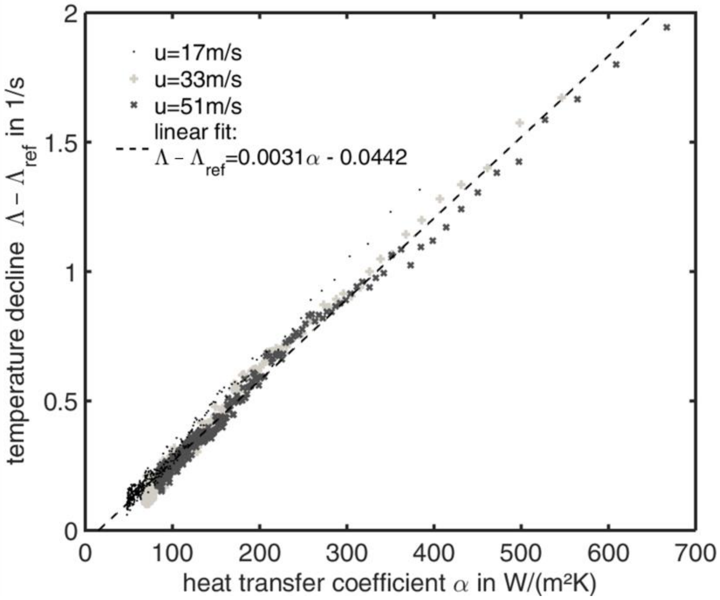

Fig. 2 Linear calibration relation between data measured by Temperature Decline Thermography (TDT) and heat transfer coefficients calculated by the Nußelt correlation for different exit velocities u of the free-jet. A linear regression (dashed line) was fitted to the data of all free-jet velocities.

By plotting $\alpha(x)$ against the measured TDT signal $\Lambda - \Lambda_{\mathrm{ref}}$, a linear calibration relation can be observed as shown in Fig. 2. Datasets of three different free-jet velocities were fitted using a linear regression resulting in the calibration relation

$$(8) \qquad \alpha = 319.1\,\frac{\mathrm{Ws}}{\mathrm{m^2K}}(\Lambda - \Lambda_{\mathrm{ref}}) + 14.1\,\frac{\mathrm{W}}{\mathrm{m^2K}},$$

where the calibration constant is determined to $C = 319.1 \pm 2.7$ Ws/(m²K). This shows that the described theoretical model in Sec. 2.2 is applicable and that TDT data can be converted into heat transfer coefficients by applying the calibration relation.

The offset of 14.1 ± 1.3 W/(m²K) at $\Lambda - \Lambda_{\mathrm{ref}} = 0$ is explained by natural convection being present during the reference measurement without forced convection. This lies within the order of magnitude predicted by a correlation for natural convection on horizontal plates in air (Chen, Tien, & Armaly, 1986).
The uncertainties given for the offset and calibration constant were derived from the fit. The total error for Eq. (8) is expected to be larger, since the uncertainty for using the Nußelt correlation in a non-ideal flow is not negligible.

4.2 Transfer of the calibration relation to turbulent flow conditions

The aim of the following experiments is to show the possibility of transferring a calibration relation recorded under known conditions to other flow situations and geometries. Since the measured temperature decline rates are independent of the flow condition, the calibration relation recorded in laminar flow holds true likewise for other flow conditions. To confirm this, the flat plate was inclined by 4° to force a laminar separation bubble to occur and a laminar-turbulent transition near the leading edge on the upper side of the plate. A TDT measurement was performed and the data were converted to heat transfer coefficients using Eq. (8). By comparing the resulting data of the turbulent flow to the corresponding Nußelt correlation Eq. (7), the validity of applying the calibration relation recorded in laminar flow to a turbulent flow situation is confirmed.
In Fig. 3, the local TDT data of the calibration measurement is shown as dark grey crosses along the chord line of the plate. This dataset corresponds to the data of Fig. 2 at $u = 51\mathrm{m/s}$ which were converted to heat transfer coefficients using Eq. (8). For the sake of completeness, the laminar Nußelt correlation which was used for calibration is shown as well, see black dotted line. The decreasing heat transfer with increasing boundary layer thickness and local Reynolds number is expected as the flow gradient at the wall decreases with increasing boundary layer thickness.
The dataset of the inclined plate is shown in light grey circles. The data converted to heat transfer coefficients using the same calibration relation Eq. (8). Within the first six millimeters from the leading edge, a characteristic change from low to high heat transfer coefficients is observed corresponding to a laminar-turbulent transition. After the transition, a turbulent boundary layer develops which results in a gradual decrease of heat transfer coefficients. The laminar-turbulent transition is taking place in the shear layer of a laminar separation bubble. Due to the lack of fluid movement within the laminar separation bubble (Ol et al., 2005), the heat transport is reduced resulting in lower heat transfer coefficients than in the laminar boundary layer. The subsequent increase marks the end of the laminar separation bubble where the flow reattaches and more heat is carried away due to the turbulent flow state after reattachment. The reattachment is a dynamic process. Small vortices develop at the end of the bubble which are detaching in an oscillating manner known as vortex shedding (Hain et al., 2009). This process is sketched in the schematic of Fig. 3.
This results in higher mean heat transfer coefficients compared to the predictions of the turbulent Nußelt correlation for flat plates (black dashed line). The detached vortices gradually disperse in the turbulent flow and a flat plate similar boundary layer develops after about three centimeters. An asymptotic approach to the turbulent Nußelt correlation is observed within the last three centimeters of the measurement area. Within this range, it is shown that the calibration relation recorded in laminar flow can be validly applied to a measurement in turbulent flow.
However, the application of the calibration relation to other flow conditions is subject to certain constrains. Although the TDT method is primarily independent of the heating temperature since only relative temperatures are measured, for high heating temperatures the amount of heat emitted into the boundary layer is not negligible. Especially in laminar flows, the convection into the flow can thereby be reduced towards downstream areas resulting in an altered calibration relation. This effect depends on flow velocity and type of fluid. If the calibration is to be applied to other measurements with similar flow velocities, a heating temperature similar to the calibration is recommended to use. For the present

measurements a heating temperature of about 10K was observed to have negligible influence on the calibration relation.

Thickness and type of the coating is expected to have an influence on calibration. To transfer the calibration to other measurements, the same coating with the same thickness should be used. Since exactly the same conditions for measurement and calibration are hardly achievable, further effort is needed to determine the sensitivity of the calibration to heating temperature and coating thickness.

In contrast, the camera angle with respect to the coated surface has negligible influence on calibration. To show this, angles between 0° – 70° from the surface normal were tested. Therefore, an application of a calibration for different measurement setups is possible.

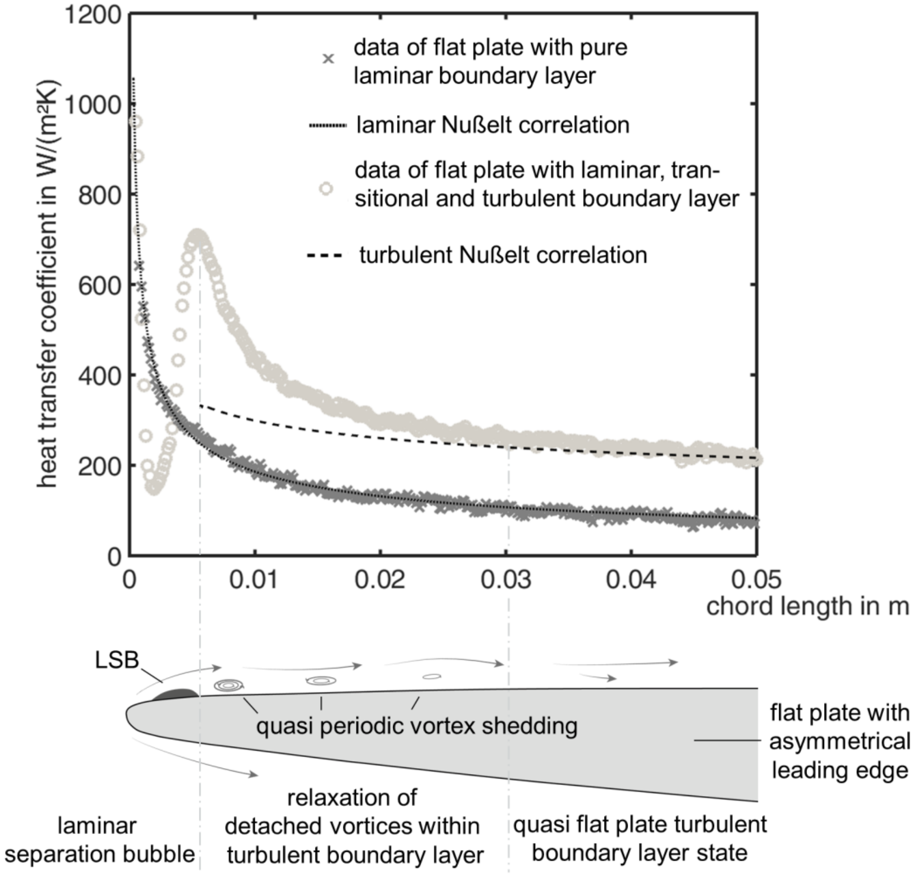

Fig. 3 TDT data recorded in a laminar boundary layer are shown as dark grey crosses which correspond to the TDT data of *u*=51m/s shown in Fig. 2. Additionally, data measured in a transitional and turbulent boundary layer on an inclined plate are shown as light grey circles. Both datasets were converted to heat transfer coefficients using the calibration relation Eq. (8). For comparison, the Nußelt correlation for laminar and turbulent flow are shown as dotted and dashed lines. The schematic below the graph shows the transitional and turbulent flow around the leading edge of the inclined plate. The laminar-turbulent transition, visible within the first millimeters of the plate, is triggered by a laminar separation bubble which is associated with quasi periodic vortex generation after reattachment of the flow. The vortices disperse gradually until a flat plate turbulent boundary layer state is observed.

5 Conclusion

The analysis conducted in this paper has four important implications:

1. It was shown that data recorded by the TDT method can be correlated to heat transfer coefficients by a linear calibration relation. This confirms the developed theory of the temporal temperature decline and the numerical simulations based on the heat equation.
2. The calibration relation recorded in laminar flow can be used to convert data measured in turbulent flow into quantitative heat transfer coefficients. Good agreement to the corresponding Nußelt correlation was observed. Constraints to the application of the calibration to measurements in other flow conditions and geometries were given.
3. With a quantitative representation of TDT data, laminar and turbulent boundary layer conditions can be characterized. Furthermore different flow states like laminar separation bubbles can as well be classified and analyzed.
4. The use of the Nußelt correlation showed that calibration of TDT data is in principal possible. In future experiments however, it would be reasonable to replace the correlation by a second measurement technique. The error of the calibration relation can then be defined more precisely.

The TDT method is capable of detecting laminar-turbulent transition qualitatively in hard-to-access geometries. Combined with the possibility to obtain quantitative heat transfer and shear stresses, the technique is beneficial for a range of high-speed applications where a two-dimensional overview of the flow situation, but also detailed quantitative information are required.

Acknowledgements

This research was partially supported by the cooperative project COOREFLEX-turbo.

References

Astarita, T., & Carlomagno, G. M. (2013). *Infrared Thermography for Thermo-Fluid-Dynamics.* Berlin, Heidelberg: Springer.

Batuello, M., Clausen, S., Hameury, J., & Bloembergen, P. (1999). The Spectral Emissivity of Surface Layers, Currently Applied in Blackbody Radiators, Covering the Spectral Range from 0.9 to 20 µm. An International Comparison. *Tempmeko*, 601–606.

Bougeard, D. (2007). Infrared thermography investigation of local heat transfer in a plate fin and two-tube rows assembly. *International Journal of Heat and Fluid Flow*, 988–1002.

Boutarfa, R., & Harmand, S. (2005). Local convective heat transfer for laminar and turbulent flow in a rotor-stator system. *Experiments in Fluids*, 209–221.

Carlomagno, G., de Luca, L., Cardone, G., & Astarita, T. (2014). Heat Flux Sensors for Infrared Thermography in Convective Heat Transfer. *Sensors*, 21065–21116.

Chen, T., Tien, H., & Armaly, B. (1986). Natural convection on horizontal, inclined, and vertical plates with variable surface temperature or heat flux. *International Journal of Heat and Mass Transfer*, 1465–1478.

Dupont. (23. Mai 2018). *www.dupont.com.* http://www.dupont.com/content/dam/dupont/products-and-services/membranes-and-films/polyimde-films/documents/DEC-Kapton-summary-of-properties.pdf

Hain, R., Kähler, C. J., & Radespiel, R. (2009). Dynamics of laminar separation bubbles at low-Reynolds-number aerofoils. *Journal of Fluid Mechanics*, 129–153.

Hanson, R. E., Buckley, H. P., & Lavoie, P. (2012). Aerodynamic optimization of the flat-plate leading edge for experimental studies of laminar and transitional boundary layers. *Experiments in fluids*, 863-871.

Incropera, F., & De Witt, D. (1985). *Fundamentals of heat and mass transfer*. New York: Wiley.

Ol, M., McCauliffe, B., Hanff, E., Scholz, U., & Kähler, C. J. (2005). Comparison of laminar separation bubble measurements on a low Reynolds number airfoil in three facilities. *35th AIAA fluid dynamics conference and exhibit*, (S. 5149).

Stadlbauer M, Gründmayer J, von Plehwe F (2014) Patentnr. WO2014198251 A1

von Hoesslin, S., Stadlbauer, M., Gruendmayer, J., & Kähler, C. J. (2017). Temperature decline thermography for laminar–turbulent transition detection in aerodynamics. *Experiments in Fluids*, 129.