Mitteilung

Fachgruppe: Turbulenz und Transition

Analysis of Separated Shear Flow and Reattachment over a Backward Facing Step using the DLR ADaMant Experiment

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In aerospace research and industry, computational fluid dynamics (CFD) and statistical turbulence models based on the Reynolds averaged Navier-Stokes (RANS) equations have become a working-horse for design and analysis. Among the different flow features, it is important to correctly predict the size of separation regions and the reattachment point. In aerodynamic flows, different types of flow separation arise. Separation regions can be thin compared to the boundary thickness δ, i.e., incipient separation near trailing edges or shock-induced separation at transonic flow speed, but also thick, i.e., of the same order or larger than δ. The accuracy of RANS models to predict flow reattachment was a central topic at the ''The NASA's 40% Challenge and CFD Prediction Error Assessment Workshop 2018''. The question arose, as to whether and why some RANS models (e.g., SSG/LRR-ω) yield good agreement with experimental data for the validation case over a backward facing step (BFS), but predict reattachment too far downstream for the flow over the wall-mounted NASA hump [4].
In order to shed light on this question, a new BFS-flow experiment was performed within the DLR internal project ADaMant (see Fig. 1). The goals were (i) to provide highly resolved data for the mean velocity and for the Reynolds stresses using Lagrangian Particle Tracking (LPT) and for the wall-shear stress surface pattern using Temperature Sensitive Paint (TSP), (ii) to study the sensitivity of the reattachment line on the appearance of a secondary bubble by a variation of the step angle (25 deg, 45 deg, 90 deg), and to provide data from two test-facilities (the 1 Meter Tunnel Göttingen (1MG) and the Large Water Tunnel Braunschweig (GWB)).

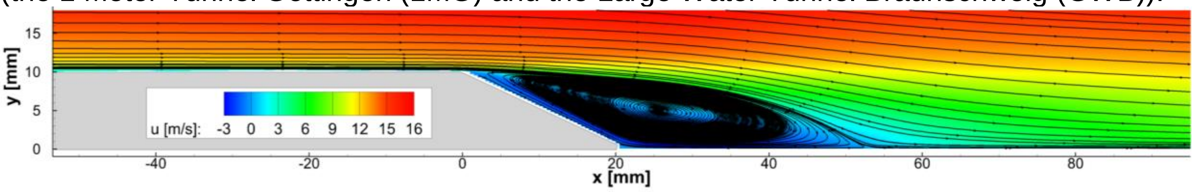

Figure 1: Backward-facing step (with 25° step angle) and mean-velocity field from LPT (bin size 500 x 50 µm²).

The aim of this experiment was to provide data for the validation and improvement of RANS and hybrid RANS/LES turbulence modelling and for the validation of the research hypotheses on the turbulence structure and the characterisation of the Reynolds stress anisotropies in separated shear flows proposed by Eisfeld [1,2]. Indeed, Eisfeld found a significant deviation in the turbulence structure (i.e., the Reynolds stress anisotropy a_{12}) in free-shear flows (e.g., the planar mixing layer) compared to attached turbulent boundary layer flows at zero pressure gradient. He reported values of $a_{12}=|\langle u'v'\rangle|/2k$ around 0.165 for free-shear flows, compared to $a_{12}=0.15$ for wall-bounded flows (with $\langle u'v'\rangle$ being the Reynolds shear stress and k being the turbulent kinetic energy). Such a larger value of a_{12} increases the turbulent shear stress at a given level of turbulent kinetic energy, and hence increases the spreading of free-shear flows and reduces the reattachment length. For the re-calibration of the SSG/LRR-ω RSM using $a_{12}=0.165$ in free-shear flow regions see [1]. Hence, as the turbulent equilibrium state is observed to vary accordingly with the flow type, locally adapted model coefficients are required to predict boundary layers and separated shear layers (and hence reattachment) correctly.

This hypothesis is studied in the present work by an evaluation of the bin-averaged 2D2C-LPT data for the 1MG with a spatial resolution of 50 µm in y- and 500 µm in x-direction. As the free-shear layer of the BFS flow is following the curved mean streamlines, the first step was to develop an automatized method to identify a suitable local coordinate system given by a locally changing unit vector basis of streamwise s-direction and normal n-direction. This flow-fitted local orthogonal basis was chosen to follow a suitable streamline. The streamline given by the peak turbulent kinetic energy in the center of the separated shear layer was selected.
The turbulent kinetic energy (TKE) of the separated shear layer was further studied. The TKE, Reynolds stress maximum and spreading rate (defined here by the 75%-maximum-TKE location) in the flow seem to also define three local regions (see Fig. 2), each associated with a different characteristic spreading rate of the turbulent kinetic energy. The spreading rate dδ/dx was found to be the largest for x/H<3, being dδ/dx~0.18, then it stays roughly constant until the reattachment point near x/H=5.5. After flow reattachment, dδ/dx is around 0.03. The correlation coefficient $S_{uv} = |\langle u'v' \rangle|/(|u'^2|^{1/2}|v'^2|^{1/2})$ was found to be near 0.4 in the attached boundary layer, but significantly larger in the separated shear layer (i.e. between 0.55-0.6 for x/H<3, and around 0.5 for x/H<5.5). However, RANS models like the SSG/LRR model are calibrated to yield 0.4 (corresponding to an anisotropy a_{12} around 0.15, see [1]) Hence the present LPT data support the work by Eisfeld concerning the deviation of turbulence structure between attached and free-shear flows and the need for a flow-type-adapted modelling.
Then, the spreading of the separated shear flow and the turbulent kinetic energy was studied in more detail. Different definitions for the spreading rate borrowed from planar mixing layer flows [3] were studied. In [3], the scaling patch approach was used to show qualitative data collapse for the free-shear layer flow. The present work attempts to likewise apply this approach to the BFS flow. Finally, the methods for data analysis are applied to the wall-resolved NASA Hump flow LES data [4].

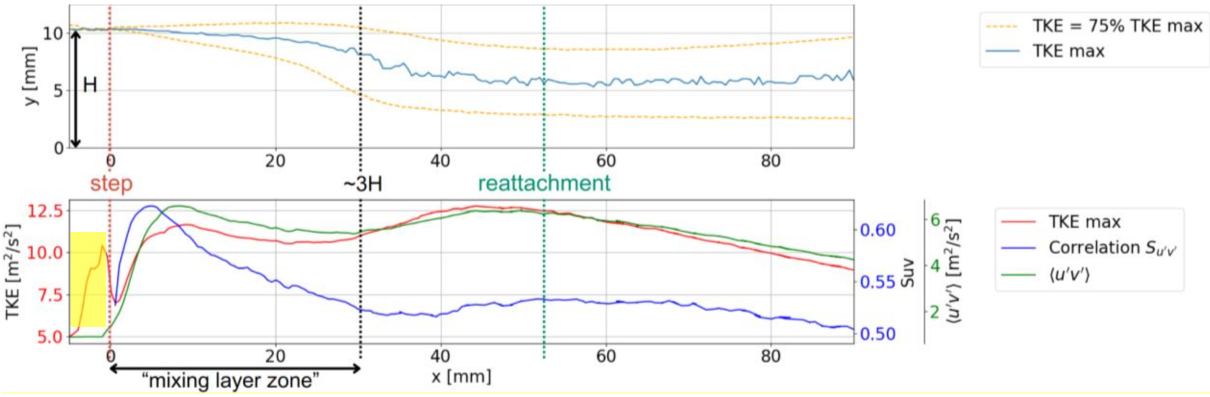

Figure 2: BFS turbulence study (for 90° step angle), step height H=10mm, entry velocity U=24.6 m/s.

To conclude, the LPT data for the ADaMant BFS flow experiment support the work by Eisfeld [2] suggesting that the local equilibrium state of turbulence is different between attached turbulent boundary layer flow and separated free shear flow. As an outlook to possible future research, closer work on the similarity and scaling analysis of the planar mixing layer, the BFS flow, and the NASA hump flow could help to refine RANS turbulence models and their calibration and to improve the understanding of turbulent free-shear flows.

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References:

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