Flow Control Applications using Countercurrent Shear

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Experiments conducted in planar unconfined and confined countercurrent shear layers, demonstrated that spatial growth rates increase rapidly with decreasing velocity ratio $U_2/U_1$. Particle image velocimetry measurements documented the shear layer development and identified significant increases in turbulence intensity, Reynolds stresses and flow three-dimensionality when comparing countercurrent to coflowing shear layers. Countercurrent shear layers also displayed increased turbulent length scales giving rise to reductions in instantaneous strain rates. Control applications exploiting the characteristics of countercurrent shear will be discussed.

1. Introduction

Liepmann & Laufer (1947) provided the first comprehensive examination of the turbulent free shear layer. Due in large part to the advances in thermal anemometry, they were able to examine the turbulent flow properties of the shear layer and thereby provide insight into the interaction between the mean and fluctuating velocity fields. Through this comprehensive study, Liepmann & Laufer concluded that the mixing length concept, as proposed by Taylor and developed by Prandtl, was not appropriate for the free shear layer. Subsequent work by Bradshaw (1966) elucidated the important role that initial conditions play in the development of a spatially developing shear layer, and the care which must be exercised to establish flow self-similarity in mean and fluctuating flow quantities. A comprehensive review at the time, by Birch and Eggers (1973), suggested further that much of the discrepancy between experimental studies was due to examination of the free shear layer prior to establishing a fully turbulent state.
Nearly three decades after the work of Liepmann & Laufer, the world of turbulent free shear flows was turned upside-down by the nearly simultaneous observations by Brown & Roshko (1974) and Winant & Browand (1974) that so-called coherent structures were in large part responsible for the flow development. Brown & Roshko demonstrated that the stochastic description of turbulent flows was incomplete and must be modified to allow for the interaction of the mean velocity field with inherent flow structures having integral scales. Winant & Browand further described the interaction of these deterministic structures, through a pairing process, which dominated the flow development.

The mean flow characteristics of turbulent shear layers have been well documented over an extensive parameter space, and have been summarized in several studies most notably by Birch & Eggers (1973) and Ho & Huerre (1984). The influence of velocity ratio and initial conditions dominates much of the literature, however systematic studies of the independent effects of density ratio and compressibility have received renewed attention, most notably due to the work of Brown & Roshko (1974). The significance of velocity ratio, defined here as \( U_2/U_1 \), where \( U_1 \) and \( U_2 \) are the primary and secondary streams, respectively, cannot be underestimated, due to the strong dependence of shear layer growth rate on \( U_2/U_1 \). However, with the exception of some isolated experiments reported in Abramovich (1963), the literature has predominately addressed turbulent shear layers whose streams are comprised of fluids traveling in the same direction relative to a stationary disturbance source such as a splitter plate. This creates velocity ratios between 0 and 1, the former corresponding to a single-stream shear layer as would be developed between a jet and quiescent surrounding fluid, and the latter to the limiting case of zero shear.

Turbulent shear layers having velocity ratios less than zero describe an important class of flows, namely those dominated by separation and flow reversal. This class of countercurrent turbulent shear layers constitutes both a challenging experimental problem as well as an important practical one, and will be the focus of this discussion. Quite recently, studies of the countercurrent shear layer have appeared in the literature, motivated partially by the expectation that global flow excitation might be achieved as a consequence of the underlying absolutely unstable nature of countercurrent shear flows (Huerre & Monkewitz, 1990). The work of Strykowski & Niccum (1991) examined a laminar countercurrent shear layer established in the near field of a circular jet, and compared the global flow development to predictions from local linear stability theory. Comparisons to theory were further strengthened by studying the influence of countercurrent shear in the presence of a strong density gradient set up by the introduction of sulfur-hexafluoride into the high-speed stream (Strykowski & Niccum, 1992). However,
the relatively low Reynolds numbers of these studies limit their generalization to more realistic flow situations.

The primary goal in examining the connection between locally and globally unstable flows is the potential benefit, which can be gained from shear flow control strategies that are relatively insensitive to external influence. Although the onset of self-excitation can be difficult to identify except in relatively clean laboratory flows, it is important to extend the local and global stability concepts to realistic flow conditions where possible. A first step in this direction was undertaken by considering the role of countercurrent shear control on a jet at elevated Reynolds numbers and for various flow disturbance levels (Strykowski & Wilcoxon, 1993; Strykowski et al., 1993). An important aspect of this work was to determine the global flow response as the streamwise domain of absolutely unstable flow was increased relative to the jet diameter. In distinction to the earlier studies where counterflow was confined to the separating shear layer near the nozzle lip leading to overall reductions in jet momentum mixing (Strykowski & Niccum, 1991), the effect of increasing the streamwise scale of the countercurrent shear layer was to cause a concomitant increase in the disturbance wavelength, thereby resulting in mixing enhancement in the jet. This work also demonstrated that the global jet response was essentially independent of the boundary and initial conditions supplied at the jet exit. Although this was not conclusive proof of self-excitation, it was circumstantial evidence of such, and an important indication of the practical implications of the approach.

Studies of turbulent flow conditions by Strykowski & Wilcoxon (1993) and Strykowski et al. (1993) were important in establishing the role of velocity ratio at elevated Reynolds numbers, but were conducted in an axisymmetric jet. The axisymmetry nature of the shear layer prevented a self-similar state from being systematically studied, and hence limited the general utility of the results. The aim of the present study was to establish nominally two-dimensional planar mixing layers in unconfined and confined geometries at velocity ratios less than zero. Lessons learned from earlier attempts to generate this flow by Humphrey & Li (1981) indicated that the global as well as local flow behavior would need to be documented. In the section to follow we describe combined flow visualization and quantitative studies of the mean behavior of this countercurrent flow field. We should also point out that an important feature of this flow is its inherent spatial development, making it fundamentally different that the temporal countercurrent layers examined by Thorpe (1968, 1971).
1. Experimental facilities

2.1 Unconfined shear layers

A planar mixing layer was studied to determine the global response to countercurrent shear. This was accomplished by modifying the test section of a closed-loop wind tunnel as shown in Fig. 1. The air of the primary stream $U_1$ was delivered to a test section having a square cross section of $H = 0.45 \text{ m}$. The secondary counterflow stream $U_2$ was created by the addition of a secondary flow path beneath the primary test section. Splitter plates located at both ends of the test section served to separate the distinct flow paths; an opening of $0.6 \text{ m}$ between the splitter plates was used during the course of these experiments. The lower boundary defining the secondary flow path was constructed of flexible acrylic plastic mounted on threaded rods which could be adjusted to accommodate changes in the cross-stream dimension of the stream $U_2$ and thereby the static pressure distribution within the test section. The secondary channel height was variable, but typically maintained a dimension of approximately $1/3 \text{ } H$ for these studies. The secondary flow, moving from right to left in Fig. 1., was created by drawing air through a contraction followed by a series of flow conditioners before passing beneath the primary flow of the wind tunnel stream and exhausting through a vacuum-blower unit. Flush mounted pressure taps located on the upper and lower surfaces were used to monitor the streamwise static pressure variation in the test section. Cross-stream pressure gradients in the test section could be effectively eliminated by adjusting the lower wall together with the placement of resistive elements in the flow path of the primary wind tunnel loop.

![Figure 1: Planar shear layer facility](image-url)
2.2 Confined shear layers

Confined shear layers were studied in a two-dimensional facility allowing for the variation in the interaction of the two countercurrent streams (shown later in Fig. 4). The jet height $h$ was approximately 1 cm and the spanwise depth of the facility was 10 cm; the jet separation was variable and given by $\delta$. Particle image velocimetry was the primary flow diagnostic used to examine the flow; both the side views and plan views of the shear layer were documented, the latter view used principally to investigate the spanwise coherence of the flow with and without counterflow. Olive oil droplets generated with a Laskin nozzle were used as seed particles. Images were captured digitally and processed using cross correlation.

3. Global flow response to unconfined counterflow

Preliminary flow visualization studies were conducted to determine the global flow behavior within the planar shear layer facility (shown in Fig. 1) in the presence of counterflow. This was necessary to assess whether stagnation-point flow was created as observed in the wind tunnel experiments of Humphrey and Li (1981). The average flow direction in the tunnel was mapped using paper tufts mounted on fine monofilament lines which were anchored to the top and bottom tunnel walls of the test section. The tensioned lines were aligned along the centerline of the test section in the streamwise direction of the flow every 5 cm. The paper tufts were carefully cut to similar dimensions and mounted so that they could rotate freely about the axis of the tensioned line. To prevent the tufts from sliding down, small glass beads were glued to the lines. In this fashion, the tufts could also move with reasonable freedom about their pitch axis. This provided an additional degree of freedom to indicate the presence of cross-stream flow as would be expected if global stagnation flow were created within the facility. Care was also taken to inspect the nearly 450 tufts for damage and misalignment occurring between runs.

We found that the best way to interpret the global flow behavior as a function of velocity ratio, was to observe the tufts over an extended period and record their behavior. Permanent records of the tuft images were also obtained using a Nikon 35 mm camera. Figure 2 shows a representation image of the tuft grid at velocity ratio $U_2/U_1 = -0.23$. For the time exposure of 0.5 sec. used to capture the image, some tufts can be seen to be blurred indicating the presence of highly disturbed regions in the flow. These disturbed tufts were used to identify the approximate location of the mixing layer developed between the forward and reverse streams, and were in sharp contrast to the relatively stationary tufts observed in the
freestream regions of forward and reverse flow. The boundary between the undisturbed and disturbed tufts provided an estimate of the cross-stream extent of the shear layer. It was observed that the disturbed region widened as the velocity ratio \( U_2/U_1 \) decreased, i.e. as the magnitude of the reverse velocity increased relative to the forward velocity. Over the range of velocity ratios studied (\( U_2/U_1 \) between 0 and -0.32) no global stagnation flow was observed as reported by Humphrey and Li (1981).

\[ \text{Figure 2: Flow visualization of countercurrent planar shear layer using a tuft grid.} \]

To maintain constant pressure conditions throughout the flow field, pressure variations were monitored in the streamwise and cross-stream directions using the static pressure taps on the surfaces of the upper and lower tunnel walls. Streamwise pressure variations were minimized at each velocity ratio by adjustments in the flexible lower tunnel wall. Cross-stream pressure variations also resulted due to the inherent closed loop nature of the facility. To minimized this effect, a series of flow conditioners providing variable flow resistance were installed both in the primary wind tunnel circuit (consisting of a pair of perforated plates adjustable relative to each other) and at the inlet to the secondary flow path (honeycomb flow straightener and layers of fine cloth screens). These later conditioning elements were particularly effective at matching the lower test section pressure to that of the upper.

The procedure for operating the facility was somewhat dependent upon the velocity ratio under consideration. For instance, to study the shear layer at a velocity ratio of zero — a single stream shear layer — the bottom wall of the test section was removed from the facility allowing free entrainment of ambient air into the shear layer region. At negative velocity ratios, the forward velocity \( U_1 \) was fixed and the secondary stream \( U_2 \) was varied. In this fashion, the initial
condition supplied by the primary flow remained essentially invariant. Hot-wire anemometry was used to measure the shear layer velocity fields.

A plot of the shear layer growth rate versus the velocity ratio is shown in Fig. 3. The plot reflects an increase of mixing rate as the velocity ratio decreases. The data indicate a rather smooth transition between coflow and counterflow at $U_2/U_1 = 0$, which is consistent with our physical intuition. The counterflowing data does display considerably more uncertainty than what has been reported in the literature for coflowing layers. This is partially due to the absence of reported uncertainty information, but was also caused by the experimental difficulty of establishing streamwise invariance in $U_2$ in the current facility.

![Figure 3: Normalized spatial grow rates](image)

Over the years, there have been many studies conducted at zero velocity ratio, due perhaps to the simplicity of establishing a single stream shear layer. The unusually large amount of scatter seen in these data is likely associated with the uncertainty of measurements obtained on the low-speed side of the layer, where most probes will be ineffective. The original measurements reported by Abramovich (1963) for counter-current layers are presented, although little detailed information could be found to assess the accuracy of these measurements or for that matter the precise configuration studied. Growth rates as measured for the present experiment increase rapidly for negative velocity ratios indicating their attractiveness for control strategies where shear layer manipulation must be achieved in compact environments. Such applications include, but are not limited to: the reduction of broadband mixing noise in jets; the control of momentum mixing (entrainment) for fluidic thrust vector control; the manipulations of the flame characteristics for high volumetric heat release; and the control of jet mixing for exhaust signature control.
4. Countercurrent shear in compact environments

The facility used to study the application of counterflow in the compact environment typical of dump combustors is shown in Fig. 4. The nominally two-dimensional facility allows for variations in several important flow and geometric parameters. The resulting complicated three-dimensional velocity field is documented using particle image velocimetry. Planar laser imaging of both the cross-stream and plan-views provides quantitative information of the primary flow response to counterflow, the role of key geometric parameters, as well as the influence of confinement on the global velocity field.

![Figure 4: Compact countercurrent shear layer facility](image)

Figure 5 provides an indication of the underlying base velocity fields which are created in the facility. In the absence of the secondary stream, the uncontrolled base flow can be observed as seen in Fig. 5a; isovelocity contours are provided to assist in observing the mean flow. The image in Fig. 5b indicates the nature of the velocity field in the presence of the secondary "control" stream which provides the counterflow. The advantages of employing a secondary stream to achieve active flow control include the following: no fragile sensors are required to achieve actuation; the base flow response to counterflow is largely insensitive to the nature of the initial and boundary conditions; and the flow is inherently compact and highly turbulent.
The compact countercurrent shear layer was shown to increase turbulence levels and integral length scales. Figure 6 provides a comparison of the rms normalized turbulence intensities with and without countercurrent shear. For the single stream shear layer, the turbulence levels reach approximately 16% of the primary stream velocity and are confined to the inner portion of the shear layer, which is in general agreement with the literature. In the presence of counterflow, the turbulence levels are increased by nearly 100% of the value in the single stream layer over extensive portions of the flow domain.

The violent nature of the countercurrent layer can be observed by examining instantaneous PIV images of the flow. Snapshots of the velocity fields of these two cases are shown in Fig. 7. Figure 7a shows a typical single jet vector field. As can be seen, the activity in the shear layer is limited. The scales present are of fairly small size. For the countercurrent shear layer, shown in Fig. 7b, the interaction is seen to result in the presence of larger flow scales.
The effect of confinement is studied through the variation of the jet spacing $\delta$, which controls the available space for mixing between the streams. As the jet spacing is reduced, the jets impinge upon one another resulting in a global stagnation flow similar to that of Humphrey and Li (1981). The resulting flow is highly nonparallel, and has different stability characteristics than the relatively parallel countercurrent shear layer. This mode of operation is inefficient at generating large energetic turbulent structures.

One important observation, which can be gleaned from studies of isothermal countercurrent shear layers, should be emphasized. Physical reasoning as well as stability theory support the argument that flow structures will convect downstream at a speed approximately given by the average velocity of the shear layer, namely $(U_1 + U_2)/2$. As the velocity ratio $U_2/U_1$ approaches -1, flow structures will grow temporally, but will remain essentially stationary. Hence, it can be anticipated that countercurrent shear layers will be effective for flow control in inherently compact geometries. Furthermore, the range of flow scales and increased turbulence intensities suggest that countercurrent shear may play a significant role in the control of reacting flows, where both entrainment (large scales) and mixing (small scales) must be appropriately manipulated. In the section to follow, we will highlight some recent studies which indicate the potential of countercurrent shear in practical flow control.
5. Applications of countercurrent shear control

5.1 Compact stable combustion

Reacting turbulent flows are an obvious target for exploiting the traits of the countercurrent shear layer. In particular, the combustion rate of hydrocarbon fuels premixed in air is strongly impacted by turbulent length and velocity scales. The high turbulence levels and large length scales present in the countercurrent shear layer will be efficient at producing large instantaneous flame surface areas through flame wrinkling. Thus the use of counterflow for combustion should lead to high levels of volumetric heat release.

While increased flow turbulence can be beneficial in combustion applications to achieve increased burning velocities, one of the inherent limitations of increased turbulence is the concomitant elevation in instantaneous strain rates which may lead to flame quench. Figure 8 indicates that one of the unique features of countercurrent shear is that the increase in integral length scales gives rise to reductions in instantaneous strain rates. The combination of increased integral scales and decreased strain rates are attractive for combustion because large energetic scales are effective at creating large flame surface areas, while the low strain rates will minimize the detrimental effects of flame stretch.

Additionally, the countercurrent shear layer was shown to eliminate the spanwise coherence that is present in single stream or co-flowing shear layers. Spanwise coherence in traditional dump combustors can result in temporal fluctuations in heat release, resulting in intense combustion instabilities as described by the Rayleigh criterion (Schadow and Gutmark, 1992).

Figure 8: Instantaneous strain rates for (a) single stream and (b) countercurrent cases

This effect is best observed in Fig. 9 which shows instantaneous planview visualizations of the flow. The images demonstrate the dramatic difference in the
three-dimensional character of the flow with and without counterflow. In the absence of counterflow (Fig. 9a), the flow displays considerable spanwise coherence. These highly two-dimensional structures are responsible for well-known thermo-acoustic instabilities. The visualization in Fig. 9b indicates the dramatic impact that counterflow has on the spanwise character of the flow. There is no evident spanwise coherence for this case, which experiences approximately the same total shear as seen in Fig. 9a. Furthermore, while the organization of the shear layer is less coherent in Fig. 9b, the scales present in the flow are still large, which is important for achieving high volumetric heat release.

Figure 9: Planview visualizations for the a) single-stream shear layer; b) for the countercurrent shear layer.

These results emphasized those aspects of countercurrent shear which will impact combustion processes in compact burners. The high turbulence levels, large length scales, and increased three-dimensionality that are achieved with countercurrent shear layer control suggest that it will be beneficial in generating higher volumetric heat release rates while reducing thermo-acoustic instabilities.

5.2 Fluidic thrust vector control

Figure 3 indicates that proportional control of shear layer entrainment could be achieved at negative velocity ratios, and at entrainment rates considerably higher than would be possible without counterflow. This observation led to the following hypothesis: if entrainment can be altered systematically and efficiently, then it is reasonable to propose that asymmetric effects of counterflow could be used to accentuated mean flow asymmetries leading to vectored thrust. A study of the asymmetric application of counterflow to a supersonic rectangular jet (Strykowski, et al., 1996a) indicated that thrust vector control was possible under realistic flow conditions. This work was important because it demonstrated that
jet entrainment could be altered proportionally to the shear layer velocity ratio, thereby essentially eliminating the bistable and hysteretic effects which have long plagued the successful implementation of fluidic schemes in jet exhaust applications.

Figure 10 shows the nozzle hardware used for thrust vector control and the corresponding flow response when counterflow is asymmetrically applied near the jet exit at Mach 1.4. The proximity of a curved surface to the nozzle exit provides the confinement necessary to direct a secondary counterflow stream against the primary supersonic jet. The action of countercurrent shear gives rise to intense mixing in the shear layer, which through entrainment, produces an asymmetric reduction in the pressure in the jet near field and jet vectoring. While the phenomenon of counterflow thrust vectoring was initially documented several years ago, the underlying physics remains largely unstudied. Recent experiments conducted in our laboratory on a rectangular Mach 0.5 jet configuration provided new insight into the shear layer dynamics and the mechanisms responsible for jet vectoring in the absence of moving parts.

Figure 10: Upper sketch illustrates side view of a counterflowing nozzle used for thrust vector control. Lower image is a schlieren photograph of a Mach 2 jet vectored.

Figure 11 provides the mean velocity-vectors obtained with PIV of the near fields of the jet with and without the application of counterflow. The unvectored flow illustrates the natural entrainment process which exists in the jet near field.
When counterflow is applied, the diffusion of the layer is clearly evident. Examining the Reynolds stresses present in the jet shear layers reveals that the turbulent transport of momentum is significant in the case of counterflow. These stresses work against the secondary stream resulting in a pressure drop along the curved surface, leading to jet vectoring. These stresses are important for creating pressure losses along the secondary flow path, which would be limited by choking if purely isentropic acceleration were responsible for the pressure distribution on the curved surface. Furthermore, the irreversible pressure drop leads to efficient production of the side forces needed to vector thrust at a minimum penalty in terms of secondary mass flow requirements.

\[ \text{Figure 11: Mean velocity-vector fields of the unvectored jet (left) and vectored jet (right).} \]

5.3 Compressible mixing control

One of the most challenging problems of free shear flow control concerns the observation that mixing between dissimilar streams is significantly reduced as compressibility effects become more pronounced. This effect motivated a plethora of research in the area owing to the considerable impact it has on the design of high-speed devices such as supersonic combustors and in the control of jet noise and signature suppression. Control strategies have been both of a passive and active nature, but are often plagued by high thrust penalties or excessive energy input requirements. We believe that any viable approach to compressible shear flow control must incorporate an efficient means of transferring energy between the mean and turbulent velocity fields. In a study reported in Strykowski et al. (1996b), we examined how alterations in the local
velocity field can be used to excite inherent instabilities of a compressible shear layer and thereby achieve a global response conducive to the rapid diffusion of the flow. This approach was based on the unique stability characteristics of the countercurrent shear layer, and leads to the formation of coherent structures in the flow which are otherwise absent at these levels of compressibility. As an example, spatial growth rates in a compressible countercurrent shear layer, at convective Mach numbers greater than unity, exceed those of coflowing layers by nearly 60%. Flow control that leads to mixing enhancement at high convective Mach numbers is attractive in a number of compressible flow applications, including jet noise control, plume mixing enhancement for IR signature control, as well as the control of shear layer separation and reattachment over cavities.

6. Concluding remarks

In conducting the work described above, we have attempted to strike a balance between fundamental research of shear flow control and applied research, which addresses the critical needs of today's technologies. The underlying stability theory is perhaps the most valuable tool we have found for providing insight into the appropriate control strategy for a given flow configuration. Judging ones success in these matters is necessarily subjective, but this approach can bear fruit when an effort is made to bridge the gap between academic and applied inquiry. We believe the thrust vector control work is a successful example of an “in progress” transition of fundamental knowledge to application. Lessons learned from linear stability theory were applied to the thrust vector control of low-speed subsonic jets. Success of the technique at subsonic velocities, subsequently led to the testing of the concept in large-scale hardware at high-temperatures and at flow conditions up to Mach 2. While much remains to be learned in the high-speed environment, the basic characteristics of countercurrent shear have proven to be a viable element in shear flow control strategies.

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8. References