A Detailed CFD and Experimental Investigation of a Benchmark Turbulent Backward Facing Step Flow

Stephen D. Hall\textsuperscript{1}, Tracie J. Barber\textsuperscript{2}
1 University of NSW, Sydney, NSW 2052, Australia. sd.hall@unsw.edu.au
2 University of NSW, Sydney, NSW 2052, Australia. t.barber@unsw.edu.au

Keywords: Backward Facing Step, Particle Image Velocimetry, Corner vortex

Abstract:

A benchmark turbulent Backward Facing Step (BFS) airflow was studied in detail through a program of tightly coupled experimental and CFD analysis. The theoretical and experimental approaches were developed simultaneously in a "building block" approach and the results used to verify each "block". Information from both CFD and experiment was used to develop confidence in the accuracy of each technique and to increase our understanding of the BFS flow.

The key step in this study compared Particle Image Velocimetry (PIV) data with CFD models. As both techniques generate velocity and turbulence statistics over a global 2D area, direct and detailed comparison of streamlines and contours was possible. PIV and Hot Wire Anemometry were used to precisely measure the inlet velocity and turbulence statistics. These profiles then formed the CFD inlet boundary conditions to ensure "exact equivalence" between CFD and experiment.

PIV and CFD results showed excellent agreement in comparison of velocity components, streamlines and vorticity and allowed complex BFS flow structures to be revealed. Access to both CFD and PIV results proved invaluable, as they tended to supplement each other and allow the BFS flow regions to be investigated in greater detail than previous studies.

Introduction

The objective of this study was to investigate the mean behaviour of a subsonic, turbulent BFS airflow, simultaneously using CFD and the advanced laser diagnostic technique of PIV. The approach was to use CFD and PIV results to compare and supplement each technique.

Turbulent Backward Facing Step

A BFS flow was chosen because it has a simple geometry, but contains many flow regimes relevant to practical engineering. In addition, the BFS has perhaps the most extensive literature base of any benchmark flow, with several reliable datasets for comparison. Typical mean flow structures that have been identified on the Cross-Sectional (CS) symmetry plane are shown in Figure 1. These structures exist only in the mean flow and are not generally present in the instantaneous flow (Le et al. 1997).

Useful characteristic dimensions and lines can be defined in the BFS mean flow (Figure 1). The shear layer is defined by the dividing streamline from the step edge to the reattachment point $X_r$. Both $X_r$ and the dividing streamline are strong measures of the turbulent interactions influencing the shear layer. The second vortex is located by the primary-secondary interface line between the reseparation point $X_s$ and the reattachment point $Y_s$. At $X_s$ both primary and secondary vortices separate from the bottom surface. These points are useful measures of how the primary and secondary vortices interact, but have generally been ignored as they are difficult to measure. The primary vortex can be further characterised by the stagnation line $\tau=0$. 

\textsuperscript{1}
Figure 1 Mean flow structures in the CS plane of symmetry of the turbulent BFS flow

The eye, or stagnation points $Sp(x,y)$ and $Ss(x,y)$ of the primary and secondary vortices respectively, define the location of each vortex. Inlet conditions can be characterised by top and bottom boundary layer thickness $\delta_t$ and $\delta_b$ and velocity and turbulence inlet profiles (Adams and Johnston 1988b).

**Turbulent Backward Facing Step Studies**

The BFS flow has been studied intensively for at least four decades and is possibly the most popular benchmark flow. Literature is extensive, with contributions from experimental, theoretical and computational fluid dynamics. Eaton and Johnston (1981) explain that the BFS is popular because it is the “simplest reattaching flow with a region of separation and reversed flow”. Despite this geometric simplicity, the BFS flow is complex and composed of many regions of different flow regimes that make for a thorough test of PIV and CFD techniques, particularly turbulence models. Thangam and Hur (1991) note that “the BFS is often used for analysing the efficiency of CFD algorithms and turbulence models, since it embodies several crucial aspects of turbulent separated flows”.

Our understanding of the BFS flow has improved with advances in fluid measurement technology. The recirculating and highly unsteady BFS flow presents a considerable challenge for most experimental techniques (Adams and Eaton 1988). Early studies relied on flow visualisation methods, such as oil, smoke, ink or tufts (Armaly et al. 1983, Kim et al. 1978) and experiments were limited to low speed laminar regions. A few studies investigated the turbulent BFS, but measurements were limited to low turbulence regions outside of the recirculation region (Kline 1959, Kim et al. 1980, Bradshaw and Wong 1972). PIV has recently revealed the global BFS flow, at higher resolution than previously possible (Scarano and Riethmuller 1999, Shen and Ma 1996, Kasagi and Matsunaga 1995).

Reliable CFD routines, such as Large Eddy Simulation and Direct Numerical Simulation (DNS) are also making a contribution to BFS research. They are revealing the behaviour of the complex, unsteady, 3D BFS flow structures (Le et al. 1997, Kobayashi et al. 1992). BFS knowledge is well summarised in the reviews by Eaton and Johnston 1981, Eaton and Johnston 1980, Adams et al. 1984, Simpson 1996, Kim et al. 1978.

**Regions of Interest in the Turbulent Backward Facing Step**

BFS literature shows that several regions of the BFS flow remain uncertain because data is limited, or contradictory. This study will examine the step corner and second vortex because it experiences very low velocities (<0.001 m/s), high turbulence and reversing flow. Early flow visualisation of this region was limited (Armaly et al. 1983, Jezek and Reznicek 1987, Kim et al. 1978) and significantly underestimated the second vortex, as simply a small circle of flow (Eaton and Johnston 1981, Bradshaw and Wong 1972). Moffatt (1964) found a third vortex (radius 0.042H) beneath the second vortex, which has not yet been confirmed. High-resolution PIV studies (Kasagi and Matsunaga 1995, Scarano and Riethmuller 1999) failed to detect it, but it has been predicted by DNS (Le et al. 1997) and a non-linear RNG $k-\varepsilon$ model (Lien and Leschziner 1994).

**CFD Approach to Turbulent BFS Flow Modelling**

The purpose of the CFD investigation was not only to validate CFD against experiment, but to reveal additional detail about the phenomena and supplement PIV results. This approach makes full use of the reliability of modern CFD (Ferziger and Peric 1996). A commercial code (Fluent) was used to solve the Reynolds Averaged Navier Stokes...
equations with two common turbulence closure models, namely the RNG $k-\varepsilon$ and Reynolds Stress Model (RSM). Second order interpolation was applied in all models and grid convergence and iterative solution convergence was assessed in a verification study following the AIAA Guide for the Verification and Validation of CFD Simulations (Mehta 1998). Convergence errors were estimated with a Grid Convergence Index (GCI) (Roache 1994). Model geometry was that of the BFS test section and temperature, pressure and air density were set to ambient values.

Two and three-dimensional solutions were investigated for the BFS flow using RNG $k-\varepsilon$. Comparisons of 2D and 3D solutions were made to reveal the influence of the 3D BFS flow and to assess the reliability of a 2D flow solution. Having established the accuracy of 2D CFD models, they were then used exclusively.

**Experimental Apparatus**

A wind tunnel was constructed to produce a consistent BFS flow with a high density of light scattering particles (scatters) for PIV (Figures 2 &3). A near 2D, turbulent BFS flow was generated, with an inlet velocity up to 35 m/s. The BFS test section geometry was determined after careful consideration of important BFS flow parameters, such as expansion ratio, step height, aspect ratio, step inlet duct length and step expansion duct length.

Air was drawn through the wind tunnel by a fan-filter unit. PIV scatters were seeded into the flow using a pneumatic venturi particle seeder (Figure 2). Compressed air was passed through a small venturi into which scatters were added and accelerated into the wind tunnel inlet. The venturi jet thoroughly dispersed the scatters into the airflow.

![Figure 2 (left) Wind tunnel BFS test section and (right) venturi particle seeder](image)

The flow with scatters then passed through a contracting transition section into the BFS test section. The inlet to the BFS test section was of sufficient length to allow the bottom boundary layer to fully develop before the step. The flow expanded across the step into the expansion duct, producing a turbulent BFS flow. The expansion duct was of sufficient length to ensure the downstream fan-filter did not influence the BFS flow. An overhanging ‘L’ shaped acrylic plate formed the actual step.

**High Resolution Particle Image Velocimetry**

A high resolution, digital cross-correlation, PIV was designed for this study to examine the BFS flow in the CS plane (Figure 3). PIV was chosen because it is a non-invasive, global technique, allowing the flow field to be measured at high resolution in turbulent, reversing flows. Reversing flow has long been a barrier against revealing the complex BFS flow structures (Eaton and Johnston 1981). A general knowledge of PIV is assumed, along the lines of the detailed reviews by Raffel et al. (1998), Adrian (1991), Grant and Smith (1988) and Huang (1994).

The chosen PIV configuration consisted of a constant intensity light sheet, light scatters and a camera (Figure 4). The light sheet is usually positioned so that the mean flow velocity vector lies within it to minimise errors (Adrian 1991). Scatters within the light sheet measurement region, scatter light in all directions. The scattered light is recorded on an image plane (by a camera), usually parallel to the light sheet. The light sheet is switched to produce two short pulses of light, separated by a short time that encodes a time signal into the scattered light images. PIV analysis extracts the change in particle position from the images and calculates the global fluid velocity within the measurement region. A more extensive discussion can be found in Hall et al. (2001).
Figure 3 Orientation of PIV components around the BFS test section

Figure 4 (left) Basic arrangement of a 2D PIV system and (right) constant intensity light sheet in BFS test section

The PIV System Details

Following the choice of optimum components, the PIV system was assembled and tested (Figure 5). The laser was a twin head Nd:YAG producing a pulsed infrared wavelength of 1064 nm for 3 ns duration. The two beams were combined optically and passed through a KTP crystal that doubled the lights frequency to 532 nm green. Laser heads received power, timing, control and cooling from a laser support unit. The laser timer unit produced a precise 20 Hz timing signals for laser Q switching and central timing of the PIV system.

The laser pulses were formed into an adjustable light sheet by the light delivery system. A Kodak digital CCD double framing camera with a “micro” f=2.8 lens captured the measurement region. Camera timing was controlled by a 3 V square wave signal to the camera input trigger that was synchronised with the laser light pulses through a delay generator. A serial link between camera and computer allowed the double framing parameters to be programmed into the camera.
Figure 5 Schematic of digital, cross-correlation PIV system

Camera images were captured to computer memory by a digital frame grabber card. PIV analysis of the images was performed on a PC using commercial software and software developed for this study. Visiflow (AEA Technology) was used only for the cross-correlation calculation, while Mathcad and Fortran programs performed image mapping and calculated flow variables and statistics. The PIV analysis system of this study was verified on the standard PIV images of Okamoto and Watanabe (1999). Velocity contours from the standard images and the PIV analysis show PIV analysis tends to smooth the velocity field in regions of high velocity gradient. An upper bound analysis error for the PIV system was taken as 0.4 m/s.

Finding an ideal light scattering particle for optimum PIV accuracy is a complex and longstanding problem (Raffel et al. 1998). Hollow polymer spheres were chosen for this study (Q Cell, 5 µm, 600 kg/m³ density, 1.55 refractive index). Compared to water, or oil droplets commonly used in PIV, the hollow polymer spheres are considerably lighter than equivalent sized droplets and have a greater refractive index.

**Results and Discussion**

PIV and CFD results revealed the global BFS mean flow in the CS plane. Results are presented for a turbulent flow with $\overline{u}_\infty = 15.5$ m/s and $Re_H = 45170 \pm 780$ (1.7%), which is standard flow 420 of the Stanford Conference on Complex Turbulent Flows (Kline et al. 1981) and has been well documented (Kim et al. 1978, Eaton and Johnston 1980 and Thangam and Hur 1991). Ambient air properties of pressure, temperature and humidity were recorded for each experiment and density calculated. Average ambient air conditions were 22°C and 1.154 kg/m³ density.

Measurements were taken at the BFS inlet to determine inlet boundary conditions for CFD. Mean streamwise $\overline{u}$ velocity is given in Figure 6 with the inlet profile of Kim et al. (1978), taken at $x=46.7$. Profiles agree well, indicating certainty for $\overline{u}$ measurements. The inlet boundary layer $\delta_b$ determined by Kim et al. (1978) is smaller than for the present study, owing to his use of boundary layer trips. Normal Reynolds stress is presented in Figure 6 and is slightly larger than for Kim et al. (1978). Profiles are characteristic of a well-developed channel flow.
The BFS Flow in the CS Plane, PIV and CFD Results

PIV and CFD results are compared at the highest possible spatial resolution, making use of coloured contours, streamlines and characteristic dimensions and lines to reveal flow structures. The time between PIV light pulses was 40 µs. The accuracy of CFD results was assessed in a verification analysis.
Mean horizontal velocity $\bar{u}$ contours are presented in Figure 7 for PIV and RNG k-\(\varepsilon\) and RSM CFD solutions. Features are highlighted by the dividing streamline, stagnation line $\bar{u}=0$, streamlines from the top and bottom boundary layer thicknesses and a central line of maximum streamwise velocity $\bar{u}_{\text{max}}$. Contours reveal a typical BFS flow with decreasing velocity in the core and very low velocities in the step corner (<0.01 m/s). Five vertical bands of slightly reduced velocity magnitude ($\approx 0.2$ m/s) are present that are unavoidable artefacts of the current PIV technique. These also appear in BFS studies by Kasagi and Matsunaga (1995) and Scarano and Riethmuller (1999). CFD contours clearly show these bands to be non-physical, highlighting the value of simultaneous CFD and PIV analysis.

![Image](image-url)

Figure 8 Mean vertical velocity in CS plane, (top) PIV, (mid.) RNG k-\(\varepsilon\), (bot.) RSM

Vertical mean velocity $\bar{v}$ measurements compared to CFD (Figure 8) show that cross-correlation PIV is sensitive to the vertical edge of the PIV image and tends to produce increased noise at these edges. The PIV of Scarano and Riethmuller (1999) shows similar, but less significant edge sensitivity, as they used a superior cross-correlation algorithm (WDM method). $\bar{v}$ contours show much lower velocity levels than $\bar{u}$ and much greater experimental scatter. While scatter, or the minimum velocity resolution is constant for both velocity components $\bar{u}$, $\bar{v}$ it is larger in proportion to the low $\bar{v}$ velocity levels and therefore more pronounced.

The stagnation line $\bar{v}=0$ passes almost exactly through the primary vortex centre $S_p$, as it must by definition. Lines of $\bar{v}$ maximum $\bar{v}_{\text{max}}$ and minimum $\bar{v}_{\text{min}}$ reveal the strong upward flow behind the step and the downward flow after reattachment, respectively. CFD contours are in good agreement with PIV, showing the region of high $\bar{v}$ near the step and accurately predicting the $\bar{v}=0$ and $\bar{v}_{\text{max}}$ lines. CFD contours supplement PIV results by revealing $\bar{v}$ without the scatter inherent in PIV.
Above the $\Pi=0$ line in Figure 7, both RNG $k-\varepsilon$ and RSM accurately predict the core flow, top boundary layer and recovery region. Below $\Pi=0$ the RNG $k-\varepsilon$ solution indicates a faster, thicker primary vortex reverse flow than PIV, which extends further towards the step wall. RNG $k-\varepsilon$ over-estimates the size of the primary vortex, resulting in a larger $Xr$ than found by PIV, by $\approx 11\%$. In contrast, the RSM solution underestimates the primary vortex and shows a lower reverse flow velocity and small $Xr$ ($\approx 10\%$).

Figure 9 Streamlines in CS plane, (top) PIV, (mid.) RNG $k-\varepsilon$, (bot.) RSM

High-resolution streamlines were calculated (using Tecplot) in Figure 9 and clearly show the primary and secondary vortices and reattachment zone. In the low velocity step corner, some PIV streamlines show non-physical behaviour of flow into the wall. This is due to insufficient PIV velocity resolution for some vectors close to the walls and at stagnation regions. Non-physical streamlines were made obvious by CFD comparison and were also observed in the BFS studies of Huang (1994) and Scarano and Riethmuller (1999). Stagnation streamlines at reattachment points ($Xr$, $Xs$, $Ys$) are expected to indicate flow into, or out of walls.

PIV streamlines in both primary and secondary vortices show inward spiralling towards the vortex centre, indicating a net inward flow from the CS plane to the vortex. As a net inward flow must be balanced (by continuity), a spanwise flow from the vortex centre must be present. Spiralling streamlines reveal that the primary and secondary vortices tend to draw flow into their cores and channel it away from the CS plane towards the BFS sidewalls. As expected, CFD does not show spiralling streamlines because perfect 2D flow has been assumed. Spiralling streamlines have been revealed in the BFS studies of Alemdaroglu and Karatekin 1997, Scarano and Riethmuller 1999.

Vorticity $\omega$ contours in the CS plane are shown in Figure 10, as a useful variable for revealing shear and boundary layer structure. Vorticity is clearly less sensitive to PIV edge noise and scatter than velocity because each vorticity value is composed of several velocity measurements, which produces a spatial averaging. The largest vorticity magnitude $|\text{Vorticity}_{\text{min}}|$ occurs in the shear layer, just after separation and decreases and disperses outwards as the
flow moves downstream. The line of minimum vorticity and lines at 20% of $Vorticity_{min}=330 \text{ 1/s}$ are defined to show the centre and thickness of the shear layer.

Figure 10 Vorticity magnitude in CS plane, (top) PIV, (mid.) RNG $k-\epsilon$, (bot.) RSM CFD contours of $\omega$ are in excellent agreement with PIV, showing the same shear layer and top boundary layer structures. CFD supplements PIV by revealing the extent of the edge noise limitations between the PIV measurement regions. In addition, CFD indicates that PIV underestimates the peak $\omega$ levels just after separation. This is because velocity gradients are a maximum in this region and the available PIV resolution was insufficient to fully capture them.

The region below the dividing streamline is shown in Figure 11 to highlight the low velocity BFS structures. The dividing streamline shows virtually no curvature from separation until $x=40$, where it begins to curve towards reattachment with steadily increasing curvature. The dividing streamline shows a slight dip, or reverse curvature above the primary vortex centre ($x=100$ to 150). This indicates that the primary vortex may influence the shear layer by drawing the flow above it downwards. The interface line between primary and secondary vortices shows that the second vortex forces the relatively high speed reverse flow to curve sharply upwards towards the separation point, where it interacts with the shear layer.

**Step Corner and Second Vortex**

The full resolution of PIV was focused on the step corner and second vortex, to reveal the flow field at higher spatial resolution than previous studies (Scarano and Riethmuller 1999 and Huang 1994). Global comparisons were made with CFD solutions using streamlines and characteristic lines.
Reverse flow in the second vortex is evident, separated by stagnation line $u=0$. Contrary to the experimental findings of Moffatt (1964) and the DNS of Le et al. (1997), a small third vortex in the step corner was not observed. Considering the resolution of PIV streamlines in this study, the third vortex would need to be smaller than $\approx 2$ mm to remain undetected. As Le et al. (1997) predicted its size to be almost twice this (radius=$0.042H=4$ mm) it was concluded that the third vortex does not exist.
PIV streamlines (Figure 12) are similar to Figure 11, but the second vortex is modified at x=37 to form a stretched structure, not evident at lower resolutions. It appears that the primary vortex acts on the downstream portion of the second vortex, causing it to elongate. Several studies have indicated the elongated second vortex shape (Kasagi and Matsunaga 1995, Scarano and Riethmuller 1999).

Conclusions

The turbulent BFS flow has been investigated at high resolution, showing flow features in greater detail than previous BFS studies. PIV and CFD results showed excellent agreement in comparison of velocity contours, streamlines and vorticity, which demonstrated the reliability of both techniques and allowed complex BFS flow structures to be revealed. Access to both “exactly equivalent” datasets proved to be invaluable, as they tended to supplement each other for any weaknesses inherent in either approach.

This comparison study between PIV and CFD is intended to contribute to the ongoing process of CFD and PIV verification and validation.

Bibliography


