# Wall-cooling for transition delay in crossflow-dominated boundary layers

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## Introduction

Understanding the laminar-to-turbulent transition driven by the Stationary Crossflow Instability (S-CFI) remains a key scientific challenge towards achieving Natural Laminar Flow (NLF). In recent years, experimental investigations of boundary-layer transition dominated by CFI have been pivotal in advancing this goal.

Wind tunnel experiments of CFI-driven laminar-to-turbulent transition typically employ highly swept wings featuring a strong favorable pressure gradient at the Leading Edge (LE) and mid-chord regions. In addition, for the particular study of the stationary CFI, the wind tunnel facility must operate at very low-turbulence intensity levels ($Tu < 0.15\%$, [1]). Such configuration has been widely used and is well-established for its ability to replicate in-cruise conditions. However, the curvature of the wing surface often complicates detailed boundary layer measurements, necessitating more complex Hot-Wire Anemometry (HWA) or Particle Image Velocimetry setups. Furthermore, stability analysis for experiments involving swept-wing configurations must account for surface curvature effects on instability growth, introducing more complexity [2].

To address the aforementioned challenges, an alternative approach involves using a swept flat plate, where the favorable pressure gradient is imposed externally via a contoured top wall, denoted as displacement body [1]. This flat-plate configuration offers significant advantages for fundamental studies of S-CFI, as it simplifies both boundary layer measurements and stability calculations. Furthermore, it provides flexibility for investigating various pressure gradient configurations through modifications of the displacement body.

Building on years of research conducted on a swept-wing model (M3J) within TU Delft's Flow Control research group (e.g. [3]), a new swept flat-plate configuration was designed and manufactured: the Swept Transition Experimental Platform (STEP, [4]). Investigations performed on the STEP setup primarily focus on the fundamental study of S-CFI laminar-to-turbulent transition under both active (e.g. wall-cooling) and passive (e.g. surface irregularities) flow control strategies. One notable application of this configuration involved investigating the impact of wall-heating on the growth and breakdown of S-CFI [5]. For further details on the STEP geometry and flow measurement capabilities, the reader is referred to [4].

An inherent limitation of the STEP setup was the restricted optical access available for detecting laminar-to-turbulent transition using IR Thermography (IRT). The proximity of the top wall to the flat-plate surface, coupled with the high cost of large IR-transparent windows, forced the IR camera to be positioned too close to the plate's surface. As a result, this configuration made it challenging to capture a comprehensive view of the transition front's spatial distribution, while at the same time ensuring a sufficient spatial resolution.

To overcome this limitation, a new swept flat-plate model was recently designed and manufactured in collaboration with the Pressure- and Temperature-Sensitive Paint Group of DLR. This new platform features a large surface area coated with Temperature-Sensitive Paint (TSP) for detecting laminar-to-turbulent transition [6]. Since TSP emits in the visible light spectrum, transition measurements can be performed using a high resolution scientific camera, eliminating the need for expensive IR-transparent materials and allowing for more extensive optical access. This new configuration is referred in what follows as the Thermal Swept Transition Experimental Platform (T-STEP).

The presented work comprises the first set of measurements using TSP for transition front detection in the new T-STEP setup. Leveraging the rapid data acquisition, simplified experimental setup, large coated surface area, and ample optical access, an extensive parametric study was conducted. The investigation systematically examined the effects of various Distributed Roughness Element (DRE) forcing conditions, including variations in S-CFI amplitude and wavelength, across multiple freestream velocities. These measurements provide a unique opportunity to build a comprehensive characterization of the experimental setup, enabling direct comparisons with predictions from stability theory.

## Experimental setup

The experiments were conducted in the A-tunnel, a low-turbulence ($T_u \leq 0.06\%$) vertical wind tunnel at TU Delft. During the experiments, the freestream velocity ($U_\infty$) was varied from 15 to 20 m/s, resulting in a chord-based

Reynolds number[1] ranging from $8.59 \times 10^5$ to $1.14 \times 10^6$.

The T-STEP setup includes a flat plate with a 45° sweep angle, a streamwise chord length ($c_X$) of 848 mm, and a span of 884 mm. The leading edge is shaped as a Modified Super Ellipse with an aspect ratio of 6. The TSP area, parallel to the LE, has dimensions of 840 mm × 358.7 mm and starts at $X/c_X = 0.397$ (see magenta area in Fig. 1a). Additionally, the flat plate is designed with a 10 mm deep pocket on the backside of the model to accommodate active thermal devices, such as a cold plate, see Fig. 1a.

To modify the pressure distribution over the flat plate, a contoured top wall is employed. This top wall consists of two sections: a solid section near the LE imposing the initial favorable pressure gradient (see green body in Fig. 1b) and a transparent polycarbonate section generating the final monotonic increase of velocity near the trailing edge. In addition, this transparent polycarbonate section allows for ample optical access to the TSP area. Surface pressure measurements are obtained using two rows of static pressure taps (99 taps in total), positioned 242 mm from the centerline on either side of the model, as shown in Fig. 1a.

An automated three-axis traversing system is located downstream of the flat plate to facilitate precise positioning of a hot-wire probe. For the current experiments, a DANTEC V-wire probe, consisting of two-wires placed at 90° (Fig. 1a), was used to measure two velocity components ($u$ and $w$), following the works of [7] and [8].

To control the amplitude and spanwise wavelength of the primary instability mode, DREs were employed. Using the same DRE thickness ($k_D = 25\ \mu$m), three spanwise wavelengths ($\lambda_z = 7, 9,$ and 11 mm) were tested at three streamwise locations ($x_D/c = 0.135, 0.1,$ and $0.053$).

The TSP layer consisted of a europium complex (luminophore) incorporated into a commercial polyurethane clear-coat binder [9]. The TSP was applied on a laminate designed in a manner similar to [10] and embedded into the main body of the model. A current-carrying carbon fiber layer of 0.1 mm thickness was integrated in the laminate and served as electrical heating for the TSP measurements. The artificial heat flux imposed between the surface and the flow led to the enhancement of the temperature gradient between laminar and turbulent flow regions, enabling accurate detection of the laminar-to-turbulent transition. The laminate temperature was monitored during the measurements using four thermocouples placed under the TSP coating.

The TSP was excited by two LEDs (HARDsoft IL-107UV Illuminators, central excitation wavelength of 385 nm), and its emission was captured using a scientific sCMOS camera (2560 × 2160 pixels, 16-bit, 6.5 $\mu$m pixel pitch). The equipment is positioned approximately 1.5 m from the measurement surface, with the camera equipped with a 25 mm focal length lens to cover the full streamwise extent of the TSP region, resulting in a final spatial resolution of 1 mm/px. The LEDs are fitted with low-pass optical filters (550 nm cut-off), and the camera is equipped with a high-pass optical filter (570 nm cut-off). This enabled the separation of excitation and emission light. During each run, 100 TSP images were captured at a 10 Hz acquisition rate.

## Preliminary results and discussion

Exemplary TSP results are shown in Figs. 1(c-e). In these figures, laminar and turbulent flow regions correspond to the dark and bright regions, respectively. The acquired TSP images were geometrically corrected (dewarped) using a structured grid of fiducials applied below the TSP layer. To identify the transition front, the maximum gradient of the intensity ratio in the streamwise ($x$) direction is determined, in a manner similar to [11].

Figures 1(c-e) shows the transition front advancement for increasing freestream velocity under a fixed DRE forcing condition. The wavelength of the forced S-CFI mode can be clearly identified ($\lambda_z = 7$ mm) from their thermal signature in the TSP results, in a manner similar to [12]. Additionally, Figs. 1(c-e) show increased spanwise uniformity of the transition front with higher freestream velocities.

The complete contribution will present results where the application of TSP is used to investigate thermal flow control. The focus will be on studying the effectiveness of wall cooling in delaying laminar-to-turbulent transition driven by stationary crossflow instabilities (S-CFI). For that purpose, a detailed parametric study is conducted, varying the cooling temperature ratio and DRE forcing parameters (amplitude and wavelength), with TSP measurements used to obtain accurate transition front location. Complementary HWA measurements, employing a V-wire probe configuration, will also be presented. The combined use of two-component HWA and TSP provides a comprehensive experimental dataset, enabling precise identification of the transition front and detailed analysis of both steady and unsteady perturbations in the streamwise ($u$) and spanwise ($w$) velocity components.

**Key Words:** Crossflow instability; laminar-to-turbulent transition; thermal flow control; TSP
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[1]The chord-based Reynolds number is defined as $\mathrm{Re}_{c_X} = U_\infty c_X/\nu_\infty$, where $c_X$ is the chord length and $\nu_\infty$ is the kinematic viscosity.

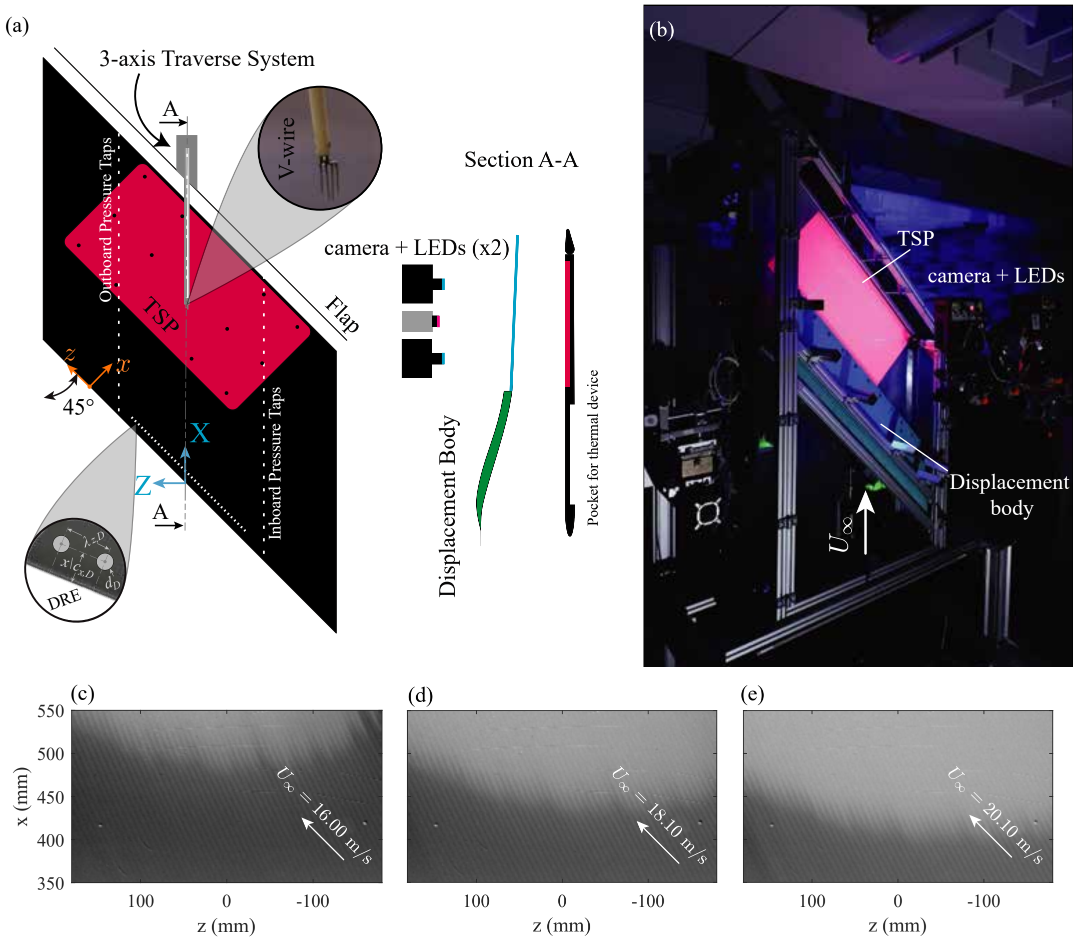


Figure 1: (a) General schematic of the T-STEP setup featuring the main components, namely the TSP region, pressure taps, DREs, 3-axis traverses, and V-wire probe. Section A-A corresponds to the cross-sectional view of the T-STEP setup showing the displacement body, together with LEDs, and camera used for TSP measurements. (b) Photograph of the T-STEP setup inside the A-tunnel with excited TSP (LEDs on, room light off). (c-e) TSP results at fixed DRE conditions ($\lambda_z = 7$ mm, $k_D = 25$ $\mu$m, and $x_D/c = 0.135$) under three different freestream velocities.

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