JAST, Vol. 2, No. 3, pp 45–50
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JAST Journal of Aerospace Science and Technology

RESEARCH NOTE

Effect of Merging Angle on Turbulent Mixing Layers

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Experimental investigations have been conducted on the two types of mixing layers produced from two streams merging at 0° and 20°. Each type of mixing layers was produced with velocity ratios of 0.7, 0.8 and 0.9, and measurements were done at six streamwise locations. The boundary layers were untripped and the initial boundary layers were turbulent in all the cases. The results show that the splitter wake play a dominant role in the development of the mixing layers. Both types of mixing layers attained self-similarity for velocity ratios of 0.7 and 0.8, but failed for 0.9 within the measurement domain. With the increasing velocity ratio, development distance was increased and growth was decreased for both types of mixing layers, but the mixing layers with non-zero merging angles have higher growth than the zero angle one for the same velocity ratio. Both types of mixing layers were found to spread more and more into the high speed region with the increasing velocity ratio.

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 systems 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. In practice, once formed, mixing layers develop through two distinct regions, namely near-field (developing) region and self-similar (developed) region as shown in Figure 1.

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. Some of the parameters that are known to affect the mixing layer behavior are: velocity ratio [1], state of the initial boundary layers [2], turbulence level of the initial boundary layer [3], free-stream turbulence level [4], and size of the test section [2,5]. High free-stream turbulence levels would lead to increased entrainment, and hence, a higher mixing layer growth rate as demonstrated by Pui and Gartshore [6].

In the present study, the effect of merging angle (α) and the velocity ratio (r) on the mean and the turbulent quantities of the mixing layers have been investigated. But there is lack of literature on the effect of α on the mixing layers, hence prompt for the present research.

MEASUREMENTS

The experiments were conducted in a suction type Mixing Layer Wind Tunnel both on parallel ($\alpha = 0^o$) and non-parallel ($\alpha = 20^o$)[3] stream mixing layers. The test section is 2470 mm long with 300 x 300 mm cross-section. One side wall is slotted for probe access but no wall is flexible for adjusting streamwise pressure gradient. The free-stream velocities of both streams were measured at 470 mm upstream. The wind tunnel was suitable for conducting mixing layer experiments with r $\geq$ 0.7 due to sidewall boundary layers. In the mixing layer, the mean core flow was uniform

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[3] *After fabrication α was found to be 18°.*

within 0.5%. The wall boundary layers were found to remain attached everywhere in the measurement domain. However, both the high and low speed streams were found to experience streamwise deceleration. The free-stream turbulence was found to be augmented by the fluctuations from the two side walls. In the experiments, the high speed side (u_1) was kept constant at 10 m/s and the low speed side (u_2) was varied between 7 m/s and 9 m/s; thus, producing mixing layers with velocity ratios: 0.7, 0.8 and 0.9. The hot-wire traces of the fluctuating component of streamwise velocity, u′(t) of the mixing layers (0^o and 20^o) at 10 mm upstream and 8.3 mm from the separating boundary layer walls indicate that the initial boundary layers are in a turbulent state.

At r = 0.7, the Reynolds numbers at the farthest downstream station based on downstream distance and mixing layer convection velocity are $1.3x10^6$ for parallel and $1.1x10^6$ for non-parallel streams, where the convection velocity is $(u_1+u_2)/2$. With these operating conditions at x =5 mm, the streamwise and cross-stream turbulence intensities were about 3% and 2% respectively for both parallel and non-parallel stream mixing layers. Details of the experimental conditions at the initiation of the mixing layer are given in Table 1. Here the momentum thickness (θ) and the Reynolds number (Re_θ) are calculated using the expressions $\theta=\int_{y_{0.05}}^{y_{0.95}} u^*(1-u^*)dy$ and $Re_\theta= u_o\theta/\nu$, where $u^* = (u$ - u_2)/(u_1 - u_2),u = local mean streamwise velocity and $u_o = u_1$ - u_2.

Individual statistics were averaged over 5000 samples obtained at a rate of 1000 samples per second, which provided adequate convergence of the mean velocities and turbulence quantities. Data were obtained in the xy-plane (Figure 1) with an x-probe at six streamwise stations between x = 107 to 2017 mm.

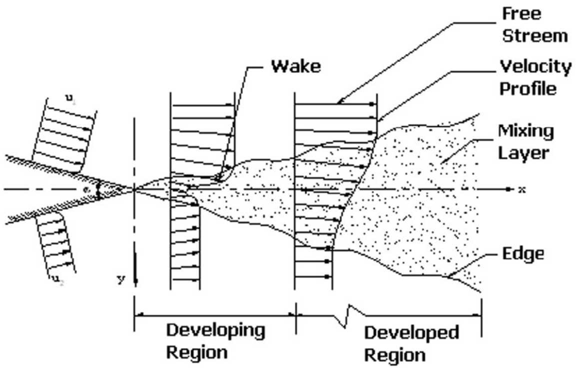


Figure 1. Development of a mixing layer

Table 1. Initial conditions (at x = 5 mm and u_1 = 10 m/s)

Conditions	$\alpha = 0^o$		$\alpha = 20^o$	
	θ(mm)	Re_θ	θ(mm)	Re_θ
r = 0.7	1.99	398	7.5	1500
r = 0.8	1.61	215	7.8	1040
r = 0.9	1.20	80	4.5	300

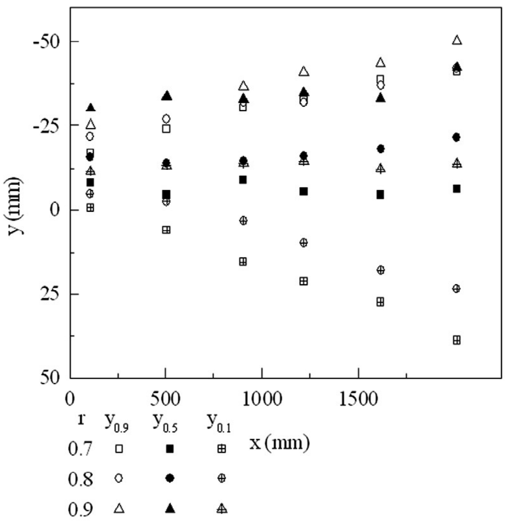


Figure 2. Spreading of mixing layers for $\alpha = 0°$.

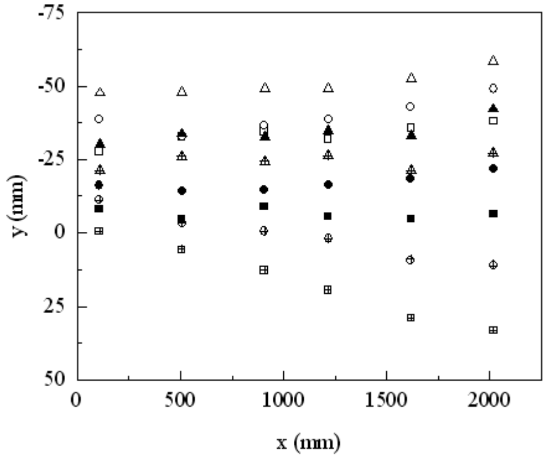
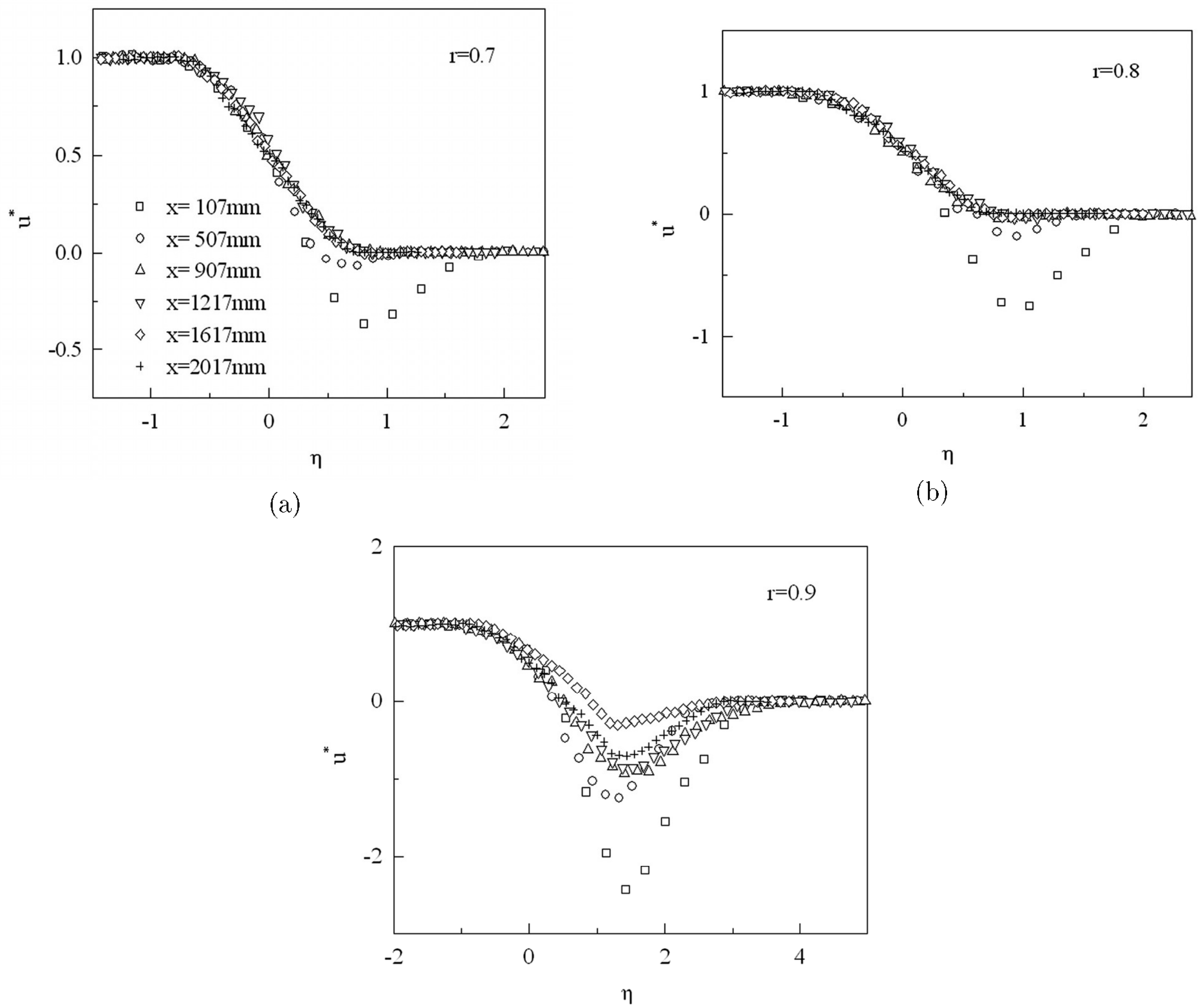


Figure 3. Spreading of mixing layers for $\alpha = 20^{circ}$(see Figure.2 for legends).

RESULTS AND DISCUSSION

The isovels $y_{0.9}$, $y_{0.5}$ and $y_{0.1}$ are shown in Figs.2-3 for r = 0.7, 0.8 and 0.9 where $y_{0.9}$ is the isovel for u^* = 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 available mixing layer data. Thus, the mixing layer spreaded more in the high speed region with an increasing velocity ratio. On the other hand, the spread of the mixing layer has decreased with the increasing velocity ratio, but the isovel $y_{0.9}$ spreaded more into the high speed side. From the momentum perspective, the isovel $y_{0.9}$



(a)

(b)

(c)

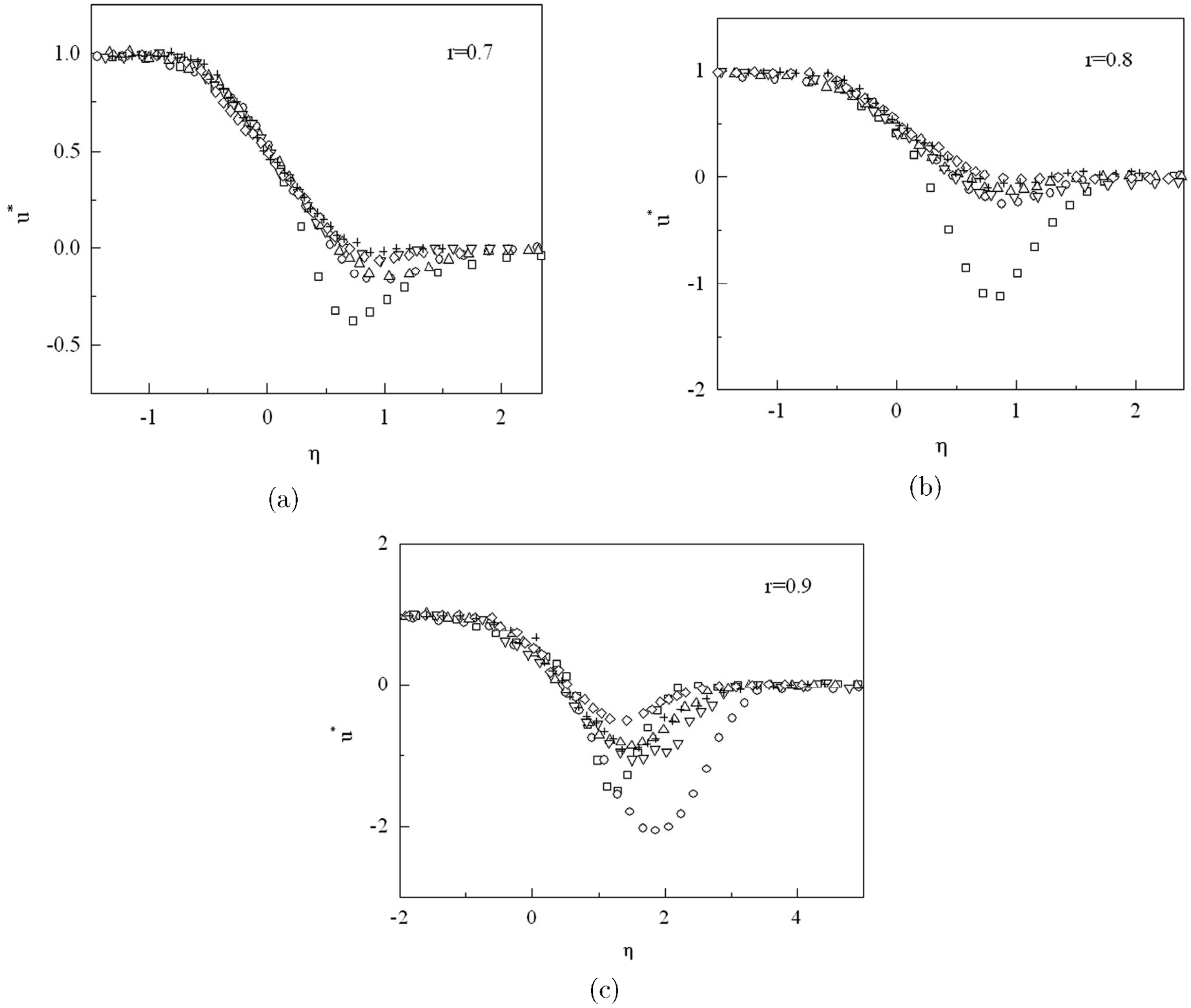
Figure 4. (a), (b), (c) Mean streamwise velocity profiles for $\alpha = 0°$, (see Figure 4(a) for legends).

Table 2. Some properties of parallel and non-parallel stream mixing layers

Conditions	$\alpha = 0^o$			$\alpha = 20^o$		
	x_o (mm)	$d\delta/dx$	$(\overline{u'v'}/u_o{}^2)_{\max}$	x_o (mm)	$d\delta/dx$	$(\overline{u'v'}/u_o{}^2)_{\max}$
r = 0.7	-386	0.033	0.024	-636	0.023	0.007
r = 0.8	-477	0.026	0.035	-568	0.021	0.009
r = 0.9	-843	0.012	0.096	-1070	0.007	0.011

should spread less into the high speed region with an increasing velocity ratio. Presumably, the growth of the mixing layer by entrainment due to significant streamwise stress in the free-stream outweighed the decrease in the mixing layer growth due to momentum consideration [7]. The virtual origin of the mixing layer (x_o) indicated by Figs.2-3 is found well upstream for all velocity ratios and goes up into the upstream with increasing velocity ratio except for r=0.8 at α=20^o (table 2). Experimental data of x_o by Mehta [4] and Oster and Wygnanski [8] for parallel stream mixing layers show a similar behavior as shown in Table 2. The growth of the mixing layer thickness (δ) is evaluated from the difference of isovels $y_{0.1}$ and $y_{0.9}$. The linear growth of the isovels indicates the linear growth of δ. The isovels in the figures show that the mixing layer for α=20^o has a higher growth than that for α=0^o for the same velocity ratio.

Mean streamwise velocity profiles for r=0.7, 0.8 and 0.9 are plotted in similarity coordinate [η=(y-



(a) (b) (c)

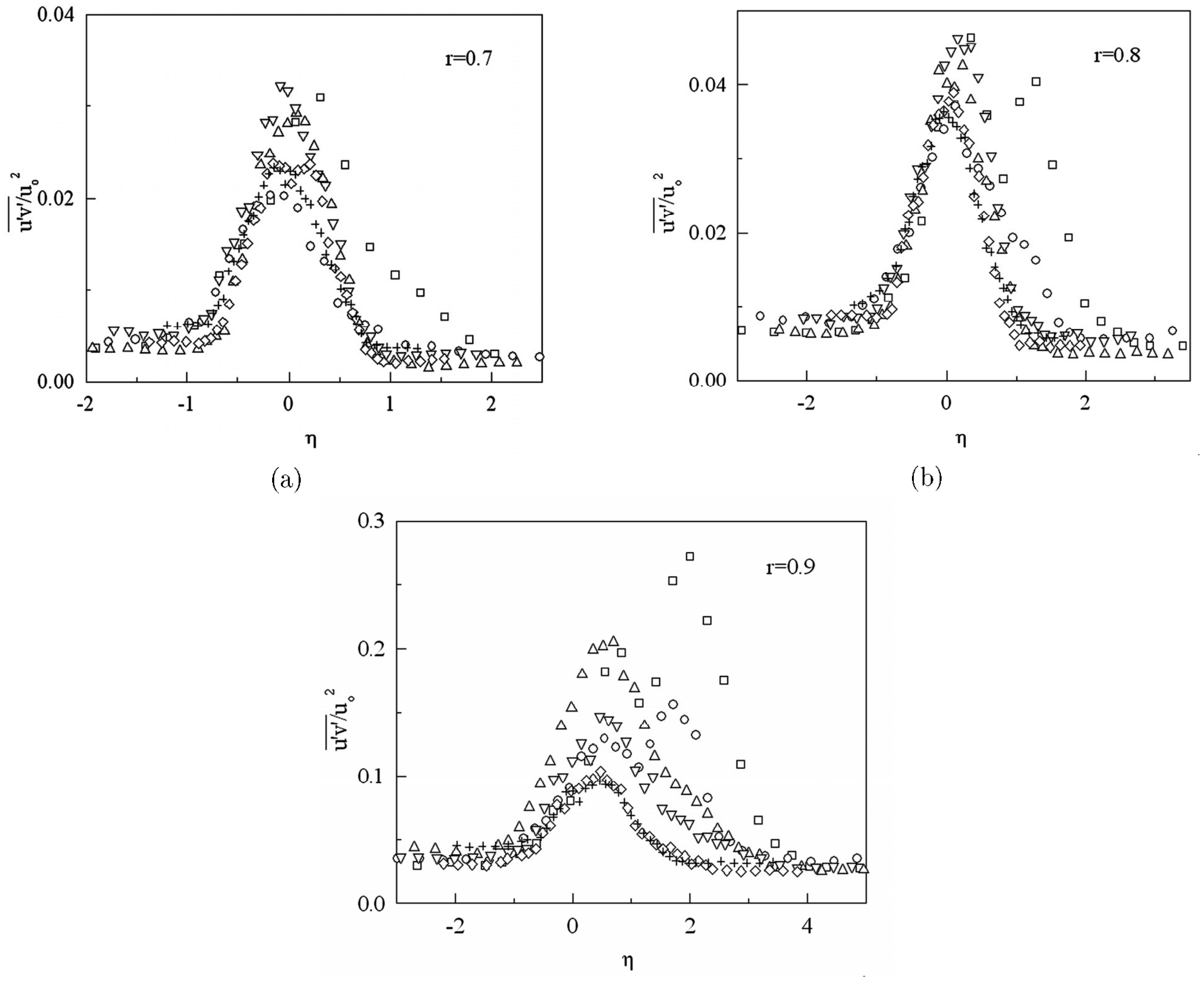
Figure 5. (a), (b), (c) Mean streamwise velocity profiles for $\alpha = 20°$, (see Figure 4(a) for legends).

$y_{0.5})/\delta]$ in Figs.4-5. In this self-preservation study, velocity is scaled by shear velocity (u_o) and y-coordinate is scaled by local mixing layer thickness. The main feature apparent in these results is the presence of a velocity defect at the upstream stations on the low speed side of the mixing layer. For r =0.7 and 0.8, the mean velocity profiles seem to collapse quite well as soon as the wake is washed out, but for 0.9 the flow did not become self-similar. As far as the effects of velocity ratio are concerned, the qualitative trends for the Reynolds stresses are found similar. The profiles for $\overline{u'}$ (Reynolds primary shear stress) are presented in Figs.6-7 in similarity co-ordinates. The stress profiles appear to be apparently collapsing beyond some distance downstream for r = 0.7 and 0.8. But for r = 0.9, the stress profiles are not collapsing within the measurement domain; thus, indicating the lack of self-similarity. The secondary peaks of the Reynolds stresses caused by the velocity defect due to the wake in the near-field are evident in Figs.6-7. Comparison shows small differences between the measured and the predicted values of maximum shear stress indicating that the mixing layers are fairly two-dimensional. An overall assessment shows that the mixing layers (0^o and 20^o) for r = 0.7 and 0.8 are self-preserving but for 0.9 is not. As the Reynolds number Re_θ became small in both types of mixing layers with increasing velocity ratio, the flows lost self-similarity.

CONCLUSIONS

Measurements were done in the mixing layers produced from two streams merging at 0^o and 20^o. The mixing layers are found to attain self-similarity in terms of linear growth of the mixing layer, collapse of the mean flow and turbulence profiles in similarity co-ordinate. It is found that non-parallel cases have higher growth and achieve self-similarity earlier than the parallel case for the same velocity ratio.

To study the effect of velocity ratio on its de-



(a)

(b)

(c)

Figure 6. (a), (b), (c) Reynolds primary shear stress profiles for $\alpha = 0°$, (see Figure 4(a) for legends).

velopment, mixing layers were produced with three velocity ratios of 0.7, 0.8 and 0.9. The mixing layers are found to decrease in growth with an increasing velocity ratio, but are found to spread more into the high speed region. The asymptotic turbulence structures are found to be similar for velocity ratios 0.7 and 0.8, but different for 0.9. The mixing layers for r = 0.7 and 0.8 became self-similar, whereas for 0.9, they did not show any indication of becoming self-similar within the measurement domain. The properties of mixing layers in Table 2 show that non-parallel stream mixing layer develops with lower growth rate and lower stress level than parallel stream case. Possibly, this type of development would help to attenuate the broadband noise generated in the propulsion systems through suppression of both vortex pairing and turbulence.

ACKNOWLEDGMENT

The authors are grateful to Professor A. Prabhu, Department of Aerospace Engineering, Indian Institute of Science, India for his kind assistance during this research work.

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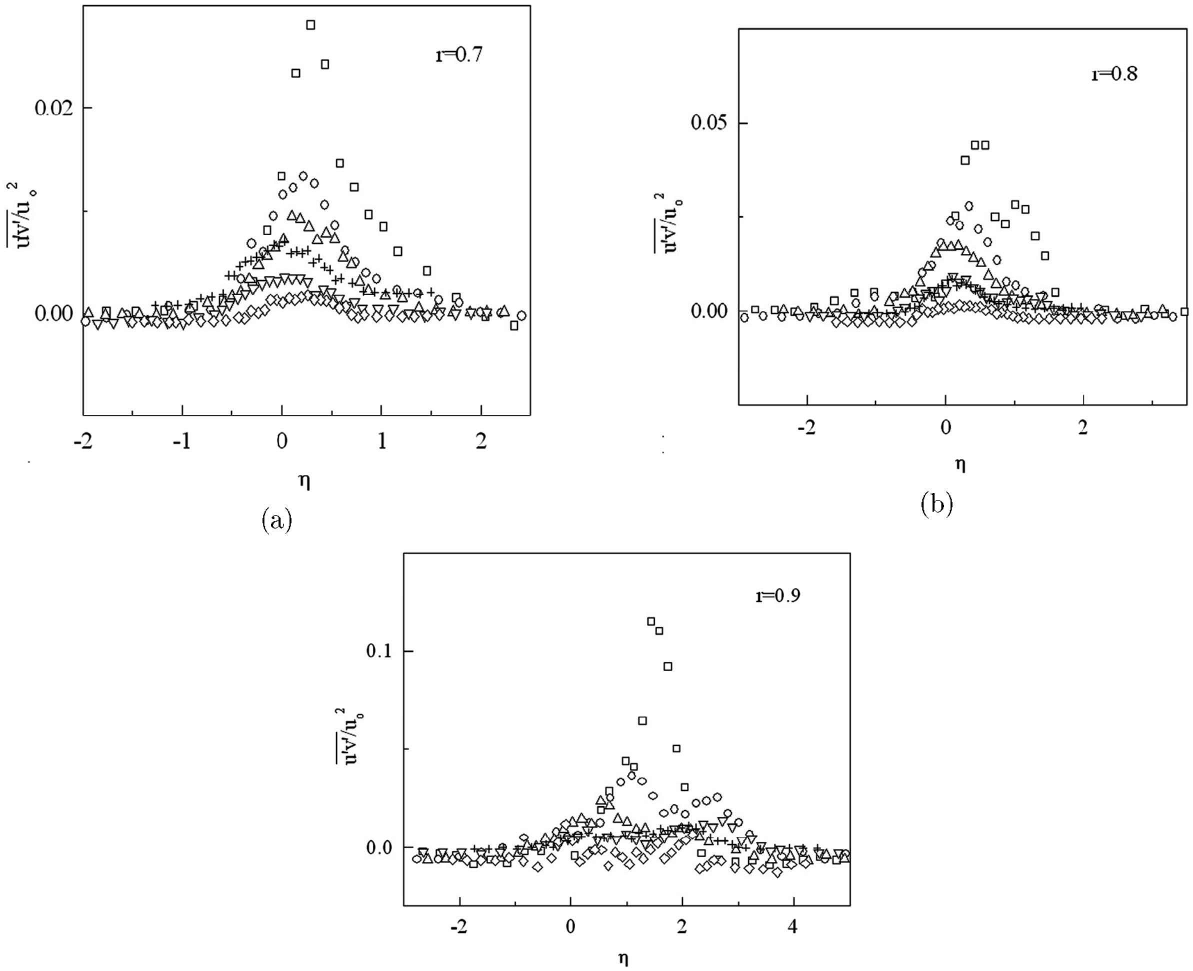

(a) (b) (c)

Figure 7. (a), (b), (c) Reynolds primary shear stress profiles for $\alpha = 0°$, (see Figure 4(a) for legends).

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