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MIXING LAYER FLOW WITH INITIALLY NON-PARALLEL STREAMS

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ABSTRACT

An experimental investigation has been conducted on the mixing layer produced from two streams merging at an angle of 20^0 with velocity ratio 0.7. The initial boundary layers were untripped and turbulent. The data from measurements are utilized for flow field characterization in terms of streamwise variation of static pressure and free-stream velocity, mean velocity vectors, isovels and drift of splitter wake center, mixing layer and momentum thicknesses, mean velocity profiles and streamwise variation of peak Reynolds stresses. All the parameters studied for the flow field characterization were found well defined and some of these indicated the attainment of self-similarity of the flow within the measurement domain. Inhibition of splitter wake drift from the geometrical centerline of the mixing layer at a certain distance in the downstream indicated the diminished wake.

Keywords: Mixing layer, Merging angle, Flow geometry.

1. 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 [1] 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 [2], trailing edge thickness [3], state of the initial boundary layers [4], presence of the trip wire [5], periodic oscillation force [6], turbulence level of the initial boundary layer [7,8], free-stream turbulence level [9], Reynolds number [7] and size of the test section [5].

Bradshaw [10] 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 [11] found that the two stream layer developed to the self-preserving state in a distance much shorter than the single stream layer.

Characterization of a 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. Linear growth of isovels and mixing layer thickness, and asymptotic invariance of the peak Reynolds stresses along the downstream indicate the self-similarity of the flow. To depict the flow geometry of the mixing layer, the following are presented in this paper: streamwise variation of static pressure and free-stream velocity, mean velocity vectors, isovels and drift of splitter wake center, mixing layer and momentum thicknesses, mean velocity profiles and streamwise variation of peak Reynolds stresses. Hardly there is publication on mixing layer with initially non-parallel streams and this lack of knowledge is the motivation behind the present study.

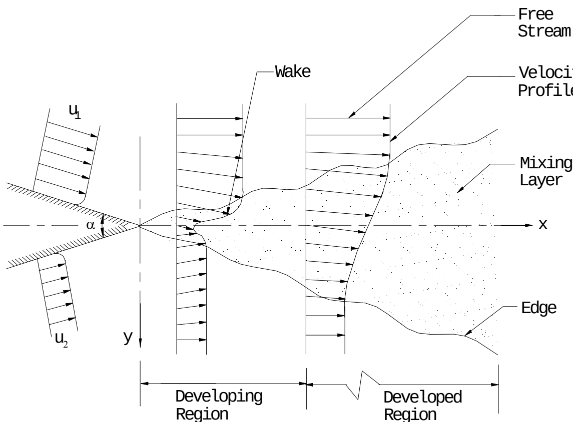

Fig 1. Development of a mixing layer

2. APPARATUS AND PROCEDURE

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 20^0 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.

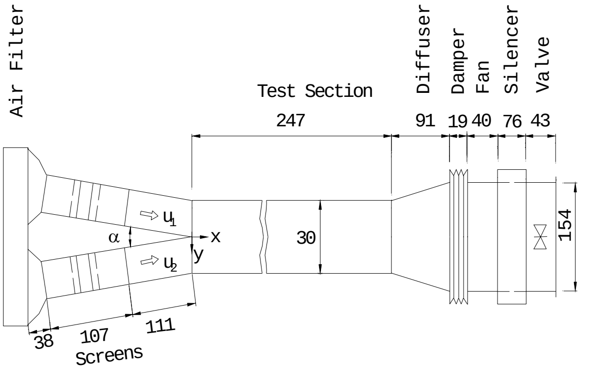

Fig 2. Schematic of mixing layer wind tunnel (dimensions are in cm)

The wind tunnel was suitable for conducting the mixing layer experiments with $r \geq 0.7$. Because at low velocity ratio, the boundary layers grow much so as to affect the mixing layer. The wall boundary layers are remained attach everywhere in the measurement domain. In the experiments, the free-stream velocities in tunnels are kept constant at u_1 =10 m/s and u_2 = 7 m/s. The Reynolds number at the farthest station based on downstream distance and mixing layer convection velocity was 1.1x 10^6. 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%. Initial boundary layers at 10 mm upstream and 8.3 mm from the splitter walls are in turbulent state with about 80% intermittency (the fraction of time for which the flow is turbulent) for a threshold value of $0.3\text{x}\left|\overline{\frac{\partial^2 u'}{\partial t^2}}\right|$ and about 2.9% streamwise turbulence intensity $\left(\sqrt{\overline{u'^2}}\,/u_e\right)$.

The experimental conditions at the initiation of mixing layer (x =5 mm) are θ = 7.5 mm and Re_θ = 1500 where $Re_\theta = u_o\theta/\nu$. This momentum thickness is calculated by using the expression

$$\theta = \int_{y_{0.05}}^{y_{0.95}} u^*(1-u^*)\, dy\,. \tag{1}$$

The measurements were made using a cross-wire probe held on a 3D traverse with precision of 0.01 mm. The x-wire probe had 5 μm tungsten sensing element and was calibrated statically in the potential core of a jet. The cut-off frequency was determined from the square wave test to be about 1 kHz. The analog signals were low passed at 1 kHz (such low passed signals give satisfactory results for time-mean velocity components, Reynolds stresses etc.) before being 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) to calculate the mean velocities and turbulence quantities. Individual statistics were averaged over 5000 samples obtained at a rate of 1000 samples per second that provided adequate convergence of the mean velocities and turbulence quantities. Data were obtained in the xy-plane of the rig (Fig.2) with an x-probe at seven streamwise stations between x = 5 to 2017 mm.

3. RESULTS AND DISCUSSION

Streamwise variation of free stream velocities and mean static pressure are shown in Fig.3. A small negative downstream pressure gradient is found with sudden fall in its value in the vicinity of diminished wake. This sudden change in pressure may be due to the redistribution of energy in absence of wake. The free stream velocities both in the high and low speed streams are found to decelerate due to the wake and dissipation losses.

Mean velocity vectors at x =5mm are shown in Fig.4 that are determined from simultaneous measurements of mean streamwise and cross-stream velocities. These velocity vectors are found to carry the effect of initially non-parallel streams.

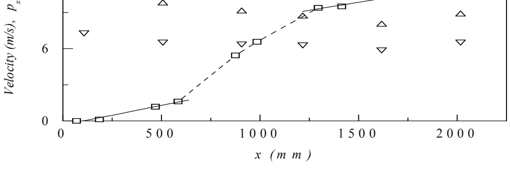

Fig 3. Streamwise variation of free-stream velocities and static pressure

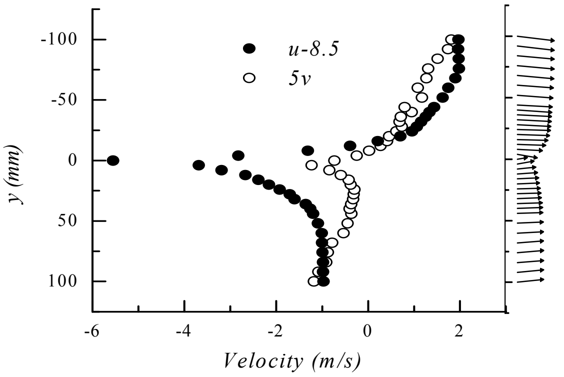

Fig 4. streamwise and cross-stream mean velocities, and their velocity vectors at x =5 mm

The isovels $y_{0.9}$, $y_{0.5}$ and $y_{0.1}$, and streamwise variation of the splitter wake drift are shown in Fig.5 where the virtual origin of the mixing layer indicated by the isovels is found well upstream (x_o = -636mm). This splitter wake center is found to drift from the geometrical centerline of the mixing layer towards the low speed stream and inhibition of drift beyond x~ 907 mm indicates a diminished wake.

The growth of the mixing layer and momentum thicknesses are shown in Fig.6 that are evaluated from the mean velocity profiles using the expressions in Eqs.(1) and (2), respectively where Eq.(2) is as follows

$$\delta = y_{0.1} - y_{0.9}. \qquad (2)$$

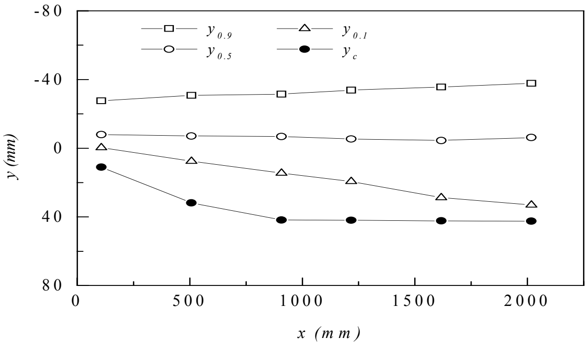

Fig 5. Spreading of mixing layer and drift of splitter wake center

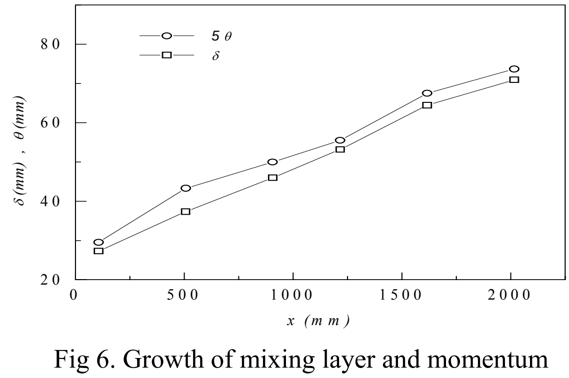

Fig 6. Growth of mixing layer and momentum thicknesses

The main feature in the mean streamwise velocity profile is 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. Mean streamwise velocity profiles are plotted in similarity co ordinates in Fig.7 by following Townsend [1] where the velocity is scaled by shear velocity (u_o) and y-ordinate is scaled by local mixing layer thickness. These mean velocity profiles seem to collapse quite well as soon as the wake is washed out.

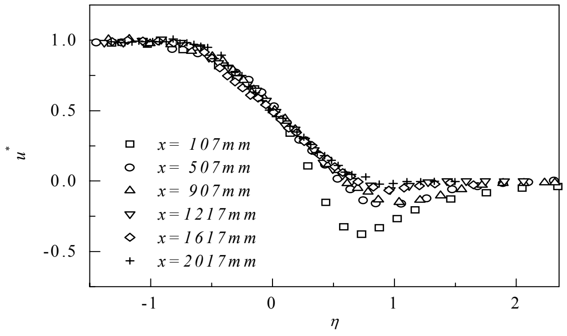

Fig 7. Mean streamwise velocity profiles

A more accurate indicator of self-similar development of a mixing layer flow is the behavior of the peak Reynolds stresses. The peak of the Reynolds stresses $\overline{u'^2}$, $\overline{v'^2}$ and $\overline{u'v'}$ are plotted as a function of streamwise distance in Fig.8. The peak stress levels approached the asymptotic values from higher values and these peak levels seem to achieve a more or less constant value beyond x~500 mm for $\overline{u'^2}$ and $\overline{v'^2}$, and x~1200 mm for $\overline{u'v'}$. This indicates that among the Reynolds stresses, $\overline{u'v'}$ takes longer distance to become self-similar.

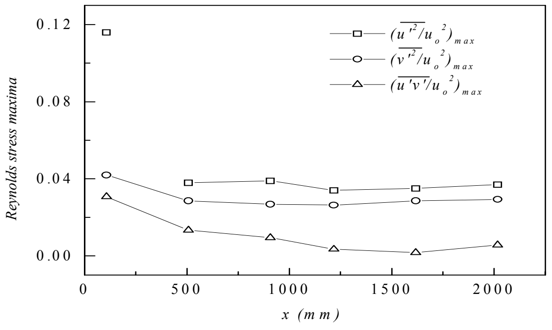

Fig 8. Streamise variation of Reynolds stress maxima

4. CONCLUSIONS

All the parameters studied for the flow field characterization are found well defined. The mixing layer is found to attain self-similarity in terms of linear growth of mixing layer thickness and momentum thickness, linearity of isovels, collapse of mean streamwise velocity and asymptotic variation of peak

Reynolds stresses in the downstream. A sudden fall in pressure gradient is observed at a downstream distance where drift of the splitter wake is inhibited that indicates a diminished wake.

5. ACKNOWLEDGEMENT

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7. NOMENCLATURE

Symbol	Meaning	Unit
α	Angle of merging	degree
δ	Mixing layer thickness (= $y_{0.1} - y_{0.9}$)	mm
η	Similarity variable [= $(y - y_{0.5})/\delta$]	_
$p_x - p_o$	Pressure with reference to first station of measurement	mmH_2O
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	mm
θ_o	Momentum thickness of initial boundary layer	mm
t	Time	s
u,v	Mean velocities in x, y directions	m/s
u*	Dimensionless velocity [=$(u - u_2)/(u_1 - u_2)$]	_
u_e	Free-stream velocity (at 470 mm upstream)	m/s
u_o	Shear velocity (= $u_1 - u_2$)	m/s
u_1, u_2	Mean velocities of high and low speed streams	m/s
$\overline{u'^2}$	Reynolds streamwise normal stress	m^2/s^2
$\overline{v'^2}$	Reynolds cross-stream normal stress	m^2/s^2
$\overline{u'v'}$	Reynolds primary shear stress	m^2/s^2
x, y	Streamwise and cross-stream directions	mm
x_o	Virtual origin of the mixing layer	mm
y_c	Distance of the wake center from x	mm
$y_{0.1}$	Isovel for u* = 0.1, similar are $y_{0.5}$ and $y_{0.9}$	mm
$(\ )_{max}$	Maximum value at given x	_