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ON THE EXPERIMENTAL STUDY OF 3D TURBULENT SHEAR LAYERS

Dipendra Gupta
Sibley School Mehanical and Aerospace Engineering
Cornell University
Ithaca, NY 14853, USA
dg535@cornell.edu

Vedant Kumar
Department of Mechanical Engineering
University of Maryland
College Park, MD 20742, USA
vkumar20@umd.edu

Johan Larsson
Department of Mechanical Engineering
University of Maryland
College Park, MD 20742, USA
jola@umd.edu

Gregory P Bewley
Sibley School Mehanical and Aerospace Engineering
Cornell University
Ithaca, NY 14853, USA
gpb1@cornell.edu

ABSTRACT

When parallel streams flowing at different speeds merge, they form planar turbulent mixing layers (2D). In the usual laboratory model, the mean flow is approximately parallel everywhere, and varies mainly in the directions of the velocity difference and of the flow convection. However, real flows are three-dimensional (3D)–the incoming flows are not parallel and have not only different speeds but also different directions, thereby giving rise to 3D turbulent shear layers, i.e., skewed mixing layers. The detailed quantitative study of 3D shear layers is missing. 3D turbulent boundary layers are relatively well understood and have been observed to have lower maximum primary Reynolds stresses, compared to their 2D counterparts. To find out if similar effects prevail in skewed mixing layers, we experimentally investigated the mean flow and other flow statistics in a wind tunnel. We generated 3D shear layers by skewing the mean flow with turning vanes near the trailing edge of a splitter plate, and used x-wires to probe the flow at different cross-, span- and downstream positions. Results show that both skewed and planar mixing layers have similar mean velocity profiles, and they both spread approximately linearly with downstream distance. However, the 3D mixing layer thickness is larger in near-downstream region and smaller far-downstream when compared to the 2D case, suggesting reduced mixing as in 3D boundary layers.

INTRODUCTION

Free shear layers are almost always turbulent and three-dimensional, and are found in a wide variety of engineering applications like flow over the finite span wings, bow and stern regions of ships, and in the annulus of turbomachinery, to name a few. Three-dimensional effects occur because of the merging of non-parallel freestreams, which results in a net spanwise velocity component at the interface, thereby giving rise to skewed mixing layers. These flows are, however, complicated and are difficult to interpret. So, most of the studies are focused on two-dimensional turbulent mixing layers resulting from different-speed coplanar flows (Liepmann & Laufer (1947); Brown & Roshko (1974); Winant & Browand (1974)).

The three-dimensional effects are well understood in turbulent boundary layers, wherein the primary Reynold stress has been observed to decrease, compared to the 2D case (Johnston & Flack (1996)). However, only a handful of research has been done on skewed mixing layers (Hackett & Cox (1970); Fric (1996); Lu & Lele (1999); Fiedler *et al.* (1998); Azim & Islam (2003)). These studies have shed some light on the flow statistics and structure and shown that 3D effects result in a change in maximum shear stresses compared to 2D case, enhancement in mixing with skewing and strong velocity gradients, 3D effects limited mostly in the early transient, and streamwise vortex breakdown.

However, there is still no consensus in the observations on skewed mixing layers. For instance, Hackett & Cox (1970) showed that the maximum primary Reynolds stress is higher in 3D- than in 2D cases. However, Azim & Islam (2003) observed otherwise. Motivated by inconsistencies like this, we aim to investigate the three-dimensional effects in shear layers. To achieve this objective, we first generated different-speed freestreams in a wind tunnel using a mesh fitted on a passive grid, then separated these streams using a splitter plate and finally skewed them using turning vanes near the trailing edge of the plate. We probed the evolution of the flow downstream using x-wires. In this paper, we focus on the effect of imposed turning on the evolution of the mixing layers. In particular, we discuss how far the flow remains twisted in down- and cross-stream directions, in addition to the mean flow properties for planar and skewed cases.

METHODLOGY

We carried out the experiments in Warhaft Turbulence Wind Tunnel at Cornell University (Yoon & Warhaft (1990)). This wind tunnel has a 0.91m by 0.91m cross-section and 9.1m long test section, and can reach up to 20 m/s (see Fig. 1 (a-c)). We generated turbulence using a 3.25” $\times$ 3.25” passive grid at the inlet of the test section, and to create parallel streams of different speeds, we covered the upper half of the grid with stainless steel wire cloth of 0.0055” opening size, thereby, giving rise to high-speed flow in the bottom half of the wind tunnel and low-speed in its top half (see Fig. 1d). The high- and the low-speed flow were separated with a 0.5” thick acrylic

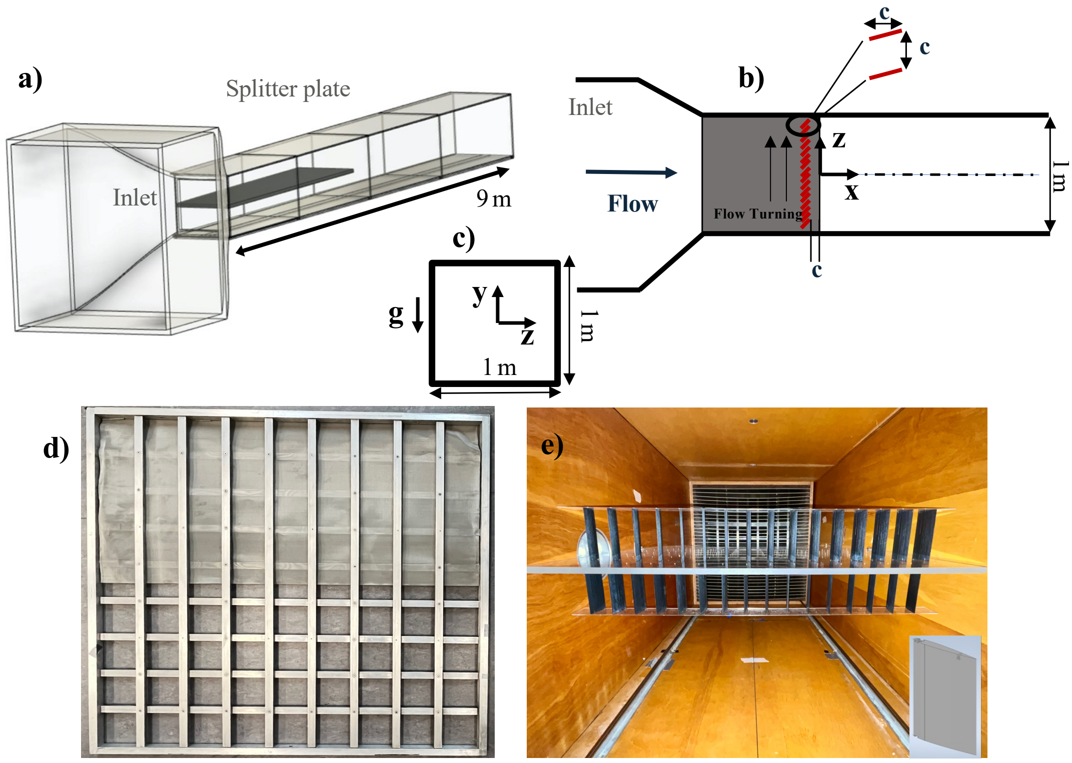

Figure 1. Experimental setup for skewed mixing layer. (a) Isometric view, (b) side view, and (c) cross-section of the Warhaft Turbulence Wind Tunnel. (d) Mesh grid used to generate different speed flows. (e) Turning vanes arrangement on the splitter plate. Flow straightener in the background. The inset shows a CAD model of a turning vane.

splitter plate (36”×48”) supported by bolts fixed to the side walls of the wind tunnel. Due to the velocity difference between the upper and the lower layers, the flows past the grid have a tendency to get deflected from the low-speed side to the high-speed side before reaching the splitter plate. To take care of this, we placed a flow straightener between the grid and the splitter plate.

To obtain skewed layers, we used turning vanes (NACA 0012, chord, $c = 2$” and height, $h = 4.7$”) on the top and the bottom of the splitter plates (see Fig. 1 (b, e)). The vane height was so chosen that it would be larger than the boundary layer thickness on either side of the plate. These turning vanes were fixed to the splitter plate using threaded rods, and can be manually set at any desired angles with an error of $\pm 0.2°$. To rule out the possibility of the vibration of the vanes at higher speed, cross-stream extremes of the vanes were covered with end-plates made of acrylic sheet. The thickness of the end plates was 0.5 mm, and these plates were wide enough ($1c$) to cover the vanes chordwise and long enough to cover them spanwise, as shown in Fig. 1(e). These end-plates were tightly fixed to the vanes using the same rods used to fix the vanes to the splitter plate. For the present experiments, we used 32 vanes in total (16 on each side of the plate). When these vanes are set to 0°, they represent the case of planar mixing layers. The spacing between the vanes was $1c$, and their trailing edge was approximately $2c$ upstream of the trailing edge of the splitter plate.

We probed the flow field using an x-wire anemometer mounted on a 3-axis stepper motor-controlled traverse system, which has a 0.001” resolution in wall-normal and spanwise directions. However, in axial direction, while the traverse is still motor-controlled, it lacks digital reading, and its distance has to be physically measured for each downstream location, thereby introducing an error of $\pm$ 0.5 cm in the x-direction.

For the present experiment, we fixed the freestream velocities and studied the effect of three-dimensionality by varying the geometrical angles of the turning vanes. In particular, we set the high- and the low-speed flows at 10.5 m/s (U_h) and 4 m/s (U_l), respectively, i.e., $U_l/U_h = 0.38$ ($\Delta U = 6.5$ m/s), and studied their evolution for two different angles of turning vanes ($\theta_h = -\theta_l$): (a) 0°, and (b) 10°. Case (a) corresponds to the planar mixing layers, while case (b) is skewed mixing layers with the effective angle of 20° between layers. Here, angle is considered positive in counterclockwise (CCW) sense when viewed planform in the downstream direction, and x, y, and z are stream-, cross-stream-, and spanwise directions in lab frame, respectively. $(x, y, z) = (0, 0, 0)$ is the trailing edge on the top surface of the splitter plate in the longitudinal symmetrical plane.

We measured the flow using x-wire probes at 15 downstream distances (from x/h = 0.02 to 6, h is wind tunnel height), and at 18 cross-stream stations (-0.3 $\leq y/h <$0.3) for each downstream distance on the longitudinal symmetrical plane. The x-wires were 5 μm in diameter, about 1mm long (active sensing part) and 1 mm apart, and they were calibrated in the potential core of a jet. We also took measurements at $z/h = \pm$ 0.15 off the symmetrical plane and found the flow to be homogeneous in the spanwise direction (not reported here).

RESULTS AND DISCUSSION

Figure 2 shows the flow angle profile at different downstream distances from the trailing edge of the splitter plate. Very close to the trailing edge of the splitter plate, the flow

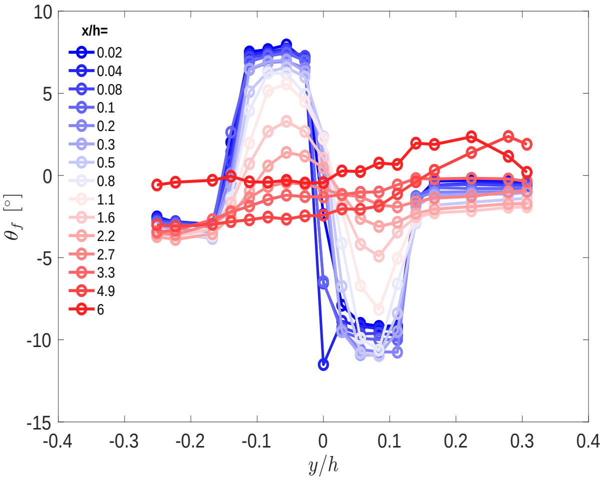

Figure 2. Flow angle, θ_f profile of skewed mixing layers relative to planar ones at various downstream distances on the longitudinal symmetrical plane. $\theta_f = \tan^{-1}(W/U)$. The vanes were rotated by $+10°$ on the high-speed side and by $-10°$ on the low-speed side, and accordingly, the flow also gets twisted by approximately the same amount as that of the vanes.Note that x- and y distances are non-dimensionlized by the wind tunnel height, h.

turns by approximately as much as the vanes are rotated on both high- and low-speed sides. The flow twisting, however, slowly decreases as it moves downstream, and finally, becomes more like an untwisted one at the furthest measurement location, x/h = 6. In the cross-stream direction, the flow gets twisted mostly within the vane height and then starts aligning with freestream, strongly indicating that the vane height dictates the cross-stream distance over which the flow remains twisted.

Mean streamwise velocity profile of the planar and skewed mixing layers at different downstream distances is shown in Fig. 3. In line with the standard convention found in the literature on planar mixing layers, the velocity is shown in a moving reference frame and is normalized by the velocity difference between the high- and the low-speed freestreams ($U_s = U_h - U_l$). Similarly, the cross-stream coordinate is transformed into a similarity parameter, $\eta = (y - y_{avg}(x))/\delta(x)$. Here, $y_{avg}(x) = (y_{0.9} + y_{0.1})/2$, $\delta(x) = y_{0.1} - y_{0.9}$, and $y_{0.1}$ and $y_{0.9}$ correspond to cross-stream coordinate where scaled velocity U^* reaches 0.1 and 0.9, respectively. U^* is given by $U_l + \alpha U_s$, α being 0.1 and 0.9 for $y_{0.1}$ and $y_{0.9}$, respectively.

Irrespective of the vane angles, the flow on either side approaches the freestream velocities within $\eta = \pm 1$ and the velocity profiles collapse for $x/h \geq 1.6$ for both types of mixing layers. The collapse is well approximated by an error function, as shown in Fig. 3, and is consistent with a self-similar form (Pope (2001)). Far from the plate in cross-stream direction, the mean speed far downstream ($x/h > 3.3$) is, however, found to decrease by as much as 25% of U_s on the high-speed side for skewed mixing layers, and by ≈10% for planar mixing layers while it remains approximately constant on the low-speed side.

We also observe a sharp decrease in velocity at vane height for both types of mixing layers up to $x/h < 1$. For planar mixing layers, the velocity drops by as much as 25% of U_s on the high-speed side while only by less than 5 % on the low-speed side. This decrease is slightly more for skewed mixing

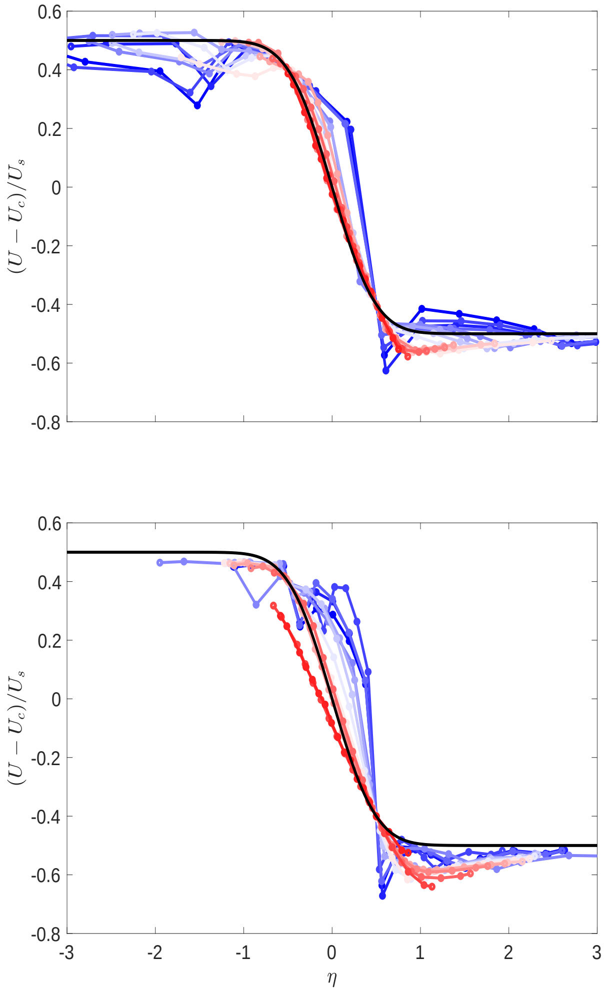

Figure 3. Mean streamwise velocity profile in moving frame of reference at various downstream distances, for planar mixing layers (top) and skewed ones (below). Here, $U_c = (U_h + U_l)/2$ is the mean convection speed of the mixing layer and $U_s = U_h - U_l$ is shear velocity. Note that cross-stream distance is expressed in similarity parameter, η (see main text for definition). Data collapse is approximated by an error function, -erf($\eta/0.55$) for both types of mixing layers. Legends as in Fig. 2.

layers (30% and 10 % of U_s, resp.). The decreased velocity region has a narrower width on the high-speed side, possibly because of suppression of momentum transport due to strong convection. Both of these observations indicate the presence of a wake region near downstream. The exact reason for this velocity defect is unknown, but we believe it might be due to the combined effect of wake of the end-plates placed over vanes and the tip vortex sheet (formed between tilted flow and outer freestream) which may quickly break up into conventional vortices aligned initially with the flow direction.

On the low-speed side, we observe another sharp decrease in the flow speed in the very near-downstream region ($0 < \eta < 1$) before it starts increasing again. This happens for $x/h < 0.2$. Since its effect is very close to the splitter plate and its thickness is of order the thickness of the plate itself, this decrease in velocity might be due to the wake of the plate.

Figure 4 shows the mixing layer thickness of the planar and the skewed mixing layers at different downstream

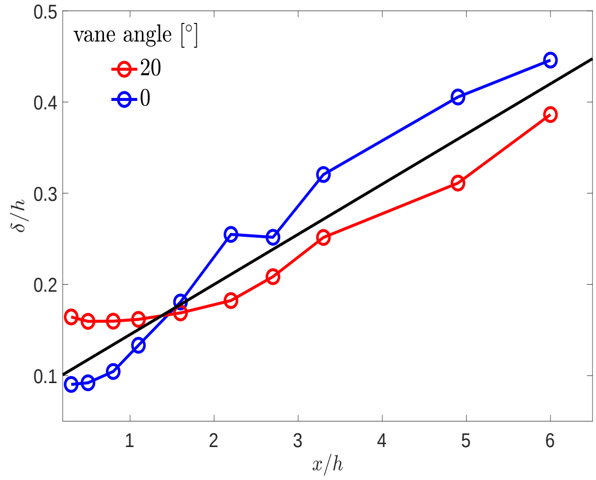

Figure 4. Mixing layer thickness, δ at various downstream distances, for planar- (blue) and skewed mixing layers (red). Black line: $d\delta/dx = 0.055$. Note that δ and x are non-dimensionalized by wind tunnel height.

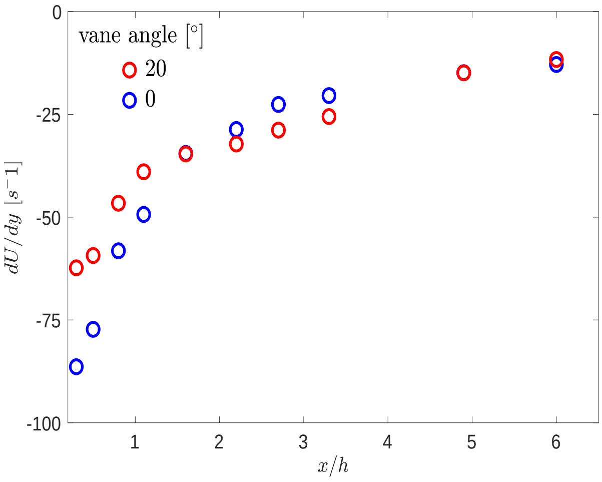

Figure 5. shear rate, dU/dy [m/s], at various downstream distances, for planar- (blue) and skewed mixing layers (red).

distances. In the near downstream region ($x/h < 1.6$), the thickness of the skewed mixing layer is larger than that of the planar ones and remains approximately constant. However, for the planar case, the thickness seems to increase non-linearly. However, after $x/h > 1.6$, it becomes larger than that for skewed case. In this region, for both types of mixing layers, the thickness starts varying approximately linearly, as expected, with downstream distance and does so at approximately equal rate ($d\delta/dx \approx 0.055$). The difference in behavior before and after $x/h = 1.6$ may be because of the strong initial effects of the flow twisting. This is further explained by the stronger shear rate in planar mixing layers than in the skewed ones near downstream (see Fig. 5) and approximately equal shear rate far downstream.

CONCLUSION

We carried out experiments on planar and skewed mixing layers in a turbulence wind tunnel. We generated different-speed streams using a passive grid half-covered with mesh, and skewed the flow using turning vanes at the trailing edge of the splitter plate. We fixed the vane angle at $\pm 10°$ to generate skewed mixing layers while we aligned the vanes parallel with freestreams to get back the planar case. We used cross-wires to measure the mean flow velocities at different cross-, span- and downstream distances.

Our measurements show that, after $x/h > 1.6$, for both types of mixing layers, the mean streamwise velocity profiles collapse and take an error function form, and the mixing layer thickness grows linearly at an approximately equal rate. Besides, we observed that the flow twisting has minimal effect on the shear rates, and if any, it is dominant mostly in the near-downstream regions.

Future research will focus on characterizing turbulent stresses and studying how they vary compared to those in the 2D case. Further, we aim to do a parametric study to isolate the effects of the velocity ratio, vane height, and angles.

REFERENCES

Azim, MA & Islam, AKMS 2003 Plane mixing layers from parallel and non-parallel merging of two streams. *Experiments in fluids* **34** (2), 220–226.

Brown, GL & Roshko, A 1974 On density effects and large structure in turbulent mixing layers. *Journal of Fluid Mechanics* **64** (4), 775–816.

Fiedler, HE, Nayeri, C, Spieweg, R & Paschereit, CO 1998 Three-dimensional mixing layers and their relatives. *Experimental thermal and fluid science* **16** (1-2), 3–21.

Fric, TF 1996 Skewed shear-layer mixing within a duct. *AIAA journal* **34** (4), 847–849.

Hackett, JE & Cox, DK 1970 The three-dimensional mixing layer between two grazing perpendicular streams. *Journal of Fluid Mechanics* **43** (1), 77–96.

Johnston, JP & Flack, KA 1996 Advances in three-dimensional turbulent boundary layers with emphasis on the wall-layer regions .

Liepmann, HW & Laufer, J 1947 Investigations of free turbulent mixing. *Tech. Rep.*.

Lu, G & Lele, SK 1999 Asymptotic growth of disturbances from spatially compact source in a skewed mixing layer. *Physics of Fluids* **11** (5), 1153–1160.

Pope, SB 2001 Turbulent flows. *Measurement Science and Technology* **12** (11), 2020–2021.

Winant, CD & Browand, FK 1974 Vortex pairing: the mechanism of turbulent mixing-layer growth at moderate reynolds number. *Journal of Fluid Mechanics* **63** (2), 237–255.

Yoon, K & Warhaft, Z 1990 The evolution of grid-generated turbulence under conditions of stable thermal stratification. *Journal of Fluid Mechanics* **215**, 601–638.