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MIXING LAYER FLOW WITH NON-ZERO MERGING ANGLE

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Abstract An experimental investigation has been conducted on the mixing layers produced from two streams merging at an angle of 18^0 with velocity ratios 0.7, 0.8 and 0.9. The boundary layers were untripped and the initial boundary layers were turbulent in all the cases. Mean flow data associated with this investigation are presented in this paper with a view to study the effect of velocity ratio and characterization of flow field. It was found that for velocity ratios 0.7 and 0.8, mixing layers attained self-similarity but failed for 0.9 within the measurement domain. The development distance and the mixing layer growth were decreased with increasing velocity ratio.

Keywords: Mixing layer, Merging angle, Flow geometry, Self-similarity

INTRODUCTION

Turbulent mixing layers occur in the flow field of many engineering applications e.g. combustion chamber, premixers of gas turbine combustors, chemical lasers, propulsion system and flow reactors. Their certain flow features e.g. presence of large vortical structure, absence of bounding walls, asymptotic behavior, faster growth rate and higher sensitivity than boundary layers have made them attractive for both experimental and computational studies. These mixing layers after their formation develop through two distinct regions namely near-field region and self-similar region as shown in Fig.1. Near-field region, also known as developing region contains wake and transition occurs in the wake flow rather than in a normal laminar mixing layer, and self-similar region, also known as developed region, contains fully developed turbulent flow. Townsend [1976] showed that plane turbulent mixing layers can yield self-similar solutions for sufficiently high Reynolds number at downstream distance.

Mixing layers are inherently very sensitive to small changes in their initial and operating conditions, the effects of which often persist for relatively long distances downstream. This hyper-sensitivity of the mixing layers to their initial and operating conditions is due to the presence of organized large coherent eddies in it. Hence it is very difficult to set up comparable experiments in different facilities. Among the parameters that are known to affect the mixing layer behavior are: velocity ratio[Mehta,1991], trailing edge thickness[Dizomba and Fiedler,1985], state of the initial boundary layers[Bell and Mehta,1990], presence of the trip wire[Bell and Mehta,1990], periodic oscillation force[Oster and Wygnanski,1982], turbulence level of the initial boundary layer[Hussain and Zedan,1978a; Hussain and Zedan,1978b], free-stream turbulence level [Chandrsuda et al.,1978], Reynolds number[Hussain and Zedan,1978a] and size of the test section [Bell and Mehta,1990].

In the present study, the effect of velocity ratio on the development and self-similar properties of turbulent mixing layer from two non-parallel streams has been investigated. Bradshaw[1966] found that a single stream mixing layer achieves self-similar state in a distance equivalent to $1000\theta_o$ but no such obvious criteria has been established for the two stream layer. Mehta and Westphal[1986] found that the two stream layer developed to the self-preserving state in a distance much shorter than the single stream layer. This implied that the development distance of mixing layers decreased with increasing velocity ratio.

The characterization of the mixing layer flow is important for its understanding. The physical picture of the flow can be depicted by the flow geometries. It is a common practice to use the flow geometry in defining similarity variable. The difference of the isovels $y_{0.9}$ and $y_{0.1}$ gives the mixing layer thickness. In most experimental measurements, the reference points are considered along some flow geometries (e.g. $y_{0.5}$) because the flow variables are best defined on those lines. To depict the flow geometry of the mixing layer, the following are presented in this paper: streamwise variation of free-stream velocity, drift of the splitter wake center, isovels, mixing layer thickness, momentum thickness and mean velocity profiles.

In the present study, the merging angle at the initiation of the mixing layer between the two streams may have strong effect on the mixing layer flow but hardly there is publication on it. This lack of knowledge was the motivation behind the present investigation.

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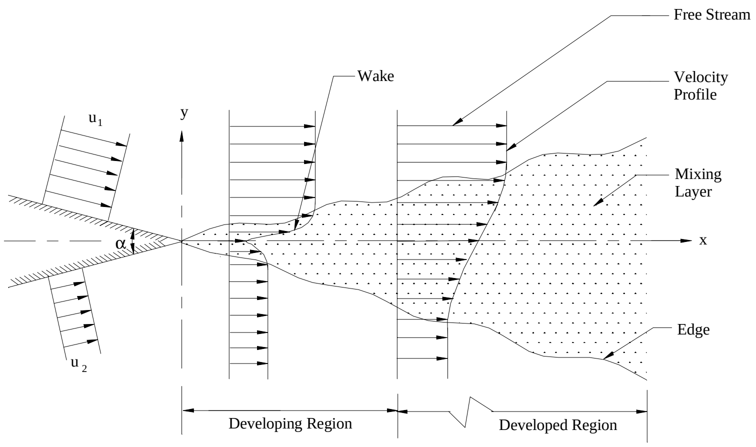

Fig.1 Development of a mixing layer.

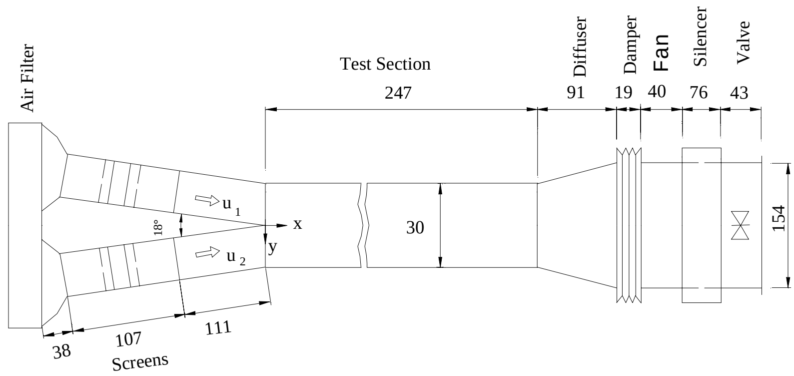

Fig.2 Schematic of mixing layer wind tunnel.

APPARATUS AND PROCEDURES

The experiments were conducted in a suction type Mixing Layer Wind Tunnel (Fig.2). The wind tunnel consists of two small tunnels which merge at an angle of 18^0 into a common test section. The test section is 2470 mm long having a cross-section of 300 x 300 mm throughout. One sidewall is slotted for probe access but no wall is flexible for adjusting streamwise pressure gradient. The free-stream velocities in each suction tunnel were measured at 470 mm upstream.

It is found that at low velocity ratio, boundary layers from both the side walls engulf the mixing layer at a short distance downstream from its initiation. But at velocity ratio $r \geq 0.7$, the boundary layers do not grow so much even in the farthest location of measurement. For this reason, mixing layers with $r \geq 0.7$ have been investigated. Though a small positive downstream pressure gradient was observed, the wall boundary layers remained attach everywhere in the measurement domain. In the experiments, the free-stream velocity in tunnel was varied between 7 m/s and 9 m/s, thus producing mixing layers with velocity ratios 0.7, 0.8 and 0.9.

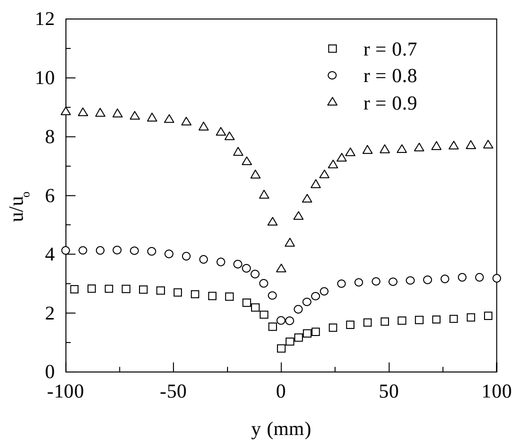

Fig.3 Initial mean velocity profiles (x=5mm).

The Reynolds number at the farthest downstream station based on downstream distance and mixing layer convection velocity was 1.1×10^6 for r=0.7. With these operating conditions at x = 5mm, the streamwise turbulence intensity and cross-stream turbulence intensity were about 3% and 2% respectively. In the mixing layer, the mean core flow was found to be uniform within 0.5%. The initial mean velocity profiles (at x = 5 mm) are shown in Fig.3. Details of the experimental conditions at the initiation of the mixing layer are documented in the Table. The momentum thickness in this table is calculated by using the expression

$$\theta = \int_{-\infty}^{\infty} u^*(1 - u^*)\,dy\,. \qquad (1)$$

Table: Initial conditions (at x= 5mm and u_1 =10 m/s)

Conditions	θ (mm)	Re_θ
r = 0.7	–49.4	9880
r = 0.8	–57.2	7626
r = 0.9	–246.0	16400

The measurements were made using a cross-wire probe held on a 3D traverse with a precision of 0.01mm. The x-wire probe had 5μm tungsten sensing element and was calibrated statically in the potential core of a jet. The analog signals were fed into a computer interface having a 12 bit data acquisition board (Daq Board/112A, IOtech) and a Dasylab software (16 bit DASYLab 5.0, IOtech) for data analysis. Individual statistics were averaged over 5000 samples obtained at a rate of 1000 samples per second that provided adequate convergence of the statistical quantities. Data were obtained in the xy-plane of the rig with a x-probe at six streamwise stations between x = 107 to 2017 mm.

RESULTS AND DISCUSSION

A small positive downstream pressure gradient is found to cause in measurable deceleration of both the streams which is shown in Fig.4. But Browand and Latigo[10] have shown for a parallel stream mixing layer that small positive streamwise pressure gradient caused measurable deceleration in low speed stream only.

The splitter wake center is found to drift from the geometrical center line of the mixing layer which is shown in Fig.5. The isovels $y_{0.9}$, $y_{0.5}$ and $y_{0.1}$ are shown in Fig.6 for r = 0.7, 0.8 and 0.9. It is indicated in the figure that the isovel $y_{0.9}$ spreads more and more into the high speed region with the increasing velocity ratio unlike the mixing layers for low velocity ratios. The virtual origin of the mixing layer (x_o) indicated by Fig.6 is found well upstream for all velocity ratios and moved downstream with increasing velocity ratio. This virtual origin experiences a lateral offset which decreases with increasing velocity ratio.

The growth of the mixing layer thickness evaluated from the mean velocity profiles using the expression $\delta = y_{0.1} - y_{0.9}$ is shown in Fig.7. The mixing layer growth rate decreases with increasing velocity ratio. An approximately linear growth is found for x ≥ 500 mm for all three velocity ratios, though there is much undulation in the growth for r = 0.9. The growth of the momentum thickness(θ) showing the effect of velocity ratio is presented in Fig.8 but not for r = 0.9 due to large scatter in its values. These momentum thicknesses are calculated by using (1). The large value of the momentum thickness in the near-field region is due to the large mean velocity defect. The negative value of θ indicates that the wake effect is dominant over the mixing layer.

The main feature in the streamwise velocity profile is

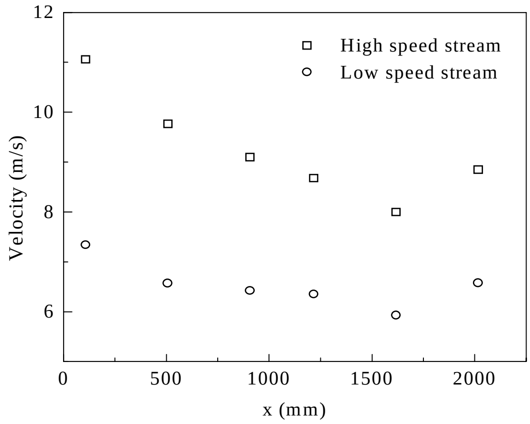

Fig.4 Streamwise variation of free-stream velocities (r=0.7).

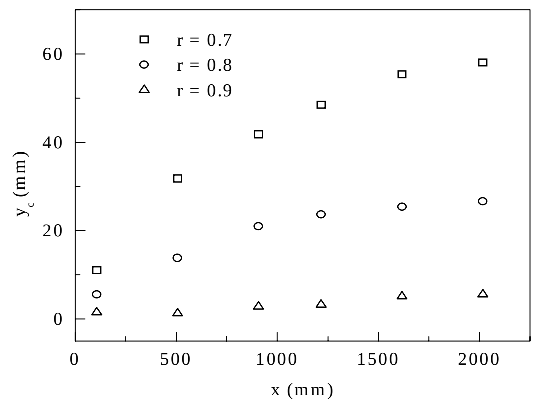

Fig.5 Drift of the splitter wake center.

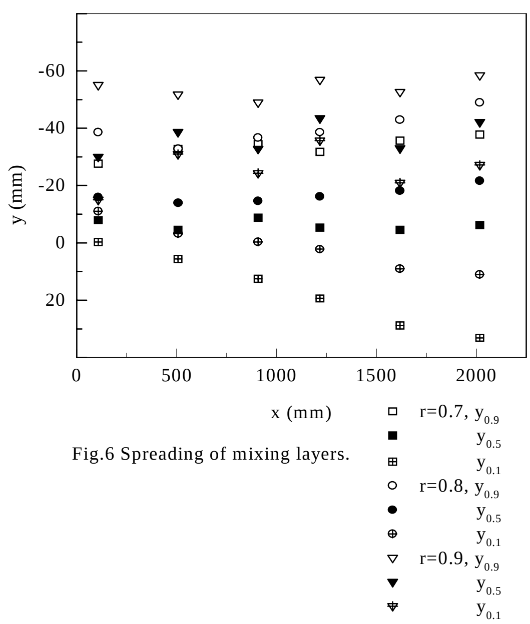

Fig.6 Spreading of mixing layers.

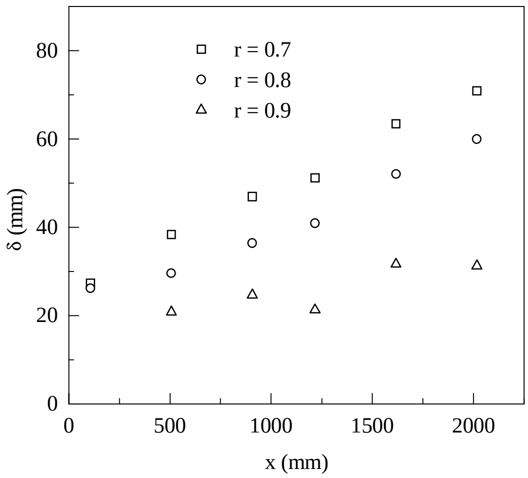

Fig.7 Growth of mixing layer thickness.

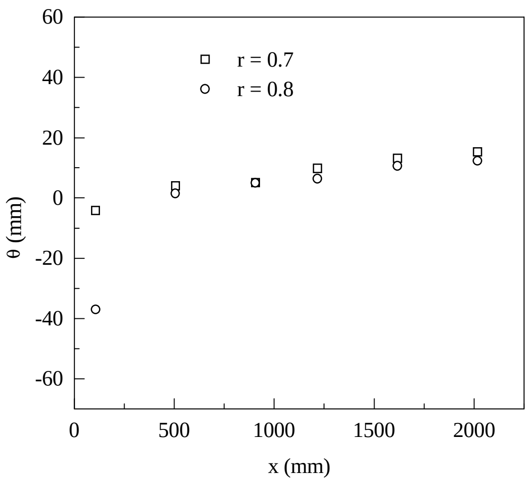

Fig.8 Growth of momentum thickness.

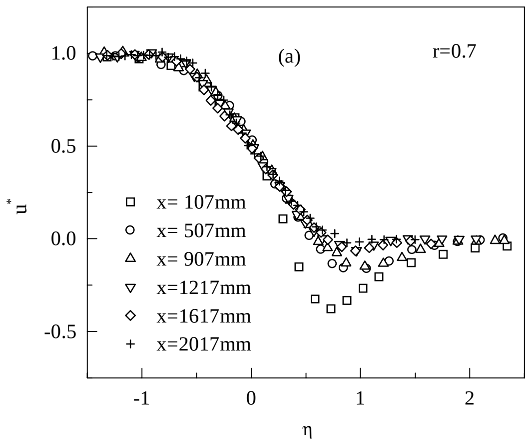

Fig.9 Mean streamwise velocity profiles.

the presence of a velocity defect on the low speed side of the mixing layer. This velocity defect is caused by the splitter wake and washed out by the mixing layer entrainment in the downstream which seems to occur rapidly with decrease in velocity ratio. Mean streamwise velocity profiles for all three velocity ratios are plotted in similarity co-ordinates in Fig.9. In this self-

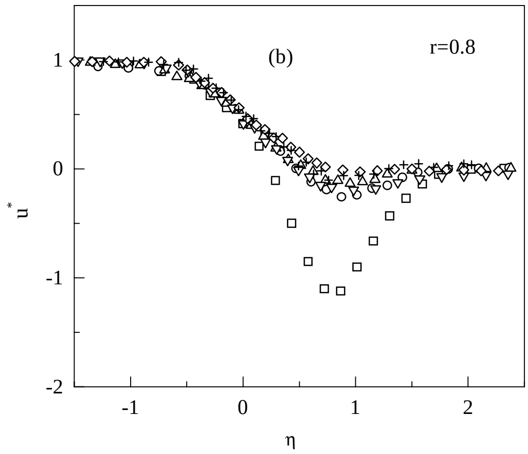

Fig.9 Mean streamwise velocity profiles (see Fig.9(a) for legends).

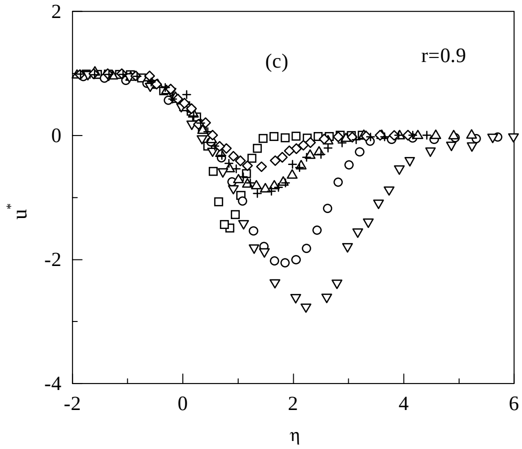

Fig.9 Mean streamwise velocity profiles (see Fig.9(a) for legends).

preservation study, following Townsend[1976], the velocity is scaled by shear velocity (u_o) and y-ordinate is scaled by local mixing layer thickness (δ). For velocity ratios r = 0.7 and 0.8, the mean velocity

profiles seem to collapse quite well as soon as the wake is washed out. In case of r = 0.9, the flow did not

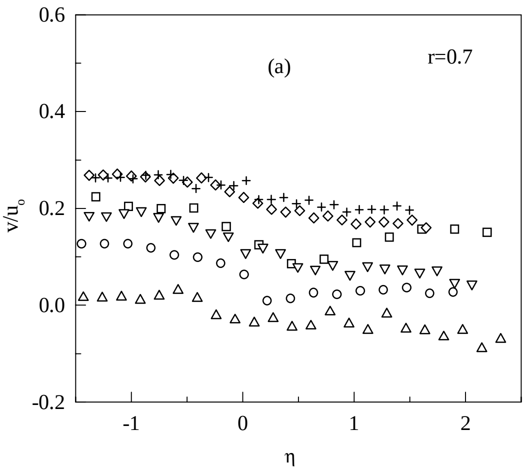

Fig.10 Mean cross-stream velocity profiles(see Fig.9(a) for legends).

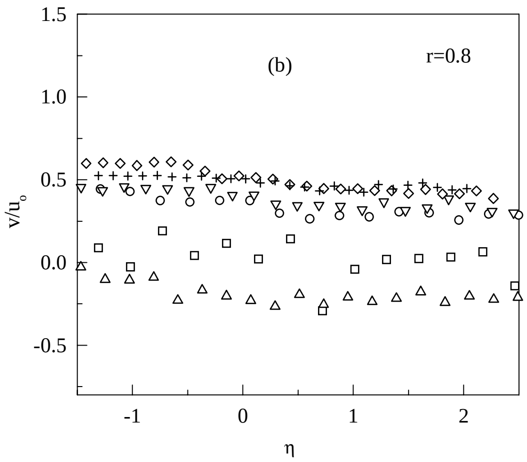

Fig.10 Mean cross-stream velocity profiles (see Fig.9(a) for legends).

become self-similar within the measurement domain. The merging of two streams at an angle at the initiation of mixing layer sets a cross-stream velocity. The **v**-velocity profiles for all velocity ratios are shown in Fig.10, using the same similarity co-ordinates of **u**-velocity profiles. The profiles did not collapse well which may be due to the effect of local **v**-velocity of the free-streams.

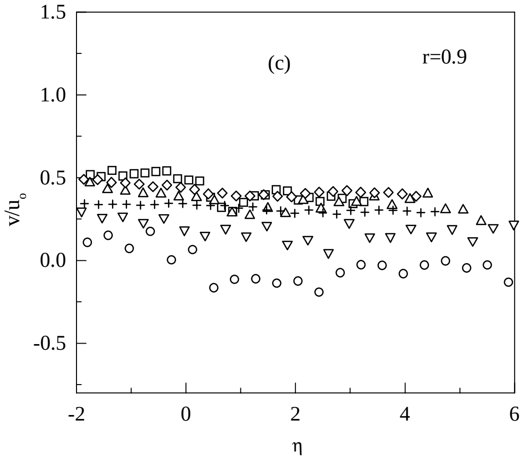

Fig.10 Mean cross-stream velocity profiles (see Fig.9(a) for legends).

CONCLUSIONS

The mixing layers in this experiment were produced from two streams merging at an angle of 18^0. The development of the mixing layer (e.g. for the case of r = 0.7) is found to attain self-similarity in terms of linear growth and collapse of mean flow with downstream distance. This mixing layer is found to spread faster and achieve self-similar state earlier than the parallel stream case for the same velocity ratio.

The effect of velocity ratio on the development of the present mixing layer has been studied with velocity ratios 0.7, 0.8 and 0.9. The mixing layer growth has decreased with increasing velocity ratio like the parallel stream one. The mixing layers for r = 0.7 and 0.8 become self-similar but for r = 0.9 did not show any indication of becoming self-similar within the measurement domain. The splitter wake is found to have lasting effect on the development of the mixing layer for r = 0.9.

NOMENCLATURE

α	angle of merging
δ	mixing layer thickness (= $y_{0.1} - y_{0.9}$)
η	similarity variable [= $(y - y_{0.5})/\delta$]
r	velocity ratio (= u_2/u_1)
Re_θ	Reynolds number based on θ (= $u_o\theta/\nu$)
θ	momentum thickness of the mixing layer
u,v	mean velocity in x, y directions respectively
u*	non-dimensional velocity [=$(u - u_2)/(u_1 - u_2)$]
u_o	shear velocity (= $u_1 - u_2$)
u_1,u_2	mean velocities of high and low speed streams
x, y	streamwise and cross-stream directions
x_o	virtual origin of the mixing layer
y_c	distance of the wake center from x co-ordinate
$y_{0.1}$	isovel for u* = 0.1 and $y_{0.5}$, $y_{0.9}$ are isovels for u* = 0.5, 0.9 respectively

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