

Transition Measurements at High Reynolds Numbers using Phenol-Formaldehyde Resin

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Introduction

Phenolic resins, such as Bakelite ©, have been used since more than one century in a variety of applications, but only recently their luminescence has been considered in experimental aerodynamics. In fact, when excited with light in an appropriate wavelength range, certain Phenol-Formaldehyde Resins (PFRs) also emit light, which is at a wavelength larger than the excitation wavelength, and which intensity depends on the temperature. These properties are analogous to those of luminophores used in Temperature-Sensitive Paints (TSPs) [1], but with the obvious difference that the material itself is temperature-sensitive. At the same time, PFRs are cheap and have low thermal conductivity (about 0.1 W/m-K). These characteristics, coupled with their temperature-sensitive luminescence, make PFR a suitable candidate as material for wind-tunnel models on which the temperature evolution in space and time should be investigated, such as in the case of heat-flux measurements in hypersonic flows [2][3]. In these experiments, the low structural strength of the used PFR (as compared, e.g., to that of metallic models) was not a limitation for the examination of the heat transfer over spherical models in short-duration facilities, where experiments at freestream Mach numbers up to $M = 7.0$ were carried out. These promising results encourage the application of PFR for aerodynamic studies on boundary-layer transition, which can be also globally and non-intrusively detected by measuring the surface temperature distribution [1][4]. As a first step towards transition measurements using wind-tunnel models fully made of PFR, the current study presents an application of PFR as temperature-sensitive material for a component of a two-dimensional flat-plate model, which was previously used for the examination of the impact of surface bumps on transition [5]. As described in the next section, a PFR insert was machined to reproduce one of the bump configurations studied in earlier work and mounted on the model in the place of the corresponding insert. The model with the PFR insert was investigated in the Cryogenic Ludwig-Tube Göttingen (KRG) [6] at freestream Mach numbers up to $M = 0.77$, Reynolds numbers (based on the model chord length $c = 0.2$ m) up to $Re = 10^7$, and various streamwise pressure gradients, implemented by varying the AoA. The focus was on the detection of bump-induced transition on the PFR insert.

Experimental Setup

The measurements were performed in KRG, which is a particular Ludwig-tube facility designed for high Reynolds number experiments at subsonic to transonic flow conditions. Experiments on boundary-layer transition are enabled by the good flow quality of KRG, which results from the absence of throttling, regulating, or mechanical driving devices. The examined flat-plate model was the *BuLASTra* model, which was designed for the study of the impact of surface bumps on boundary-layer transition. The cross-section of the *BuLASTra* model is shown in Figure 1 (left). The flat-plate cross-section was designed to achieve a uniform streamwise pressure gradient over a large portion of the model upper surface, which is the surface of interest. This enables a decoupling of the effects of different factors (Reynolds number, Mach number, pressure gradient, wall temperature ratio, and surface bumps) on boundary-layer transition, thereby also enabling their systematic study [4][5].

In the present work, the *BuLASTra* model was modified with an insert (shown by the dark red color in Figure 1, left) that reproduced the “clean / mid-bump insert” of previous work [5], but was made of PFR. The modified model is shown in elevation view in Figure 1 (right). As can be seen in this figure, the PFR appears as a dark orange surface, whereas the TSP-coated upstream and downstream regions appear as pale yellow areas. These regions were coated with a Europium-based TSP [5][7]. The mid bump was manufactured on the port half surface of the insert, whereas the starboard half surface was left clean (i.e., bump-free). Contour measurements conducted by means of a contact profilometer confirmed the attainment of the design bump contour with sinusoidal shape in the streamwise direction; the bump height was $h = 0.24$ mm, corresponding to a bump height-to-length ratio $h/a = 0.012$. The connection of the PFR insert to the main part of the model was ensured by metallic threaded inserts, which were then covered by a filler that was eventually polished to the surface contour. The filled areas appear as gray in Figure 1 (right). The *BuLASTra* model was also instrumented with three rows of pressure taps (each with an orifice diameter of 0.25 mm) to measure the surface pressure distribution, which are indicated in blue in Figure 1 (right). Note here that two rows of pressure taps were also installed in the PFR insert, where the design tap shape and size were also attained.

The used PFR was a paper-based phenol-formaldehyde resin similar to that with the highest luminescent output

in the investigations reported in [8]. When excited by light at approximately 455 nm, it emits temperature-sensitive luminescence with peak intensity at approximately 550-560 nm. In this respect, it should be remarked that both the PFR luminescent intensity and temperature sensitivity are lower than those of many TSPs, including those of the TSP applied on the remaining model areas in case of appropriate excitation at about 405 nm [7]. Although PFR luminescent intensity and temperature sensitivity can be improved by adding luminophores [2], this was not done for the present study, where the scope was to investigate the feasibility to conduct transition measurements via PFR without chemical modifications.

The PFR was excited by means of four LEDs with a peak wavelength at 455 nm, and the emitted light was detected by two 12-bit CCD cameras with a 1392×1024 pixel sensor. As shown in Figure 2 (left), one camera and two LEDs were mounted behind a window integrated in each flange (turntable) in which the model was fixed. The cameras were equipped with Scheimpflug adaptors and pinhole lenses with a focal length of 8 mm. Band-pass filters for the wavelength range 450-490 nm were mounted in front of the LEDs, whereas long-pass filters with cut-off wavelength at 525 nm were installed in front of the camera lenses.

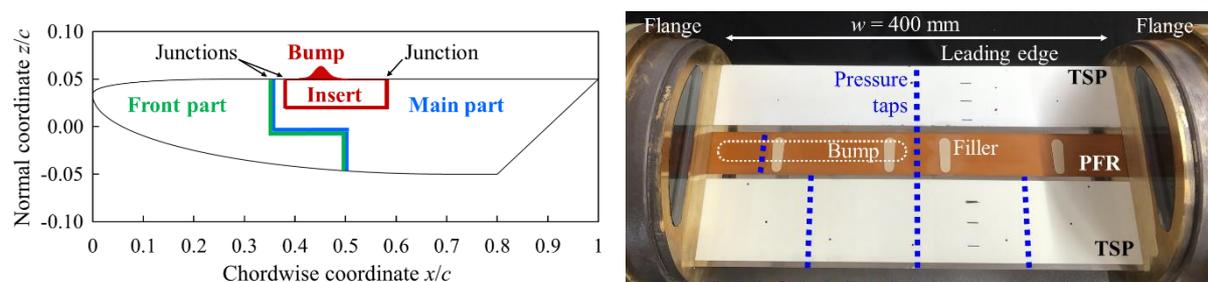


Figure 1: *BuLASTra* model with PFR insert. Left: simplified drawing (elevation view). Right: picture of the model mounted in the flanges (plan view); the instrumentation and the test-section width (w) are also indicated.

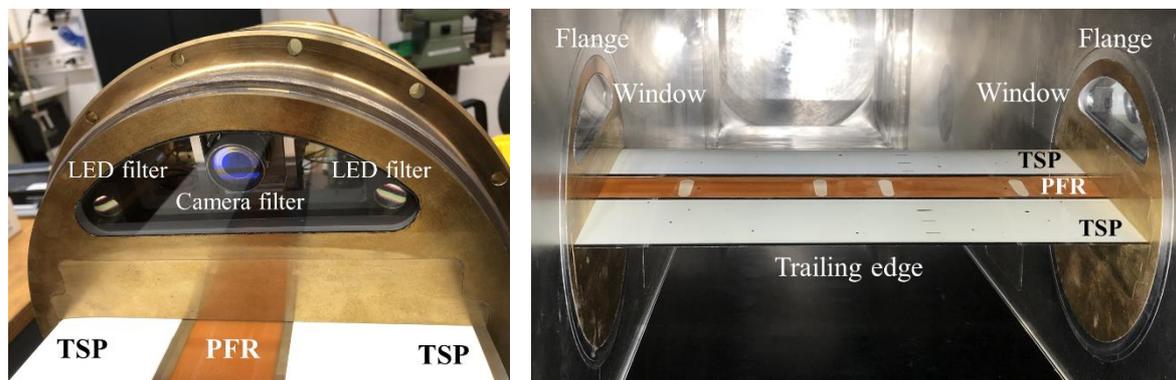


Figure 2: Left: detail of the optical setup (the starboard-side flange is shown). Right: *BuLASTra* model mounted in the KRG test section, as seen from a downstream position.

Results

The experiments were conducted at freestream Mach numbers $0.35 \leq M \leq 0.77$, chord Reynolds numbers $3.5 \cdot 10^6 \leq Re \leq 10 \cdot 10^6$, and Hartree parameters $-0.012 \leq \beta_H \leq 0.112$, where β_H characterizes the global streamwise pressure gradient for the clean configuration (i.e., in the absence of bump-induced, localized pressure changes) [5]. The charge temperature of the facility was $T_c = 283$ K. A very fast temperature drop occurs in the flow during a run in KRG according to the working principle of this blowdown wind tunnel. This is advantageous for transition measurements via TSP and PFR, since the temporal variation of the model surface temperature is smaller, as compared to that occurring in the flow. This temperature difference, combined with the different forced-convection heat transfer coefficients of laminar and turbulent boundary layers, leads to a significant surface temperature difference between laminar and turbulent areas [1][4]; the laminar-turbulent temperature difference is measured via TSP and PFR, thus enabling the detection of boundary-layer transition at the location corresponding to the maximal gradient of the streamwise surface temperature [4]. The luminescence distributions were acquired with an exposure time of 0.3 s, in order to capture a sufficient signal-to-noise ratio from the PFR. Two reference (*wind-off*) images were acquired before the actual runs were started, whereas one *wind-on* image was acquired for each run under steady flow. Following the procedure described in [5], the *wind-off* images were averaged and divided by the *wind-on* image conditions, thus providing normalized intensity images with enhanced intensity differences between laminar and turbulent regions, while at the same time compensating for the influence of inhomogeneous excitation light distribution. The divided images were

projected onto a three-dimensional grid representing the model upper surface, and the two mapped images (one from each camera) were merged in the vicinity of the test-section centerline, providing a combined image for the model upper surface. This resulting image appears as it would be seen from the test-section top wall, as shown in Figure 3. In this figure, the flow is from the left; laminar and turbulent regions correspond to the bright and dark regions, respectively. The data were obtained at $M = 0.77$, $Re = 6 \cdot 10^6$, and $\beta_H = 0.096$ (favourable global pressure gradient). The result on the left shows the reference data measured via TSP in [5]: in this case, the flow remained laminar over the whole chord length for the clean surface (model starboard half), whereas transition occurred $x_T/c = 51.5 \pm 1.5 \%$ on the port half surface because of the influence of the bump. (The transition location is indicated here by the yellow dashed line.) Turbulent wedges were also observed superimposed on the natural transition front; they were due to disturbances originating from the pressure taps and from localized, micron-sized surface roughness [1][4][5].

The results on boundary-layer transition were notably confirmed in the measurements performed via PFR, as shown on the right of Figure 3. Note here that, as a side effect of the relatively long exposure time of the cameras, information on boundary-layer transition could be obtained also from the normalized intensity distributions of the TSP regions upstream and downstream of the PFR insert, although with a reduced signal-to-noise ratio because of the suboptimal excitation light for this TSP. Further results obtained via PFR at the other investigated test conditions will be presented and discussed in the final contribution.

The reproduced bump shape showed the capability to accurately machine PFR to the contour quality required for transition studies at high Reynolds, while the reported results demonstrate the feasibility to measure boundary-layer transition via PFR at test conditions relevant for commercial transport aircraft. These findings open a possibility to use PFR for models to be experimentally investigated under limited aerodynamic loading.

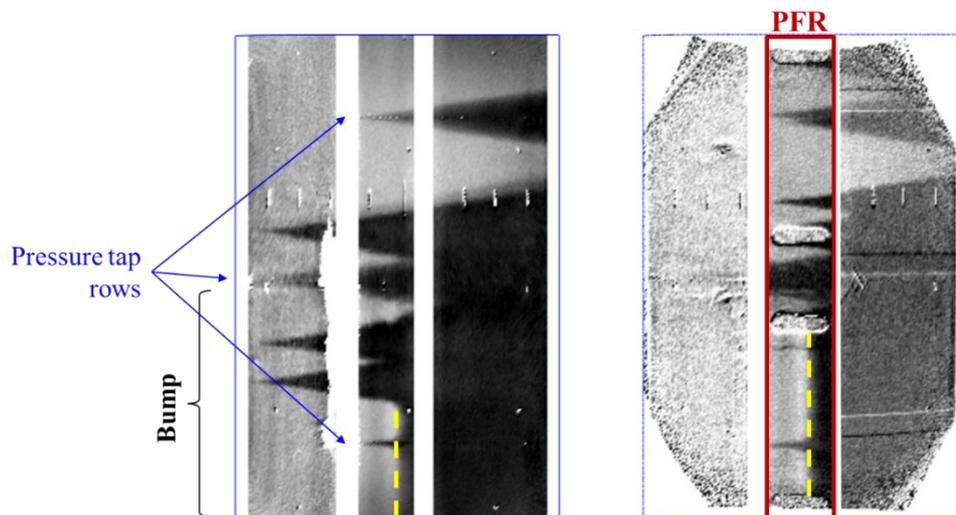


Figure 3: Transition results obtained at $M = 0.77$, $Re = 6 \cdot 10^6$ and $\beta_H = 0.096$. Flow is from the left. Left: reference data with TSP insert (from [5]). Right: result obtained with PFR insert. On the port half surface, bump-induced transition occurred on the insert region and was measured at $x_T/c = 51.5 \pm 1.5 \%$ in both cases. On the starboard half surface (bump-free), the boundary layer remained laminar for the whole model chord length.

Key Words: Phenol-Formaldehyde Resin, Temperature-Sensitive Paint, Boundary-Layer Transition, High Reynolds Number, Bump.

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