Experimental investigation of flow through an asymmetric plane diffuser

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1. Motivation and objectives

There is a need for experimental measurements in complex turbulent flows that originate from very well-defined initial conditions. Testing of large-eddy simulations and other higher-order computation schemes requires inlet boundary condition data that are not normally measured. The use of fully developed upstream conditions offers a solution to this dilemma in that the upstream conditions can be adequately computed at any level of sophistication. Unfortunately, experimenters have only recently been sensitized to this issue and there are relatively few appropriate data sets.

The plane diffuser experiment by Obi *et al.* (1993) has received a lot of attention because it has fully-developed inlet conditions and it includes separation from a smooth wall, subsequent reattachment, and redevelopment of the downstream boundary layer. Each of these features offers challenges for modern turbulence models. In particular, Durbin, Kaltenbach, and Mittal of CTR have devoted considerable effort in developing several different computations of the flow. Unfortunately, they found that the experiment had several deficiencies as they began careful comparison to the data. The most glaring problem is the fact that the data set does not appear to satisfy mass conservation, a problem that is most likely due to three-dimensional effects in the diffuser.

The objective of this study is to provide careful qualification and detailed measurements in a re-creation of the Obi experiment. The work will include extensive documentation of the flow two-dimensionality and detailed measurements required for testing of flow computations. Also important to this study is the close interaction of the experimental and computational groups to improve the utility of the data obtained and the accuracy of computation.

2. Accomplishments

The diffuser geometry as specified by Obi *et al.* is shown in Fig. 1. The expected flow includes flow separation approximately one third of the way along the diffuser followed by reattachment in the tailpipe. The problem with this flow is that separation is likely to occur on the end-walls, causing an acceleration of the mid-plane flow. Our approach has been to modify an existing blower wind-tunnel to accommodate a very high aspect ratio version of the diffuser in hopes of minimizing end-wall effects. Unfortunately, the separated regions on the end-wall can be quite large and

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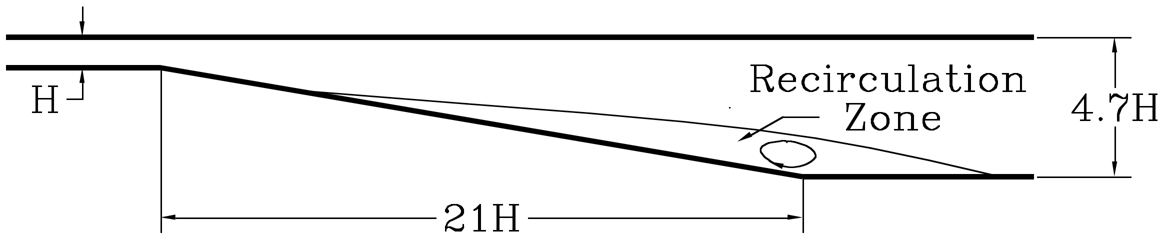

FIGURE 1. Plane diffuser.

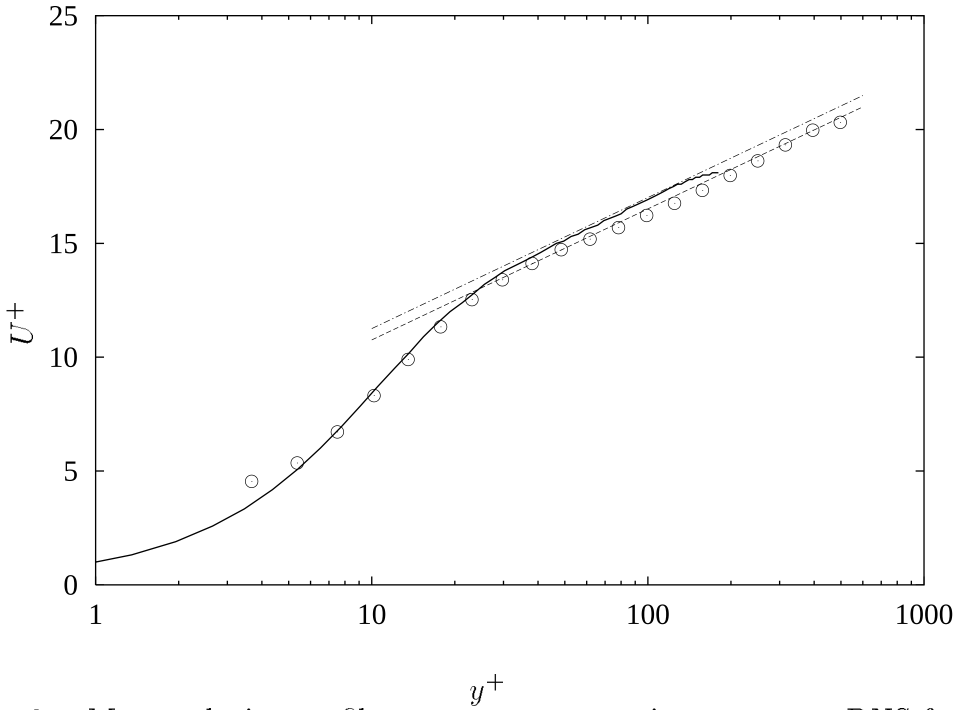

FIGURE 2. Mean-velocity profiles: ○ , current experiment; ——— ,DNS from Kim *et al.*; ---- , law of the wall with constant = 5.0; —·— , law of the wall with constant = 5.5.

have a significant effect on the mid-plane flow. After construction, the majority of our efforts have been in controlling the end-wall boundary layer separation.

The experimental facility is described in last year's CTR briefs (Buice and Eaton 1995). The facility has an upstream channel width ($H = 2\delta$) of 1.5cm. The experiment is being conducted at a channel Reynolds number ($U_{cl}H/\nu$) of 20,000.

2.1 Tunnel qualification

Our basic approach for qualification of this experiment was to first verify that the inlet conditions corresponded to those of a known fully developed turbulent channel flow. In Fig. 2, the inlet velocity profile for this experiment is compared to the turbulent channel profile produced by the DNS calculation performed by Kim *et al.* The primary difference between these two profiles is the additive constant in the log law. While our profile follows the log law with the traditional additive constant of 5.0, the DNS follows the log law with a value of 5.5. According to Kim

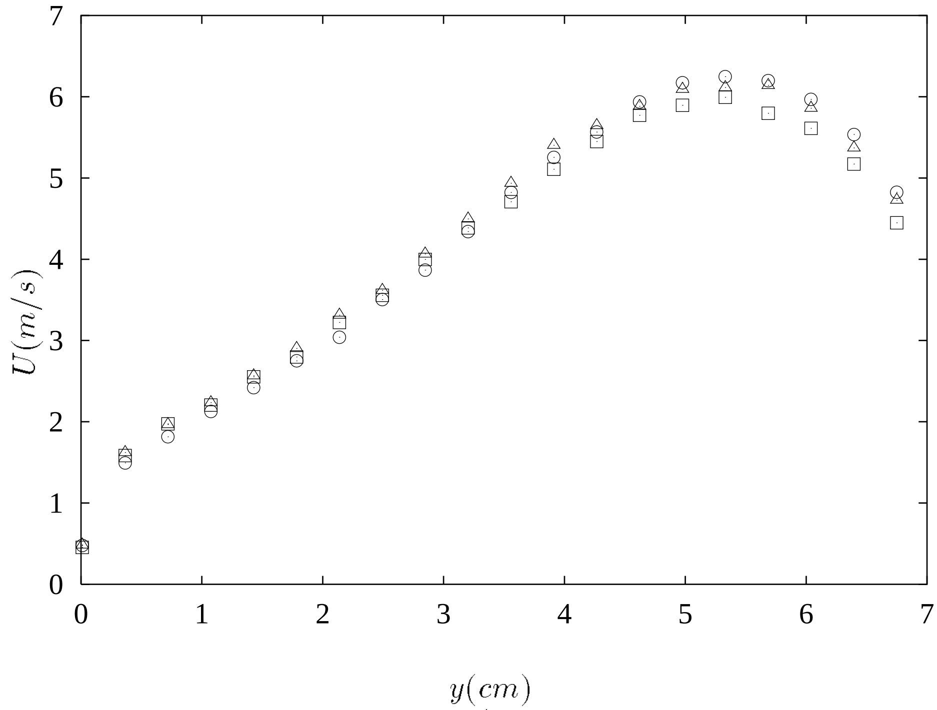

FIGURE 3. Mean-velocity profiles at $x/\delta = 59$: ○ , centerline; △ , near end-wall; □ , far end-wall.

et al. the higher constant is a low Reynolds number effect, $Re_\tau = 180$, for the DNS compared with $Re_\tau = 490$ for our experiment.

The second step in the tunnel qualification process was to verify that mean velocity profiles taken near the end-walls closely matched the centerline profile. Figure 3 shows three similar mean velocity profiles taken just downstream of the reattachment point at the centerline and two stations approximately 1/6 of the span away from the two end-walls. The final qualification step is the integration of the mean velocity profiles to verify that the conservation of mass holds throughout the measurement region. Although this step is not complete because we lack the final pulsed-wire data in the recirculation region, the preliminary results look very good. The profiles before and after the separation integrate to within 3% of the initial mass flow at the inlet of the diffuser. The primary difficulty with the results of Obi *et al.* was the 15% increase in mass-flow along the core section of the diffuser downstream of $x = 40\delta$, see Kaltenbach (1995), which was most likely due to secondary flow produced by end-wall separation.

2.2 Preliminary results

We have completed single-wire and cross-wire surveys outside of the separation region throughout the measurement domain, from $12H$ upstream of the beginning of the diffuser to $77H$ downstream of the inlet. We have also taken frequency spectra at a number of locations in the recovery region along with the associated time records. The thermal tuft was used to determine the separation location and will be used in the near future to determine the reattachment location. The pressure

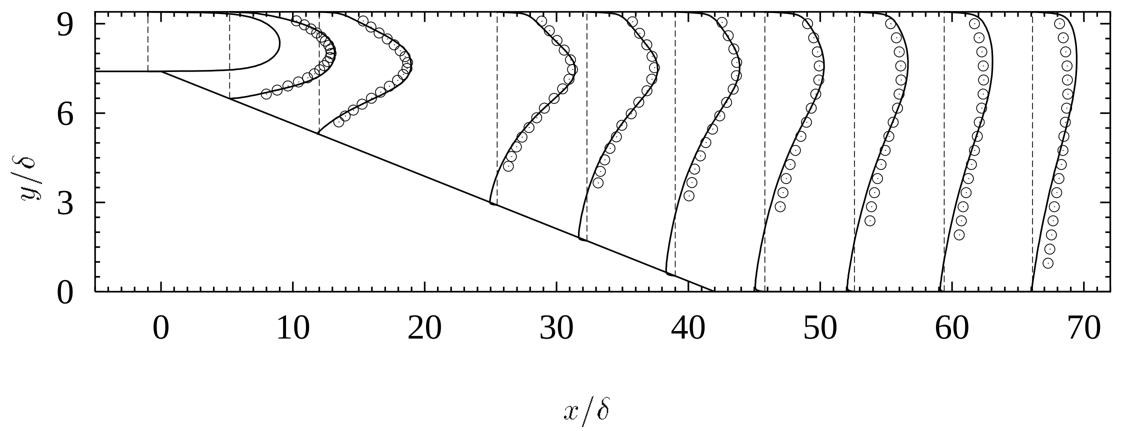

FIGURE 4. Mean velocity $U/U_{cl,in}$: ○ , current experiment; ——— , $k-\epsilon-v^2$. Where $U/U_{cl,in} = 1.0 = 10\delta$.

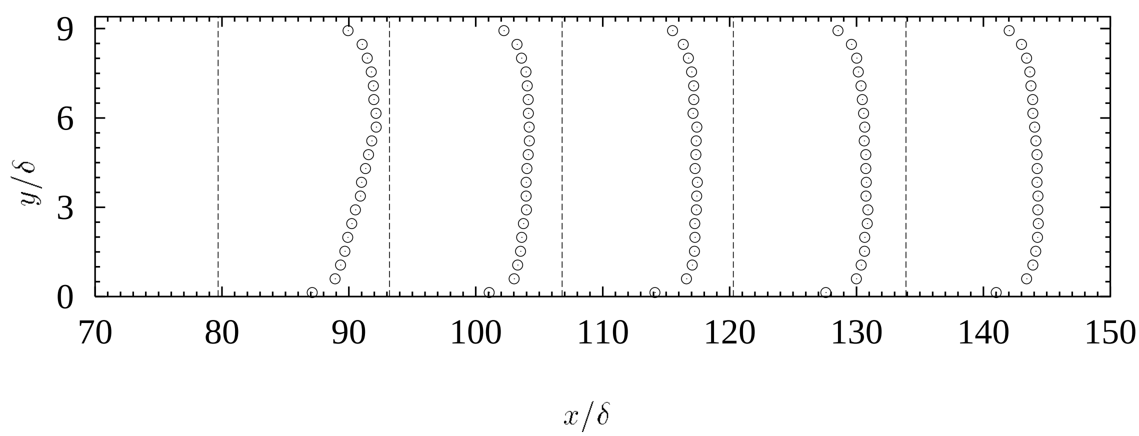

FIGURE 5. Mean velocity $U/U_{cl,in}$: ○ , current experiment. Where $U/U_{cl,in} = 1.0 = 60\delta$.

distribution along the upper and lower walls has been measured.

2.2.1 Mean flow data

Figure 4 shows the mean velocity profiles taken using a single-wire anemometer compared to the results from a calculation performed using Durbin's $k-\epsilon-v^2$ model. They compare favorably until the region after reattachment where the computed recovery lags the measured recovery. The mean velocity profiles from the redevelopment section of the experiment are shown in Fig. 5 and on a different scale than the previous figure. Near the end of the measurement region, the flow has almost returned to fully developed turbulent channel flow.

Using the thermal tuft, the mean separation point was found to be $6H$ downstream of the beginning of the diffuser, which corresponds well to the $7H$ found in the Durbin calculation and differs significantly from the experiment performed by Obi *et al.*, which found that the flow separated at $11H$. End-wall separation would be expected to relieve the adverse pressure gradient and delay separation.

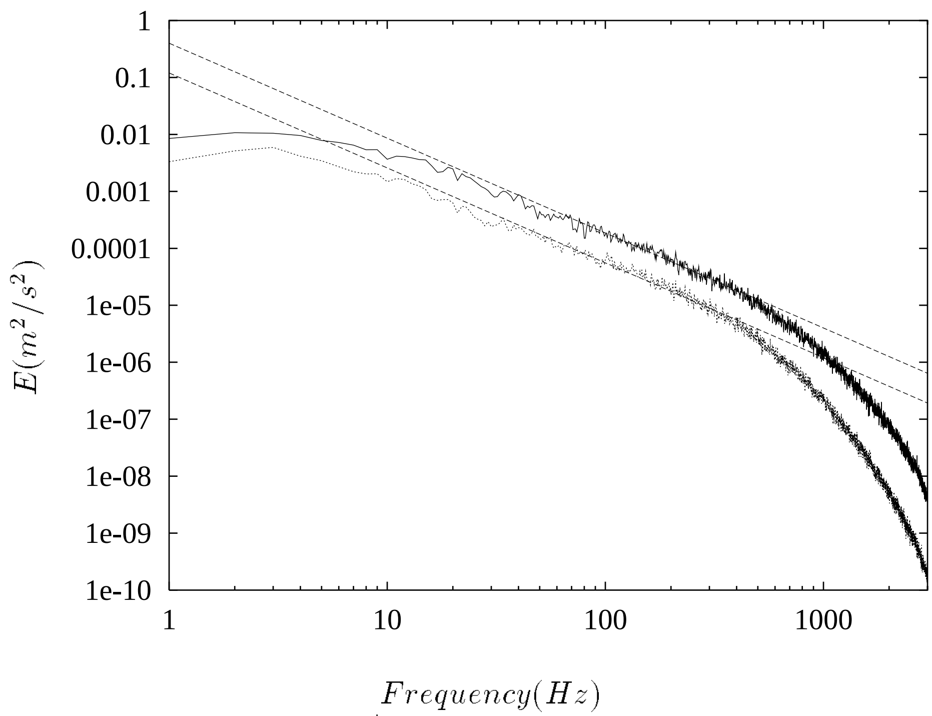

FIGURE 6. Energy spectra at $y^+ = 300$: ——— , $x/\delta = 93.2$; ········ , $x/\delta = 133.9$; ---- , Kolmogorov's $-5/3$ law.

2.2.2 Turbulence statistics

We have measured Reynolds stresses and triple products in the region of the flow outside of the recirculating region. The pulsed-wire is currently being used to measure the mean and fluctuating components of the streamwise velocity. We have calculated the frequency spectra using velocity measurements recorded by a single wire at two locations in the boundary layer, $y^+ = 30$ and $y^+ = 300$, at various stations in the recovery region downstream of the diffuser. Figure 6 shows the frequency spectra at two stations, $x/\delta = 93.2$ and $x/\delta = 133.9$. Also plotted are two lines with the $-5/3$ slope given by Kolmogorov's law for the inertial subrange. The decay in turbulent kinetic energy as the flow recovers from separation is apparent.

3. Future work

We are now in the final stages of the experiment. The pulsed-wire data is nearly complete and preliminary spatial correlation measurements have been made. The tunnel will require some minor modification to get the final spatial correlations with the two-point correlation probe and the skin-friction data using the pulsed-wall probe.

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