A Massively Parallel Particle Tracking study of Adverse Pressure Gradient Effects in Diffusers

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Vision and Ambition

The efficiency of many engineering systems relies upon boundary layers remaining “attached” to the wall under adverse pressure gradients (APGs), while minimising turbulent energy losses. Classic examples include the flow in diffusers or over the trailing edge of aerofoils. Here, as the wall turbulence is forced to adapt to the deceleration of the bulk flow, the momentum deficit near the wall increases and outer layer turbulence increases, resulting in reduced pressure recovery, flow separation and stall. Predicting and controlling the state of the APG boundary layer is therefore essential to optimising performance.

The long-term ambition of this project is to facilitate the design of flow control systems for more efficient transportation vehicles, wind turbines and other aerodynamic devices. The potential benefits of realizing such systems include *“saving billions of dollars in annual fuel costs for land, air, and sea vehicles, reversing or at least slowing down dangerous global warming trends”* [1]. Several obstacles stand between the state-of-the-art and this ambition. The range of scales involved, from O(μm) inner layer motions to O(m) outer layer motions, challenges both experimental and computational approaches. Current PIV/PTV techniques offer a spatial dynamic range (SDR, the ratio of largest to smallest resolvable scales) of O(100), which prohibits seeing the full picture. To design devices near separation and stall, a hybrid RANS/LES approach such as wall-modelled LES is essential [2]. This approach models the inner layer motions and resolves only the largest, slowest outer layer dynamics. However, this task remains an outstanding grand challenge for even the most advanced approaches [3], [4]. Moreover, to conceive effective designs, it is first necessary to identify flow features which can be efficiently manipulated to modify flow behaviour [5]. Inherently, these must target large-scale, outer layer motions, due to the size of actuators needed [6] and their dynamical role in flow separation [7].

This project will address the these challenges by **creating new measurement modalities that resolve a wider range of scales,** and applying them to **build the knowledge to improve the fidelity of numerical models and design effective flow control**. The project therefore has two aims. First, **we aim to develop and validate a new experimental methodology, Massively Parallel Particle Tracking Velocimetry** (MP-PTV), which offers extremely high SDR sufficient to resolve inner- and outer layer motions simultaneously. Preliminary tests of this technique have demonstrated the potential to achieve an order of magnitude increase in SDR and has applications far beyond the current project. **Subsequently, we will apply MP-PTV to systematically characterise the response of diffuser flows to varying strengths of APGs**, to better model the unresolved inner layer motions, and to establish the prospects for flow control by manipulating the outer-layer motions. This complements our ongoing efforts on rough-wall boundary layers under APGs (AFOSR FA8655-22-1-7163).

Background

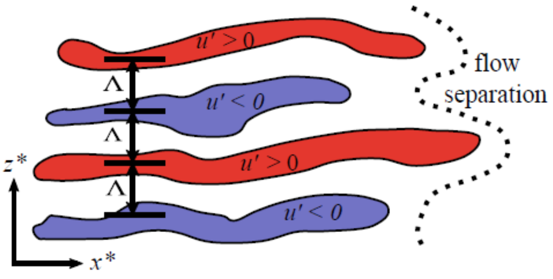

Figure 1: sketch of the impact of very large scale “streak” motions upon flow separation in an APG TBL, from [7].

The last two decades have seen renewed efforts to understand the physics of APG wall turbulence [7]–[12]. The most pronounced effects alter the outer layer, namely an increase in the relative strength of wake region and outer layer turbulence compared to the inner layer [8], [9]. At high Reynolds numbers, this outer layer turbulence is dominated by very large scale motions (VLSMs) which exceed several boundary layer/channel heights in length and are intensified by APGs [9]. As illustrated in Figure 1, VLSMs manifest as elongated, meandering streaks of below- and above-average streamwise momentum, which modulate the turbulence in the inner layer [9], [11], [13]. The amplitude modulation effect is increased under APG conditions [10]. Moreover, VLSMs have recently been shown to strongly modulate flow separation in an APG TBL [7], [11]. These results highlight that **the response of wall turbulence to adverse pressure gradients and the initiation of flow separation is a strongly multi-scale, three-dimensional phenomenon** which depends upon the interaction of VLSMs with the near-wall flow. These observations, among others, have previously proved essential to manipulate VLSMs with active and passive flow control to reduce drag [1], [6], [14], [15] and noise [16] and highlight the significance of VLSMs to the present flow separation problem. To date, studies on the response of VLSMs to APGs have exclusively focused on TBLs [7], [9], [10]. However, in a TBL, the outer layer is free to thicken in response to the APG, in contrast to internal flows such as diffusers which are confined by their geometry. Even under zero pressure gradient, there are marked differences between the outer layer of TBLs and other internal flows [17]. **Therefore, given the significance of the diffuser case, a systematic characterisation of the response of the wall turbulence and VLSMs to varying APG is needed**.

The modelling side of the flow separation problem has been historically challenging. Hybrid LES/RANS approaches, such as wall-modelled LES (WMLES), are now recognised as essential to predict separation reliably [2]. However, as highlighted by two recent reviews, these models require improvements to predict separation even under mild APGs [3], [4]. The first need for this effort is to create a "well-defined experimental validation problem" which resolves both the wall shear stress and the dynamically active large-scales [3]. Experimentally, the challenge lies in resolving both of these quantities simultaneously, due to large $O(Re_\tau)$ separation of scales between the inner layer motions which transfer shear stress to the wall and the large, outer layer motions which modulate it. It is further compounded by the highly three-dimensional nature of separated flows. Stitched planar PIV and 2D particle tracking approaches [12], [18] can partially address this problem, but the low SDR (~30-50) of volumetric techniques [19] needed to resolve 3D effects is still one order of magnitude too small. Therefore, to address the physics and modelling problems experimentally, **new 3D measurement modalities are required that resolve a wider range of scales.**

The last decade has seen increasing industrial and academic interest in obtaining 3D flow measurements at large scales O(1m^3) [20]–[22]. Such volumetric PTV measurements are typically performed with 3 or 4 cameras. The SDR is determined by number of particles which are tracked ($SDR \propto \mathrm{N}^{1/3}$), which is proportional to the camera sensor resolution. With state-of-the-art hardware and software, simultaneous tracking of up to N=10^5 particles is possible [23]. Since all cameras share the same field of view (FOV), the SDR is fundamentally limited by sensor resolution, so there is a compromise between spatial resolution and FOV size. Robotic PTV partially overcomes this by capturing multiple volumes with an automated robotic arm, at the expense of time and intrusion into the flow [21], [22]. To achieve high seeding densities, timeseries or multiple pulse images must be acquired for Shake-The-Box analysis [24], which require expensive high-speed or double-frame camera hardware. Furthermore, the technique usually requires high-speed (or multiple low-speed) lasers with large pulse energies to provide adequate volumetric illumination, seriously limiting applicability and scalability.

Figure 2: Illustration of planar camera array concept: (a) simulated reconstruction of 1.1x10^5 particle tracks in a turbulent channel flow (b) 8-camera array installed in channel flow facility and (c) inverted shadowgraph image of particles obtained using pulsed LED backlighting. Initial tests show that sharp particle images can be obtained with good depth of field for volumetric PTV.

To address these issues, we have recently initiated a new approach: Massively Parallel Particle Tracking Velocimetry (MP-PTV). The concept, illustrated in Figure 2, is to use a planar array of O(10-100) inexpensive colour cameras to each record a part of the flow with high spatial resolution, creating a composite reconstruction with an order of magnitude improvement in spatial dynamic range. The fields of view overlap, but remain coplanar, so every particle can be triangulated by three cameras. Colour is used to encode time through sequential red-green-blue pulsed LED illumination (as in e.g. [25], [26]), eliminating the need for expensive high speed or double-frame cameras. We have already developed hardware and software systems for MP-PTV and are currently testing them in our turbulent channel flow facility (shown in Figure 2b). The flow is imaged using a shadowgraph technique (as in e.g. [25]), which drastically reduces the intensity of light required for illumination: the sample image in Figure 2c was backlit by a 3μs pulse from an inexpensive (£15) RGB-LED, suitable for flow measurements at speeds up to ~30m/s. By using Raspberry-Pi cameras, data acquisition is easily coordinated and can scale to O(100) cameras with networked storage. The key to scalability is the planar array with inexpensive hardware: additional cameras/backlighting can be added for ~£250/module and stacked to achieve greater extent. While other authors have used the RGB-PTV approach [25], [26], they have not adopted our scalable design. Moreover, they have not adopted our dense PTV approach. We have two particle tracking codes adapted to particle tracking in RGB images: conventional PTV [27] and a prototype Shake-The-Box implementation [24]. The conventional algorithm works well with seeding densities up to 0.0125ppp (Figure 2a) on synthetic images, and the prototype STB algorithm has been tested with seeding densities up to 0.125ppp.

Objectives

The central goal of the proposed project is to develop the high SDR MP-PTV technique and apply it to systematically characterise the response of inner and outer layer motions in diffusers to varying strengths of adverse pressure gradients. This ambitious goal will be achieved by completing the following objectives (encapsulated in work packages, WPs) over a 3.5 year research programme by a PhD student. These are:

WP1) **MP-PTV development**. Develop an open-source MP-PTV system, validated against a baseline mild APG case measured with conventional 2D PIV/PTV

WP2) **Parametric study**. Capture extensive MP-PTV datasets to create data-driven models of the wall shear stress, via a parametric study of near-separation and separated APG diffuser flows

WP3) **Large scale dynamics**. Using these datasets, characterise the role of large scale, coherent motions in wall-normal momentum transport and flow separation in diffusers

The PhD will be supervised by John Lawson, with the Bharath Ganapathisubramani as a second supervisor. They will benefit from the experience of a senior PhD student (Thomas Preskett) working on the related AFOSR project (FA8655-22-1-7163) on APG rough wall TBLs, as well as postdocs/PhDs of the Experimental Fluids group, who attend a group-wide weekly meeting and share techniques in weekly PGR seminars.

Research Programme

WP1: MP-PTV development and validation (18 months)

The first aim of WP1 will be to validate and improve the capabilities of our MP-PTV technique, which we will apply in WP2/3. The second aim of WP1 is to establish a baseline case of an APG boundary layer in a weakly diverging channel. We will achieve this by comparing MP-PTV measurements against conventional 2D-PIV and pressure drop measurements in the baseline case.

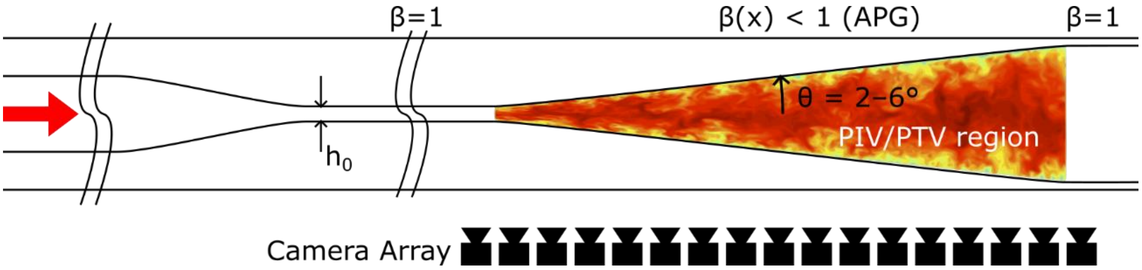

Figure 3: schematic of proposed APG TCF experiments in channel flow facility

All measurements will be carried out in the University of Southampton's new turbulent channel flow facility, shown schematically in Figure 3. The channel is 6.25m long with a 400 x 90mm cross-section, adjustable false floor/ceiling, streamwise pressure taps, magnetic flow meter, heat exchanger and bubble deaeration system. It is capable of achieving smooth-wall friction Reynolds numbers $Re_\tau = 500 - 4400$ within the application-relevant high Reynolds number regime. We will replace a section of the parallel false floor/ceiling with a contraction followed by a 1.1m long symmetric diffuser (2° half-angle), which is expected to develop a classic self-similar solution after 40h$_0$ = 0.4m. This sets up an adverse pressure gradient $dP/dx > 0$, described by the modified Clauser parameter $\beta(x) = -\frac{h}{\tau_w}\frac{dP}{dx}$ where h is the diffuser half-height and τ_w is the skin friction (in equilibrium channel flow, $\beta = 1$). We will obtain 2D-PIV measurements of the velocity field at multiple locations along the diffuser over a range of Re_τ. This will provide a reference measurement for the MP-PTV and allow us to determine velocity profiles and skin friction in conjunction with pressure tap measurements.

We will then apply our MP-PTV technique to measure the full streamwise development of the diffuser flow simultaneously. This will require an array of 32 cameras and pulsed LED backlighting to capture shadowgraph PTV images over the length of the diffuser. Initially, we will process the images with our low-density RGB-PTV particle tracking code, which is capable of analysing low-density particle images (0.0125ppp) with minimal ghost particles and measurement noise correction [27]. Part of the WP will be dedicated to improving the capabilities of our RGB-PTV code using the Shake-The-Box algorithm [24]. The objective of this is to increase the instantaneous SDR of features that can be resolved by increasing the seeding concentration. This will also allow us to improve the statistical convergence our measurements for a given number of images. We already have a prototype version of this algorithm which has been tested on synthetic data. The PTV based method provides spatial resolution of mean quantities proportional to particle image diameter (~10µm), which allows us to resolve mean skin friction directly from the wall-normal gradient $\tau_w = \nu\, dU/dy$ [18]. Comparisons against the 2D-PIV and pressure tap data will be used to validate the MP-PTV technique.

We anticipate our MP-PTV technique will have applications far beyond the current project: its capability and scalability makes it a good option for studying large-scale, turbulent 3D flows with large spatial dynamic range and its relatively low cost reduces the barrier-to-entry to adoption. We will release open-source software for particle tracking and data acquisition, as well as hardware designs for pulsed illumination, which will enable other research groups to adopt our technique immediately.

Deliverable: a validated, open-source software and hardware system for MP-PTV

WP2: parametric study of diffuser flow (12 months)

The aim of WP2 is to **perform a parametric study of near-separation and separated APG boundary layers in diffusers and develop data-driven models of the wall shear stress**. We will test three further symmetric diffuser geometries with our MP-PTV setup with θ = 4°, 6° and 8° and an asymmetric diffuser with θ = 8° by replacing the false floor/ceiling with different sections. These cases have been chosen to survey varying strengths of the APG parameter β(x) and therefore increased tendency to separate. Again, the survey will be conducted over a range of skin-friction Reynolds number $Re_\tau = 500 - 4400$.

Our first objective will be to recover mean velocity profiles, turbulence statistics, skin friction coefficient c_f and pressure gradient along the diffuser for each geometry and Reynolds number using MP-PTV. These simple observations address calls for a "well-defined experimental validation problem" for non-equilibrium wall models, which captures the skin friction profile, mean flow and turbulence statistics in both mild and strong APGs [3], [4]. Our second objective is to use a data-driven approach to address wall stress modelling: given a (coarse grained) velocity distribution $\widetilde{U}(\boldsymbol{x},t)$ resolved at a height y above the wall, estimate the instantaneous wall shear stress. Our starting point will be to determine *instantaneous* coefficients for the wake strength Π, log-law slope κ and intercept B used in algebraic WMLES models:

$$\frac{\widetilde{U}(x,y,t)}{u_\tau} = \frac{1}{\kappa}\ln(yu_\tau/\nu) + B + \frac{\Pi}{\kappa}W\left(\frac{y}{\delta}\right) \tag{1}$$

Here, $\widetilde{U}(x,y,t)$ is the *instantaneous, local*, spatially averaged streamwise velocity (representing filtered fluid velocity, as in WMLES), $u_\tau = \sqrt{\tau_w/\rho}$ is the (coarse grained) skin friction velocity, $\delta(x)$ is the diffuser height, ν is the fluid viscosity. Note that equation (1) is usually applied to the *time average* flow, but in WMLES, is applied as an *instantaneous, local* closure. Determining the suitability of this parametrisation near separation, as well as the variation of the unknown coefficients κ, B and Π with dimensionless pressure gradient β and friction Reynolds number Re_τ, already informs the applicability and accuracy of algebraic wall models [4]. The wake correction Π is particularly significant, because it corrects the (presumed universal) inner log-law scaling for non-universal outer layer behaviour, for which there is little data for internal APG flows such as diffusers.

Deliverable: a journal article reporting our parametric study experiments and the data-driven model

WP3: dynamics of large scale motions (12 months)

The aim of WP3 is to **characterise the role of large scale, coherent motions in wall-normal momentum transport and flow separation in diffusers**. By doing so, we will establish the potential for flow control strategies which target VLSMs, and what length- and time-scales future studies should target for manipulation.

To do this, we will first identify the VLSMs in the volumetric datasets collected in WP2 using two-point correlations and the related Proper Orthogonal Decomposition technique. We will then decompose wall-normal momentum fluxes and statistics of flow separation using the POD basis. The objective of this analysis is to quantify the contribution of the educed VLSMs to the turbulent momentum transport and the extent to which they modulate flow separation. This analysis will also identify how the characteristic lengthscales of the VLSMs vary as a function of streamwise distance and APG strength. To identify a *timescale* of VLSMs from the snapshot data collected in WP2, we will use an approach based on resolvent analysis [28]–[30]. The idea is to identify the frequency ω at which spanwise travelling wave perturbations $\hat{\boldsymbol{u}}_{k\omega}\mathrm{e}^{i(kz-\omega t)}$ with wavelength k are most strongly amplified by the base flow. This allows us to associate a timescale $2\pi/\omega$ for each spanwise wavelength $2\pi/k$ and its spatial mode $\hat{\boldsymbol{u}}_{k\omega}\mathrm{e}^{ikz}$, which can be used similarly to the POD basis to analyse momentum transport and flow separation or directly compared to the POD modes. To extract these resolvent modes from the mean flow fields obtained in WP2, we will use the FreeFEM++ based code [29] developed by AFM academic Dr. Sean Symon. As in previous studies based on experimental data [28], a parametrised fit of the mean flow field will be used to minimise the influence of missing or uncertain data.

Deliverable: a journal article reporting the role of large scale, coherent motions in wall-normal momentum transport and flow separation, covering the parameter space studied in WP2

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