Reattaching Flow Behind a Forward-Backward Facing Step Investigated with Temperature-Sensitive Paint[*]

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Abstract

The flow features developing in the presence of a two-dimensional forward-backward facing step of small width are visualized. The flow visualizations were conducted by means of Temperature-Sensitive Paint (TSP). The tests were conducted in the Laminarwasserkanal (laminar water channel) at the Institute for Aerodynamics and Gas dynamics (IAG) in Stuttgart. A step Reynolds number Re_k *from 199 up to 1890 enables the investigation of laminar, transitional and turbulent reattachment of the flow. The variations of flow separation and impinging structures related to reattachment are well captured by the TSP technique. The TSP method requires a temperature difference between the model surface and the flow to visualize flow phenomena. This temperature difference alters the flow structures around the forward-backward facing step for low Reynolds numbers by inducing buoyancy forces in the boundary layer and recirculation zone.*

I. INTRODUCTION

Reattaching flow is of major concern for the aerodynamic performance of airfoils or automobiles. In combination with heat flux, this phenomenon is significant for the design of heat exchangers and future application of laminar wings at non-adiabatic wall conditions, e.g. in case of warmed fuel [1]. The flow features of backward- and forward-facing steps have been studied extensively, i.e., the reattachment length of the flow with respect to the step Reynolds number [2] and the coherent structures in the reattached flow [3]. For forward-backward facing steps (FBFS), primarily the excrescence's influence on laminar to turbulent transition has been investigated [4] or tests have been performed in turbulent flow [5]. The combination of excrescences and heat

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flux has been investigated mainly for heat exchanger configurations in low and narrow ducts with a short distance between leading edge and excrescence [2, 3].

The Temperature-Sensitive Paint (TSP) method is a non-intrusive surface visualization technique, which is able to visualize flow phenomena characterized by a varying heat transfer coefficient, e.g. laminar to turbulent transition, vortex footprints, and laminar separation bubbles [6, 7, 8]. If a temperature difference between surface and flow exists, these flow phenomena will change the surface temperature locally, which leads to spatial variations of the amount of light emitted by TSP. Consequently, an intensity variation in the recorded images gives indications of the predominant flow features. Application of TSP in water [7, 9] is favorable because of low flow speeds, propagation speeds of structures and a high heat capacity.

A systematic study of the wall-bounded flow features caused by a FBFS of small width in a Blasius boundary-layer flow is performed using the TSP technique. The current setup differs from heat exchanger configurations due to the large channel width and the small step height in comparison to the water level. The heated surface and the detailed view close to the FBFS distinguishes the current experiment from previous work investigating the influence of surface excrescences on transition. The step Reynolds number Re_k based on the step height k and the free stream velocity u_∞ spans $199 \leq \mathrm{Re}_k \leq 1890$. This Reynolds number range includes reattachment conditions that are three-dimensional for a two-dimensional excrescence [3]; therefore a large-area is visualized by TSP.

II. Experimental Setup and Data Acquisition

The experiments were conducted at the IAG's Laminarwasserkanal, which is a closed-loop, laminar water channel with an open channel flow test section. The facility has a turbulence level of 0.05 % in the frequency range of 0.1 to 10 Hz and provides velocities up to 0.2 m/s. The test section measures 1.2 m in width and 10 m in length. To create a new, undisturbed boundary layer, a flat plate of 8 m length is installed in the test section with a water level of 0.15 m above the plate [10]. For the experiment, a thin element needed to be designed and manufactured, which has to serve two purposes: A substrate for the TSP coating that can be placed at different locations directly on the water channel's flat plate, and providing a possibility to heat the surface. The water resistant TSP coating is described in detail in [9, 11]. A tailored composition of fiber reinforced plastics is used to fulfill both requirements for the TSP element. The element is heated by a layer of carbon fiber reinforced plastic [8] with a constant electrical power of $P_e l = 40\,\mathrm{W}$. Copper tape with a conductive adhesive is glued onto the dry carbon fibers and the electrical contact is improved by applying a conductive epoxy onto the junction of the copper tape and the carbon fiber mesh. This heating layer is laminated between layers of glass fiber reinforced plastic for thermal and electrical insulation. The heat signature of the carbon fibers is reduced with an additional layer of aluminum foil between the heating and the TSP coating as proposed in [12]. This design provides very homogeneous heating and the overall thickness of the TSP element of $d = 0.85\,\mathrm{mm}$ is thin enough to neglect the influence of the TSP elements forward-facing step $(d(_{0.15\mathrm{m/s}})^*) = 0.25)$ [4]. A sketch of the top view of the TSP element is pictured in Fig. 1. The heating layer is split into two independent parts. These parts are separated by 0.02 m in streamwise direction, which causes a dark area in the visualizations, e.g. at about $(x - x_k)/k = 14$, see Fig. 3.

Due to the high flow quality, the TSP images can be acquired in the top view through the free water surface by a scientific b/w Charge-Coupled Device (CCD). The optical system has a spatial resolution of 2.8 px/mm. Two light-emitting diodes (LEDs) with a peak emission at 405 nm are used for the excitation of the TSP. The images were acquired with the

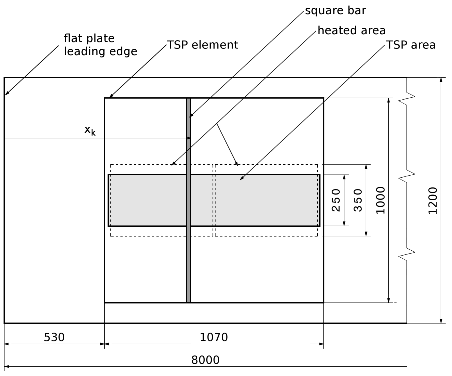

Figure 1: *Sketch of TSP element in top view, dimensions in millimeter.*

intensity method at a frame rate of 10 Hz. For each data point 40 reference images were recorded. 40 run images, i.e. with a heated wall, are taken for data points with stationary flow structures and 600 images with unsteady flow structures. The visualizations present the temperature difference between surface temperature (T) and fluid temperature (T_{ref}). The two-dimensional channel flow is disturbed by a rectangular bar (10 mm × 20 mm) placed at $x_k = 0.9\,\mathrm{m}$ (Fig. 1) with sharp edges and a height to width ratio k/w of 0.5 or 2, depending on its orientation. The step Reynolds number was adjusted by changing the flow velocity and was kept small enough to avoid a distortion of the water surface due to the displacement caused by the step.

III. Results

The experimental conditions lead to flow separation both upstream and downstream of the FBFS placed on top of the TSP element. The separation bubble upstream of the FBFS is characterized by a laminar flow, whereas three different conditions can be distinguished in the downstream recirculation region for the investigated Reynolds number range [13]: A laminar separation bubble with laminar reattachment occurs for $k/w = 0.5$ and $\mathrm{Re}_k < 500$. For larger Re_k a transitional separation with a shear layer induced transition close to reattachment follows. Under this condition reattachment occurs at the greatest distance from the FBFS [13]. Finally, for $k/w = 2$ and $\mathrm{Re}_k = 1890$ turbulent reattachment with a negligible length of the laminar region compared to the whole separation is observed.

For the largest Re_k investigated, see Fig. 2 (a), a bright vertical line indicates a high surface temperature ($-5 \leq (x - x_k)/k \leq -4$) and therefore, the beginning of the upstream influence of the FBFS on the skin friction. The high surface temperature indicates a low heat transfer, which is an indication for a separation bubble. This is followed by a region with a surface temperature slightly higher than in the laminar flow upstream of the separation bubble, which is in this case an indication for a recirculation zone. Downstream of the FBFS follows a region of warmer surface temperature that decreases gradually until $(x - x_k)/k = 5$. This area shows cloudy structures. Further downstream the temperature is again uniform but lower than upstream of the separation bubble, this indicates a reattached turbulent boundary layer. The fluctuations are smeared due to averaging the 600 images.

For further analysis, the standard deviation of the recorded intensity values is calculated for each pixel. The standard deviation highlights regions with a significant variation in temperature during the acquisition, is calculated for this flow condition and presented in Fig. 2 (b). The break between the two heating parts is not visible, which indicates that a steady surface temperature was reached before acquisition start. Upstream of the FBFS, the separation bubble is not displayed by the standard deviation indicating a steady separation bubble and recirculation zone. In contrast, a region of locally greater standard deviation appears downstream of the FBFS. Therefore, it is concluded that this region is a turbulent recirculation zone. In a time-resolved visualization this area is characterized by a highly dynamic flow with impinging vortices.

A result for a significantly lower Re_k is shown in Fig. 3 and differences in the temperature distribution are clearly visible. A

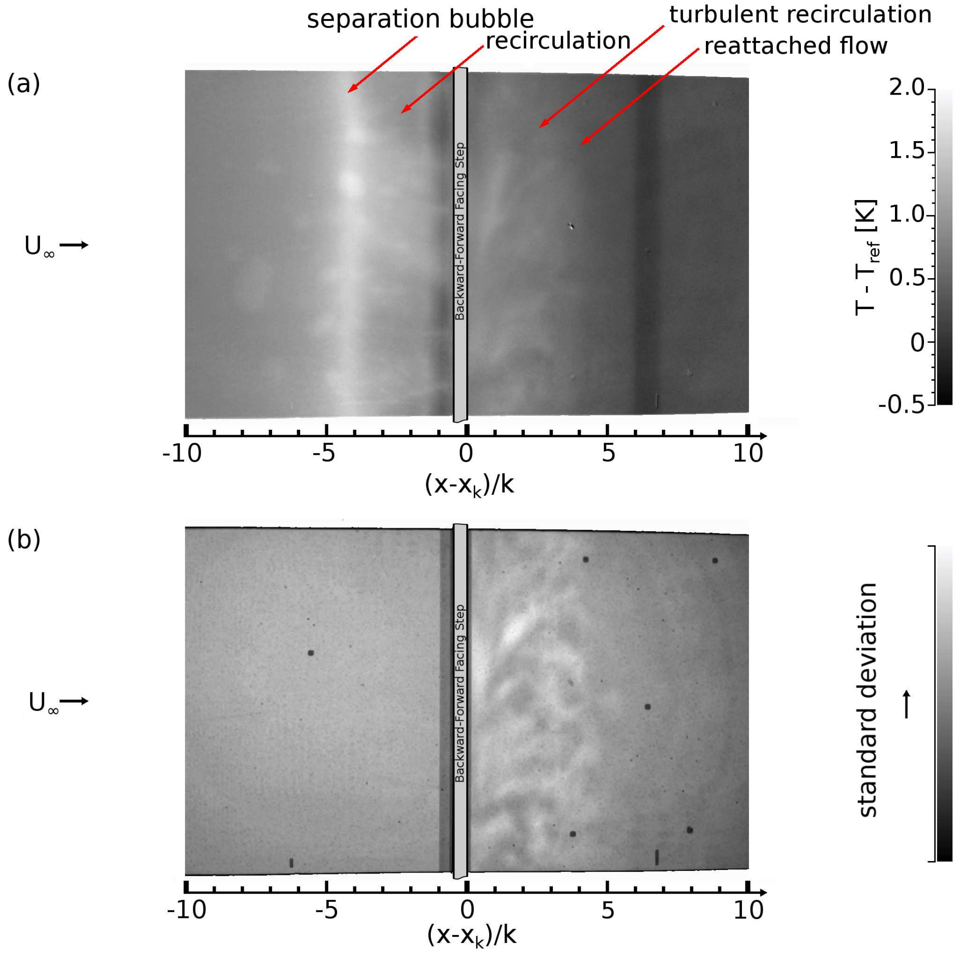

Figure 2: *Flow features in presence of FBFS with* $k/w = 2$, $Re_k = 1890$. *The TSP visualization (a) and standard deviation (b) are shown.*

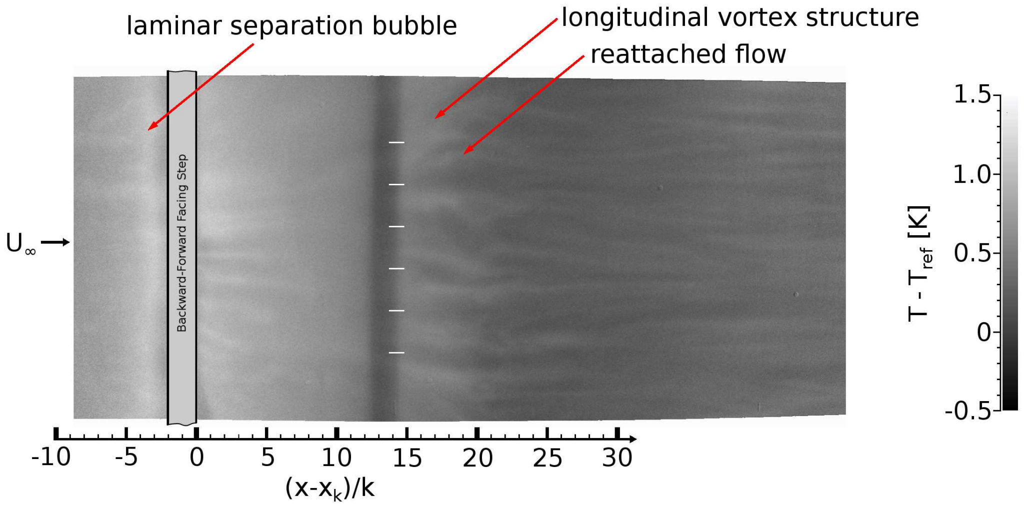

Figure 3: *Flow features in presence of square bar with* $k/w = 0.5$, $Re_k = 759$.

bright line perpendicular to the main flow direction at $(x - x_k)/k = -4$ indicates the beginning of the separation upstream of the FBFS. The downstream end of the separation bubble is about one step height away from the FBFS. Downstream of the FBFS, a lighter grey shade up to $(x - x_k)/k = 15$ shows the recirculation region. Between the FBFS and the location of beginning flow reattachment at $(x - x_k)/k = 15$ the brightness gradually decreases, which indicates a decreasing surface temperature and therefore an improving heat transfer. The flow reattachment ranges from $(x - x_k)/k = 15$ to $(x - x_k)/k = 20$ and is characterized by alternating bright and dark structures in flow direction. These streaks could be generated by vortices, which are aligned with the flow close to the surface. They might originate from a centrifugal instability (Görtler instability) close to the reattachment location outside of the recirculation zone [3]. Their spacing of about 30 mm (indicated by white, horizontal lines in Fig. 3) is in accordance with the results of a backward facing step configuration without heat flow [3]. This result supports the finding of [3], that the spacing of the instability is independent of step Reynolds number and step height and shows that the reattaching flow in the current experiment is similar to the unheated backward facing step flow. Furthermore, the present experimental setup can also exclude significant effects from side walls.

Despite the disturbance of the FBFS, the flow can also reattach as laminar flow for $Re_k < 500$ [13]. Such a configuration is shown in Fig. 4 exemplarily. The low heat transfer in the vicinity of the separation upstream of the FBFS at $(x - x_k)/k = -3$ is again clearly visible as a bright line perpendicular to the main flow direction. In contrast to the previous cases the separation bubble is touching the FBFS. Downstream of the FBFS, the image shows bright, longitudinal streaks of significant length which start at the FBFS and meander in main flow direction. These streaks result from the so-called lift-up effect [14]: counter-rotating vortices oriented in main flow direction [15] develop due to buoyancy forces generating plumes of warm fluid rising inside the boundary layer. Such thermals are intrinsic for mixed convection flow and lead to thermal instability of the boundary layer [15].

The low flow speed in the separated region behind the FBFS enables the appearance of thermally induced vortices. It seems that the vortices are stable enough to prevent flow reattachment, which should appear at approx.

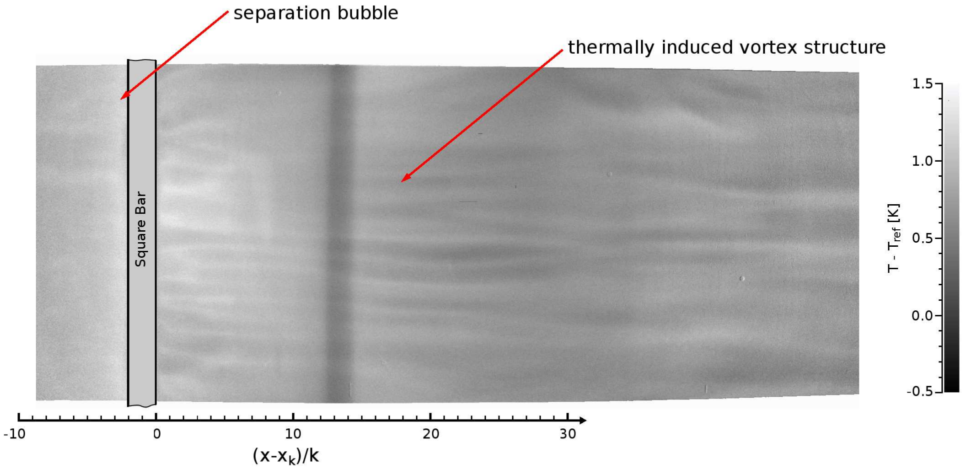

Figure 4: *Flow features in presence of FBFS with $k/w = 0.5$, $Re_k = 427$.*

$(x - x_k)/k = 14$ [13] or $(x - x_k)/k = 12.5$ [3]. A small variation in the surface temperature is visible there, but this could also result from the gap in the heating. The FBFS causes the streaks to develop earlier than under the same boundary conditions without surface excrescence, this is not shown in this paper. It is noticeable that the structures are less regular in presence of the surface excrescence (Fig. 4) compared to the case of pure mixed convection.

The TSP method requires a temperature difference of at least $\Delta T = 0.1\,\mathrm{K}$ for a satisfying contrast in the TSP images [11] but in this measurement this was not sufficient because of the short exposure time need for the time-resolved measurement.

The variations of the spanwise-averaged location of flow separation x_s and flow reattachment x_r with respect to Re_k are summarized in Fig. 5. The upstream flow separation moves gradually away from the forward step of the FBFS with increasing Rek,, as shown in Fig. 5 (a). However, the turbulent reattachment downstream of the FBFS has a very short reattachment length, see Fig. 5 (b), and at large Re_k, it is shorter than for the backward-facing step [16]. With decreasing Rek the reattachment length increases before it reaches a maximum at $500 \leq \mathrm{Re}_k \leq 800$. For even lower Reynolds numbers it can be assumed that the reattachment length becomes again shorter, as it is the case for the backward-facing step [2]. With the TSP technique it was only possible to determine a reattachment location for $\mathrm{Re}_k \geq 500$, when the shear layer is already subjected to longitudinal instabilities (Fig. 3) or becomes already turbulent before reattachment (Fig. 2). For $\mathrm{Re}_k \leq 500$ the reattachment location could not be visualized due to induced buoyancy forces (Fig. 4), which significantly alters the flow downstream of the FBFS.

IV. Conclusions

Experiments were conducted at the IAG's Laminarwasserkanal investigating laminar, transitional and turbulent reattachment behind a forward-backward facing step (FBFS) ($199 \leq \mathrm{Re}_k \leq 1890$) placed on top of a flat plate by means of TSP. The surface visualization method is capable of capturing the developing two- and three-dimensional flow phenomena very well and allows a detailed analysis of the flow topology of turbulent or transitional shear layers. Two conditions of flow separation upstream of the FBFS were identified, i.e. a laminar separation bubble attached to the FBFS or one detached from it. The spa-

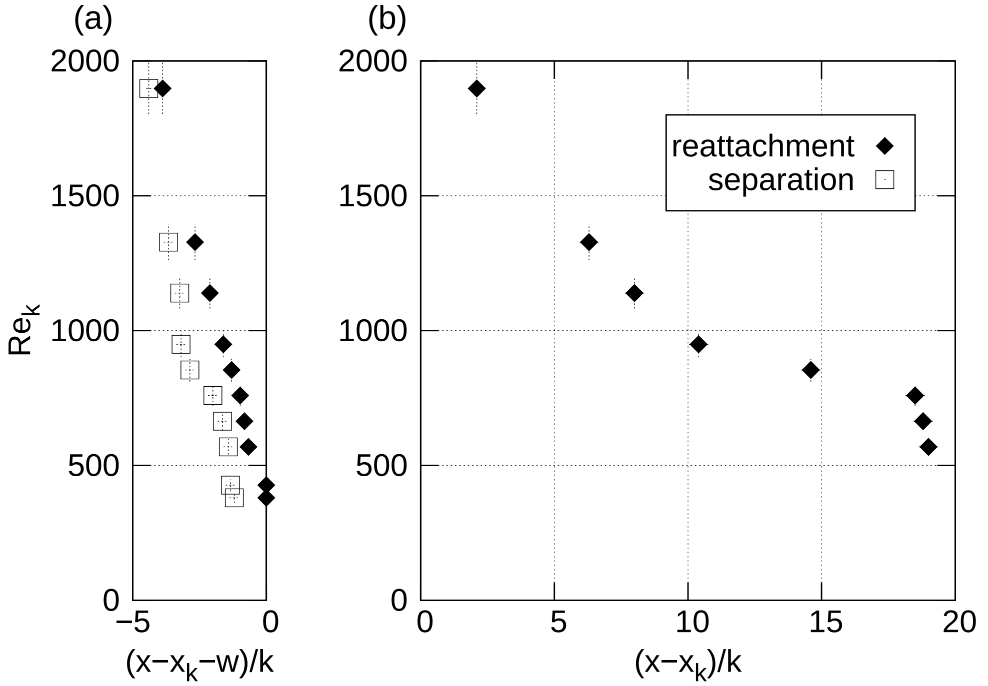

Figure 5: *Spanwise average of relative distance of flow separation and reattachment upstream (a) and downstream (b) of FBFS.*

tial analysis of the standard deviation can be used to distinguish between steady and unsteady flow phenomena. Laminar reattachment ($Re_k \leq 500$) could not be studied because of streaks generated by the surface heating, which is necessary for the TSP technique. This problem is not expected for TSP investigations in air or nitrogen. Further investigation of the interaction of the thermally induced streaks and the vortex system of the reattaching shear layer (Görtler instability) could be interesting to pursue, especially with the TSP technique in water facilities.

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