

Recent Developments in Time-Resolved Temperature-Sensitive Paint Application in Incompressible to Transonic Flows

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ABSTRACT

Temperature-sensitive paints enable the determination of the temperature distribution on the surface of an object under investigation. They have been successfully used since more than 30 years in experimental aero(thermo)dynamic and hydrodynamic studies, with a main focus on laminar-turbulent transition detection and heat flux determination. Recent advancements in temperature-sensitive paint formulations, optical setup components, and data analysis methods have however allowed an improvement of the achievable spatial, temporal, and temperature resolution, and thus an expansion of the capabilities to capture essential flow phenomena and flow quantities via temperature-sensitive paint. The current contribution summarizes recent developments in the application of time-resolved temperature-sensitive paint in incompressible, subsonic and transonic flows, focusing on the study of characteristic phenomena of the laminar-turbulent transition process, on the determination of the wall shear stress, and on the identification of flow separation and reattachment. The presented investigations range from fundamental research on generic configurations (flat plates, elliptic profile) in incompressible and compressible flows to the most recent study of a newly designed airfoil at subsonic to transonic flow conditions.

1. Introduction

Temperature-Sensitive Paint (TSP) is an optical measurement technique based on luminescent molecules (called luminophores) as sensors incorporated into an appropriate coating, which is applied onto the surface of interest (Liu et al., 2021). When the luminophores are excited by light in a specific wavelength range (typically using UV or blue LEDs), they emit light in a longer-wavelength range (typically red light). The intensity and luminescent decay time (also called lifetime) of the emitted light depend on the TSP temperature, thus providing the foundations for the intensity- and lifetime-based methods for TSP measurements, respectively. In this manner, the surface temperature distribution can be measured non-intrusively with high spatial and temporal resolution – typically via scientific (high-speed) cameras. In wind-tunnel experiments, this has enabled since the 1990s the detection of the laminar-turbulent boundary-layer transition front (see, e.g., Campbell et al., 1992, and Asai et al., 1997) and the determination of the wall heat flux (as

reported, for example, by Liu et al., 1995). A review of TSP applications in aero(thermo)dynamic and hydrodynamic experiments up to 2021 is provided by Liu et al. (2021). The current contribution presents recent developments in the application of time-resolved TSP in incompressible, subsonic and transonic flows, focusing on the investigation of transitional phenomena, on the determination of the wall shear stress, and on the identification of boundary-layer separation and reattachment.

2. Investigation of transitional phenomena in incompressible and compressible flows

As introduced above, TSP has been used for more than 30 years for boundary-layer transition detection. In a manner analogous to that of other thermographic methods (such as infrared thermography), boundary-layer transition is visualized in TSP images as a region where the surface temperature significantly changes from laminar to turbulent values. As discussed by Costantini (2016), Costantini et al. (2016), Miozzi et al. (2019), Costantini et al. (2021a), Dimond (2024), and Dimond et al. (2026b), among others, boundary-layer transition is a process that occurs over a certain distance (the transition region). The definition of a single "transition location" is reasonable if it refers to a specific point in the transition region, which has to be unequivocally and consistently defined and which corresponds to a position in the flow with physical significance related to the transition. For a quantitative detection of the transition "location", the TSP data are analyzed to identify such a characteristic point, for example the location corresponding to the maximum of the streamwise temperature gradient (see Costantini, 2016; Costantini et al., 2016; Miozzi et al., 2019; Costantini et al., 2021a). This enables the determination of the transition front over the entire TSP region, and thus the systematic investigation of the influence of several physical parameters on boundary-layer transition (such as Mach number, Reynolds number, pressure gradient, etc.). Nevertheless, this approach does not allow directly capturing other physical phenomena characteristic of boundary-layer transition, such as intermittency and turbulent spots. In contrast, time-resolved TSP measurements enable the identification of these phenomena, as recently shown by Costantini et al. (2026a) for an incompressible flow and by Dimond et al. (2026a,b) for a compressible, subsonic flow. In the first study (Costantini et al., 2026a) an elliptic profile with 16 % relative thickness was investigated in the Large Water Tunnel (GWB) of TU Braunschweig (Scholz et al., 2013). The model, shown in Figure 1 (left), was coated with a europium-based TSP (Ondrus et al., 2015), which provided sufficient temporal resolution of the transitional phenomena in the examined water flow. In the second series of experiments (Dimond 2024, Dimond et al. 2026a, Dimond et al. 2026b), the *PaLASTra* flat-plate model (Costantini, 2016; Costantini et al., 2016) was investigated in the Cryogenic Ludwig Tube Wind Tunnel (KRG) of DLR Göttingen (Rosemann, 1997). The port half surface of the model, shown in Figure 1 (right), was coated with a ruthenium-based TSP (adapted from Ozawa et al., 2015, and Martinez Schramm & Hilfer, 2020). This fast-response TSP enabled the study of transitional phenomena in a high Reynolds number flow at Mach numbers up to $M = 0.8$. The excitation and emission spectra of the used europium- and ruthenium-based TSPs are shown in Figure 2 (left and right, respectively).

As examples of the achieved results, Figure 3 shows: a turbulent spot identified on the elliptic profile at an angle-of-attack $AoA = 3^\circ$ and a Reynolds number $Re = 5 \cdot 10^5$, based on the model chord length $c = 0.2$ m (left figure); and another turbulent spot identified on the flat-plate configuration at $AoA = -3^\circ$, $Re = 6 \cdot 10^6$ (also based on a reference length of 0.2 m), and $M = 0.8$ (right figure). Both figures show a downstream-pointing arrowhead footprint, characteristic of turbulent spots, which could be captured via TSP with high spatial and temporal resolution: 3 pixels/mm and 1 kHz, respectively, for the measurements on the elliptic profile in the GWB water tunnel; and 17 pixel/mm and 20 kHz, respectively, for the measurements on the flat plate in the KRG wind tunnel. In both cases, a CMOS Photron FASTCAM Mini AX200 camera, with a 12-bit dynamic range, was used to acquire the TSP images.

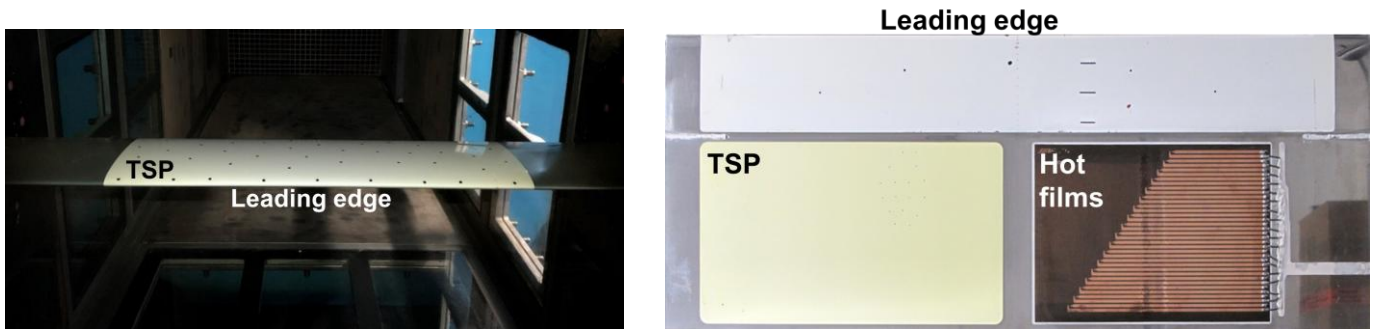


Figure 1 Experimental setups for the study of transitional phenomena. Left: elliptic profile model mounted in the GWB water tunnel (view in flow direction), with TSP applied over most of the model span (Costantini et al., 2026a). Right: top view of the modified *PaLASTra* flat-plate model for time-resolved TSP measurements in KRG wind tunnel, with TSP on the port model half and hot films on the starboard model half (Dimond et al., 2026b). TSP appears as a pale-yellow coating in both figures.

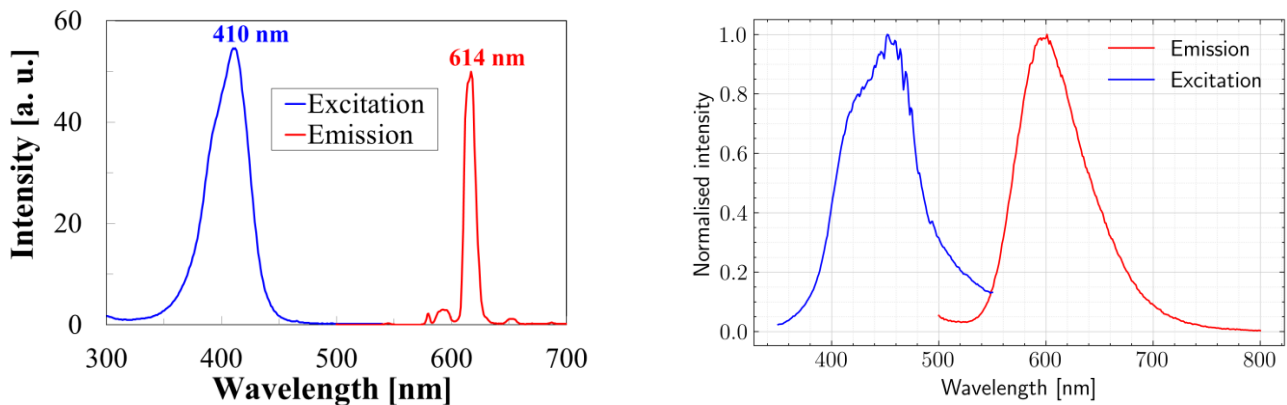


Figure 2 Excitation and emission spectra of the used TSPs. Left: europium-based (see Ondrus et al., 2015, and Costantini, 2016) Right: ruthenium-based TSP (see Dimond, 2024, and Dimond et al., 2026b).

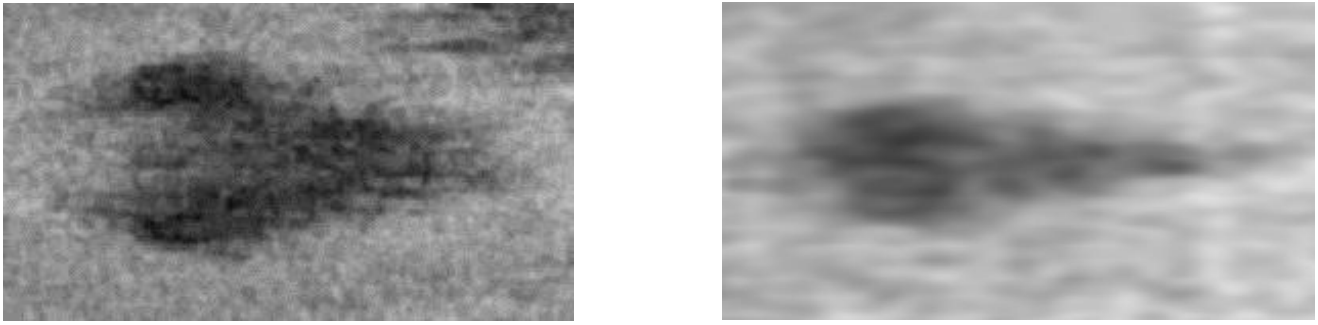


Figure 3 Identification of turbulent spots via time-resolved TSP (plan views with the flow from the left). Left: turbulent spot on the elliptic profile, identified via temporal gradient of the surface temperature ($\text{AoA} = 3^\circ$, $\text{Re} = 5 \cdot 10^5$) – see Costantini et al. (2026a). Right: turbulent spot on the *PaLASTra* flat plate, identified via unsteady heat flux determination ($\text{AoA} = -3^\circ$, $\text{Re} = 6 \cdot 10^6$, $M = 0.8$) – see Dimond et al. (2026b).

3. Determination of wall shear stress and flow reattachment in incompressible flow

In canonical flows, the relation between skin friction and wall heat flux has been exploited to determine the wall shear stress from surface temperature measurements via empirical correlations, such as the Reynolds-Colburn analogy. An adapted version of this analogy has been used, for example, by Lemarechal et al. (2021) to determine the time-averaged skin friction field from TSP data in a laminar water channel. A generalized formulation of the Reynolds-Colburn analogy, derived from the energy equation at the wall and applicable also to non-canonical flows, was proposed by Liu & Woodiga (2011). It enables the estimation of normalized, even instantaneous skin-friction fields from surface temperature measurements, as shown, e.g., by Miozzi et al. (2016), for a circular cylinder in crossflow. This approach, however, suffers from the impact of flow-independent thermal effects, such as those due the variation of the thermal properties along the surface of the investigated object. A more promising approach, based on time-resolved surface temperature maps, has been recently developed and applied to determine skin-friction distributions in water flows over an isolated hydrofoil (Miozzi et al., 2019 & 2020), over a hydrofoil in the wake of a marine propeller (Miozzi & Costantini, 2021) and over a flat plate with a wall-mounted cube (Miozzi et al., 2024). The approach relies on observations of the near-wall behavior of the fluctuations of flow quantities, and in particular of the temperature, which is assumed to behave as a passive scalar. As discussed in more detail in the companion contribution by Miozzi et al. (2026), close to the wall the propagation velocities of the flow quantity fluctuations (called "celerities" because of their analogy with a wave behavior) are in relationship with the friction velocity. In canonical flows, the relationship between the near-wall propagation celerities and the friction velocity is reported to be linear, while in non-canonical flows it is expected to be more

complex. If the relationship between friction velocity and celerity of propagation of temperature fluctuations at the wall is known, the skin friction can be retrieved from surface temperature measurements. In the approach proposed in the aforementioned publications, the (time-averaged) celerity of propagation of temperature fluctuations $\overline{U}_T$ is determined from the analysis of time-resolved TSP data by minimizing the dissimilarity of the observed surface temperature behavior with that conform to the Taylor hypothesis of "frozen turbulence", in analogy with the approach proposed by Del Álamo & Jiménez (2009) for the celerity of propagation of velocity fluctuations. An example of a recent application of this celerity-based approach (called "TH approach") is presented in Costantini et al. (2026b) for a turbulent boundary layer over a flat-plate configuration, which undergoes separation and reattachment as induced by a 25° backward-facing ramp. The examined configuration is sketched in Figure 4 (top). The experiment was performed in the GWB water tunnel within the DLR project *ADaMant* (Grabe, 2022) at Reynolds numbers based on the ramp location x_h (measured from the model leading edge) in the range $Re_{xh} = 1.2\text{--}2.7 \cdot 10^6$. The europium-based TSP from Ondrus et al. (2015) was used also in this case. The TSP images were acquired at 1 kHz using a 12-bit CMOS Phantom v2640 camera, employing its full image sensor (2048×1952 pixels²). An instantaneous map (snapshot) of surface temperature fluctuations T' (defined as the difference between instantaneous temperature maps and the time-averaged temperature map of the data series) measured via TSP at $Re_{xh} = 1.2 \cdot 10^6$ is shown in Figure 4 (bottom-left). As can be seen in this figure, both regions upstream and downstream of the backward-facing ramp (left and right in the figure, respectively) were investigated via TSP. It should be emphasized here that the temperature resolution of these resulting temperature maps was below 0.001 K, as presented in Costantini et al. (2026b). The inspection of the TSP data shows three different patterns of traces of wall temperature fluctuations: one in the region upstream of the ramp, a second one downstream of the ramp up to approx. $X = x - x_h = 40$ mm, and a third one further downstream. The regions at $X < 0$ and at approx. $X > 40$ mm correspond to attached flow regions and are populated by streamwise-oriented wall thermal traces representing the wall thermal signature of high/low streamwise velocity streaks, which are characteristic of attached turbulent boundary layers (see Costantini et al., 2026b). The substantially different pattern in the region at approx. $20 \text{ mm} < X < 40 \text{ mm}$ is due to the flow separation induced by the backward-facing ramp. Focusing on the downstream TSP field, the TH approach has been applied to determine the time-averaged celerity of propagation of temperature fluctuations; the spanwise-averaged profile of its streamwise component U_T is shown in Figure 4 (bottom-right). As can be seen in this figure, U_T is negative up to $X \sim 40$ mm and positive further downstream; according to its relationship with the friction velocity, flow reattachment is identified at the zero-crossing location of U_T , i.e., at approx. $X = 40$ mm. This result is in reasonable agreement with the data

obtained via Lagrangian particle tracking by Shake-The-Box in a complementary experimental campaign (Schanz et al., 2025; Costantini et al., 2026b), as discussed also in the companion contribution by Miozzi et al. (2026).

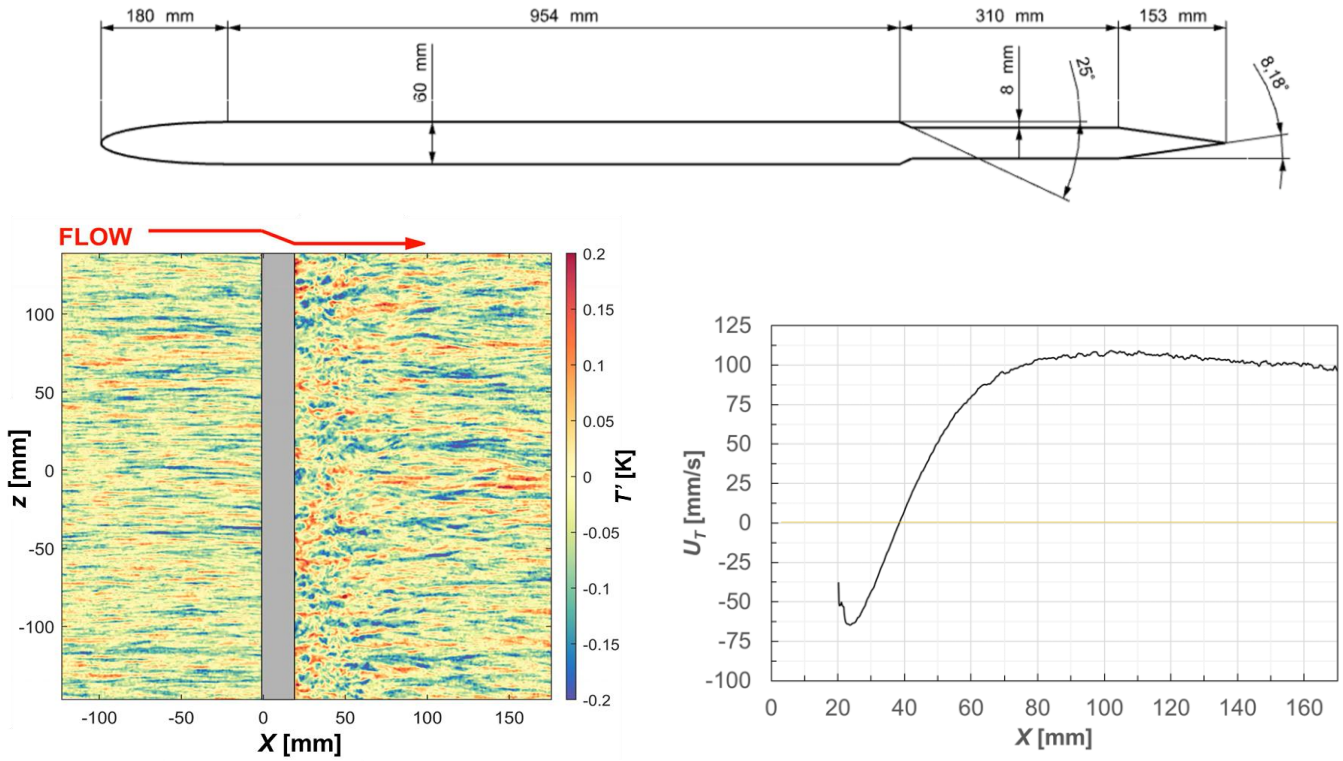


Figure 4 Top: sketch of the flat-plate model with 25° backward-facing ramp (side view) examined in the GWB water tunnel (Costantini et al., 2026b). Bottom, left: instantaneous distribution of the surface temperature (snapshot of the temperature fluctuations T') on the TSP fields upstream and downstream of the ramp at $Re_{xh} = 1.2 \cdot 10^6$. Bottom, right: corresponding profile of the streamwise component of the time- and spanwise-averaged celerity of propagation of temperature fluctuations in the region downstream of the ramp.

4. Identification of boundary-layer separation in subsonic to transonic flow

The developments in skin-friction estimation from time-resolved TSP data and in the celerity-based identification of critical lines (flow separation and reattachment) reported above for incompressible flows have encouraged the adaptation and application of this approach to air flows. A first application was presented by Costantini et al. (2021b) for a supercritical airfoil examined at transonic flow conditions ($M = 0.72$) and high Reynolds number ($Re = 9.6 \cdot 10^6$, based on the model chord length $c = 1.0$ m) in the Transonic Wind Tunnel Göttingen of the German-Dutch Wind Tunnels organization (DNW-TWG, see Binder et al., 1992). The critical lines were identified at the zero-crossing of the U_T -distribution (or at the minimum of its modulus), which was determined via

the TH approach applied to the time-resolved TSP data. However, it should be noted that, at the examined flow conditions, the used TSP (europium-based, from Ondrus et al., 2015) and the acquisition frequency of the TSP images (1 kHz) were not suitable to adequately capture the displacement of the surface temperature fluctuations far from the critical lines. For this reason, the aforementioned ruthenium-based TSP (see Sec. 2) was used in the most recent experiment in air flow, performed in DNW-TWG within the DLR *ACTIVATE* project (DLR, 2024). The measurements were conducted at subsonic to transonic flow conditions ($M = 0.3$ to 0.74) on a novel airfoil developed at DLR and named *AC-HKKS-02*, which was designed for a pronounced ("aggressive") adverse pressure gradient on the airfoil upper surface in the rear airfoil region. A photograph of the *AC-HKKS-02* airfoil model in the DNW-TWG test section is shown in Figure 5. The TSP (visible as a yellow coating) was applied on the starboard half surface of the model upper side, and extended from $x/c = 25\%$ (where $c = 0.3$ m is the airfoil chord length) to the airfoil trailing edge. The model was also equipped with three rows of pressure taps (aligned with the freestream) to measure the airfoil pressure distribution at three different spanwise locations: along the centerline ($y = 0$), at $y/c = -1.067$, and at $y/c = -1.5$. (The latter two pressure taps rows were placed on the model port half.) Additionally, the pressure distribution in the airfoil wake was measured by means of a wake rake to determine the airfoil drag, and shock waves occurring on the airfoil were visualized via Schlieren photography. Configurations with both free and forced boundary-layer transition were examined, but the current work focuses on the experiments performed with free transition. TSP images were acquired at acquisition frequencies of up to 30 kHz using the Photron FASTCAM Mini AX200 camera introduced in Sec. 2.

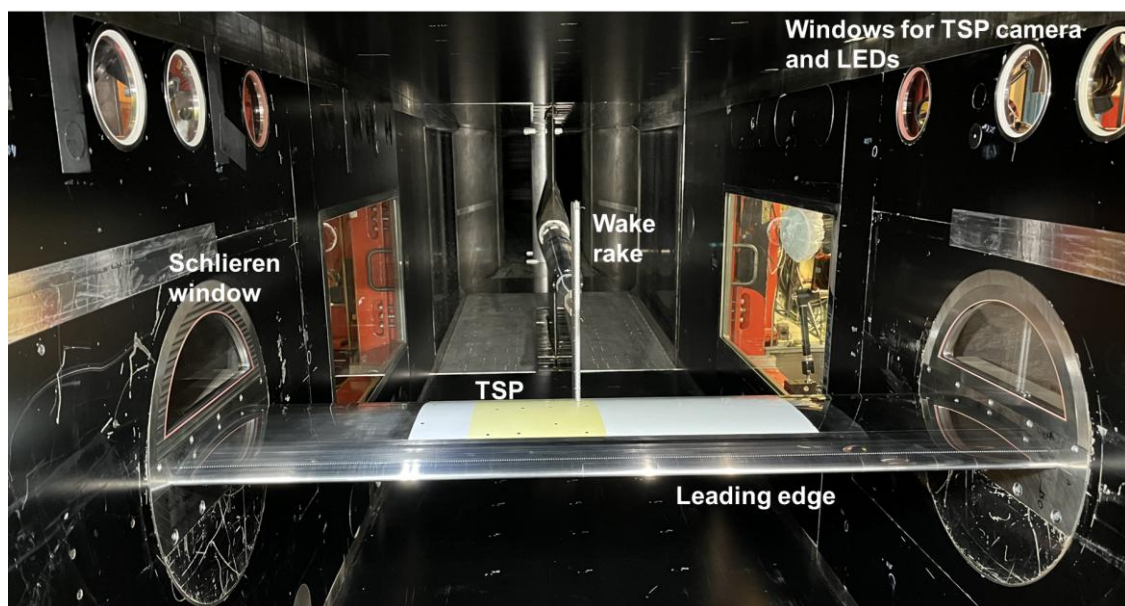


Figure 5 *AC-HKKS-02* airfoil model and experimental setup in the DNW-TWG test section (view in flow direction).

As an example of the obtained results, the surface pressure and temperature distributions measured at $M = 0.3$, $Re = 1.5 \cdot 10^6$ (based on the model chord length), and $AoA = 10.5^\circ$ are shown in Figure 6. The time-averaged pressure distributions measured by means of the three rows of pressure taps are shown in the left figure. Here, the top and bottom sets of curves correspond to the pressure distribution measured on the upper and lower model surfaces, respectively. As can be seen in this figure, at these test conditions a very pronounced pressure minimum formed on the leading-edge region of the model upper surface. The marked adverse pressure gradient following this pressure minimum very likely induced boundary-layer transition close to the leading edge, with the subsequent development of a turbulent boundary layer. In the region between approx. $x/c = 85\%$ and the trailing edge, a nearly-zero streamwise pressure gradient was observed on the model upper surface, indicating a separated flow region.

Further insights on the flow evolution over the airfoil upper surface are provided by the time-resolved TSP data. An instantaneous map of surface temperature fluctuations, defined in the same manner as in Sec. 3, is shown in Figure 6 (right), where the flow is from the left. Note that this result was obtained after mapping of the TSP images on a three-dimensional grid representing the model surface of interest, as discussed, e.g., in Costantini (2016) and Dimond (2024). The TSP result is shown as if the TSP surface would be observed from the (inaccessible) top wall of the DNW-TWG test section. Temporal filtering, analogous to that described in Costantini et al. (2026b) was applied to the TSP data series. The instantaneous distribution of the surface temperature fluctuations T' clearly shows a change in the pattern of wall thermal traces at $x/c \sim 85\%$. Temperature fluctuations of low absolute values are observed in the upstream region, with the appearance of streamwise-oriented wall thermal traces that seem to be similar to those described in Sec. 3 with regard to the attached turbulent boundary layer regions. In contrast, a more chaotic pattern of temperature fluctuations with higher absolute values is found at approx. $x/c > 85\%$, where an upstream displacement of the wall thermal traces is also seen in the temporal series of the TSP results. These experimental observations provide a visualization of turbulent flow separation in the trailing edge region based on the time-resolved surface temperature maps, which is in line with the considerations based on the surface pressure distributions presented in Figure 6 (left). It should be noted here that the captured temperature fluctuations are well within a total range of 0.1 K – see Figure 6 (right). Accordingly, also in this case the obtained surface temperature resolution is at least an order of magnitude better than that reported as typical for TSP (Liu et al., 2021). The available spatial, temporal and temperature resolution supports the further analysis of the time-resolved TSP data for the determination of the fields of celerity of propagation of temperature fluctuations (see Sec. 3), which will be the focus of future work.

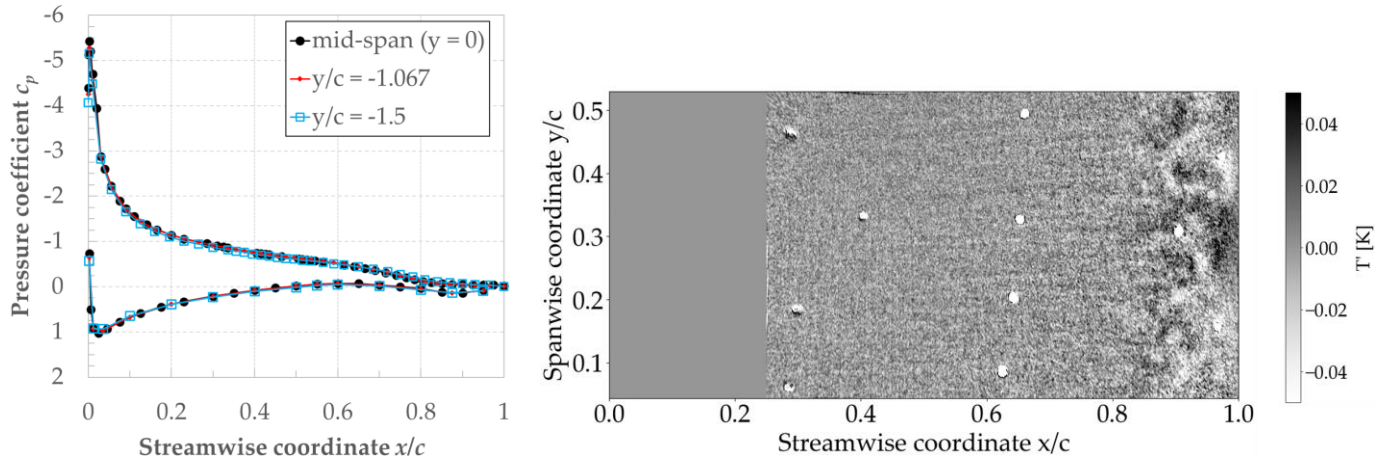


Figure 6 Results of the measurements on the *AC-HKKS-02* airfoil model at $M = 0.3$, $Re = 1.5 \cdot 10^6$, and $AoA = 10.5^\circ$.

Left: surface pressure distributions, measured via pressure taps. Right: surface temperature fluctuations, measured via time-resolved TSP (flow from the left).

5. Conclusions

The presents contribution provides an overview on recent developments in the application of the TSP measurement technique beyond the established research goals of laminar-turbulent transition detection and heat flux determination. In fact, the advancements in TSP formulations, optical setup components, and data analysis methods have allowed a progress in the attainable spatial, temporal, and temperature resolution, thus enabling an expansion of the capabilities of TSP measurements in aerodynamic and hydrodynamic experiments. In particular, time-resolved TSP now permits characteristic phenomena of the laminar-turbulent transition process to be captured, the field of the celerity of propagation of temperature fluctuations (which is related to the skin-friction field) to be determined, and flow separation and reattachment to be identified. These capabilities are demonstrated in recent experiments performed in incompressible, subsonic, and transonic flows, as summarized in the current contribution. Intermittency and turbulent spots were captured for transitional boundary layers developing on an elliptic profile in an incompressible flow and on a flat-plate configuration in a compressible, subsonic flow. Surface temperature fluctuations with a resolution below 0.001 K allowed the determination of the time-averaged map of celerity of propagation of temperature fluctuations for a turbulent boundary layer undergoing separation and reattachment in an incompressible flow, thus enabling the quantitative determination of the reattachment line. Time-resolved maps of surface temperature fluctuations were obtained also on an airfoil model examined at subsonic to transonic flow conditions, and allowed the distinction of attached and separated turbulent flow regions.

The presented results encourage the application of the TSP technique for fluid dynamic studies in a variety of flow regimes as well as the further development in the TSP data analysis methods for the determination of surface flow quantities that were previously considered unattainable; these efforts should be also accompanied by further research to critically evaluate the current limits for

TSP application and the potential to overcome these limits by progressing in sensor development, optical components, and noise reduction techniques, among other aspects.

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