Effects of Velocity Ratio on turbulent Mixing Layer at high Reynolds number

Fude Guo, Bin Chen*, Liejin Guo, Ximin Zhang
State Key Laboratory of Multiphase Flow in Power Engineering, Xi’an Jiaotong University, Xi’an 710049, China
chenbin@mail.xjtu.edu.cn

Abstract. In this paper the effect of velocity ratio on plane mixing layer was experimentally investigated by Particle Image Velocimetry (PIV). The velocity ratio between low and high speed side are 0.25 and 0.50, respectively. The Reynolds number based on the velocity difference of two streams and hydraulic diameter of the channel is 66000. The results indicate that the maximum mean Reynolds stress on the same cross section is decreasing with the velocity ratio increasing. The maximum dimensionless mean vorticity is decreasing according to an exponential law along the stream-wise direction and the decreasing speed of dimensionless mean maximum vorticity is increasing with the velocity ratio increasing. The dimensionless vorticity caused by plate wake is decreasing sharply in a very short distance along the down stream wise direction and the decreasing speed is faster when the velocity ratio is larger.

1. INTRODUCTION
Mixing layer flow can be found widely in engineering and nature with many applications ranging from chemical reaction to combustion, where the turbulent mixing of two flowing streams is of primary significance to the efficiency of such devices. As a result, many researchers have studied mixing layer flow for very long time, and many important results have been obtained on the effect of parameters on the evolution of mixing layer. Brown and Roshko (1974) concluded that the large coherent vortical structures were the intrinsic features of the mixing layer. Almost at the same time, Winant and Brownand (1976) showed that the growth of a mixing layer is governed by the pairing mechanism of these vortical structures. Ho and Huang (1982) showed the initial condition had a long-lasting effect on the development of the mixing layer. Bernal and Roshko (1986) indicated that the critical Reynolds number of the instability decreases as the velocity ratio increases. Yet the distributions of turbulent parameters in the mixing layer are sensitive to many factors even small changes in initial conditions may significantly affect the Reynolds stress distributions in the near-field (Plesniak et al. 1993). Mehta (1991) found the splitter wake played a very dominant role, in some cases, a lasting role in the development of the mixing layer. Mehta (1991) pointed, for velocity ratios between 0.5 and 0.7, self-similarity of the mixing layer was observed with the asymptotic states comparable with the Reynolds number range from 686~1301. Wiecek and Mehta (1998) found that the peak mean stream wise vorticity levels decrease with increasing velocity ratio at all the stream wise locations investigated when one side of the mixing layer was set to 12 m/s and the other side was varied from 6 to 10.8 m/s in wind tunnel. Azim (2003) showed that with the velocity ratio increasing the development distance of mixing layer was increased when the Reynolds number ranges from 300~1500. M. D. Slessor et al.
(1998) reported the influence of inflow conditions on turbulent mixing layer with chemical reaction under Reynolds number $2 \times 10^5$.

Although many researchers have studied the factors which effect the distributions of turbulent parameters and development of the mixing layer and some useful conclusions are given, the understanding of the turbulent mechanism of mixing layer especially effect of velocity ratios is still lack. So the motivation of this paper is to investigate the effect of velocity ratio on turbulent plane mixing layer by Particle Image Velocimetry (PIV), and try to get some quantitative conclusions.

2. EXPERIMENTAL SET-UP

The experiments were conducted in a vertical mixing layer water tunnel, which is specifically designed for free-shear flow experiments with multi velocity ratios. As shown in Fig.1, the main test section of the system consists of a glass vertical water channel to visualize the development of the turbulent mixing layer. Three different splitters are used to generate two streams of flow with designed velocity ratio between low and high side of the mixing layer following the principles proposed and discussed by previous researchers (Paule Dimotakis etc.1976, Daniel Bernard Lang 1985, E. Loth etc. 1995, B. Ford etc. 2000), which are made by 3mm thickness plastic-glass curved into “s” shape with two sharp splitters at the up- and down-flow end parts separately. In order to visualize the mixing layer, a LaVision GmbH PIV system is adopted, which integrates a double pulsed, 15 Hz, 532 nm, 200 mJ Nd-Yag lasers including sheet optics to generate a light sheet from the laser beam. In present paper, the velocity ratios between the low and high speed side $r$ are 0.25 and 0.5, respectively. The Reynolds number based on the velocity difference of two steams and hydraulic diameter of the channel is 66000.

In this section, we analyze and discuss the variations of turbulent quantities with different velocity ratios. In the following figures, the origin is at the starting point of the mixing layer (center of the splitter plate edge down-stream). The $x$ axis is along the down-stream-wise direction, while $y$ axis is from the low to the high speed side across the mixing layer. Both $x$ and $y$ are normalized by the actual extracted half width of the channel $d$ as $x^* = x/d$ and $y^* = y/d$.

3.1 Velocity

Fig.2 shows the mean stream-wise velocity profiles in different cross-section of the mixing layer with Reynolds numbers 66000 for different velocity ratio. In these figures the dimensionless mean stream-wise velocity $u^+$ is normalized by the low speed side velocity $u_l (u^+ = u_l/u_l)$. It can be seen that the average velocity ratios between the low and high speed side $r$ are consistent with the designed parameter 0.25 and 0.50, which verifies that the design of our experimental setup is good enough to study the effect of velocity ratio on the development of mixing layer. It can be noticed that there are deficits of the average velocity profile at the low speed side at $x^* = 0$ (the location just near the end of the splitter plate) because of the influence of the splitter plate wake. The impact of the splitter plate wake disappears rapidly along the down-stream direction and the mean velocity at high and low speed sides both become flat at $x^* = 1$. In other words, the effect of the splitter wake on the mean velocity only exists at a very short distance along the stream-wise direction.
3.2 Reynolds stress

The instantanenous distributions of Reynolds stress for different velocity ration are shown in Fig. 3 combined with the instantaneous velocity fluctuation vectors $u'$ and $v'$. The negative values of Reynolds stress mainly concentrate at the central region of the mixing layer as the blue contours shows in Fig.3, while the small red regions indicate the positive Reynolds stress. Compared with Fig.3.(a) and (b), we can find that the intensity of velocity fluctuations in Fig.3(a) almost distributes homogeneously in the whole flow field when velocity ratio is 0.5. Different with Fig.3(a), it fluctuates more tempestuously at the central part than the other place of the flow field in Fig.3(b) when velocity ratio is 0.25.
Fig. 4 gives the mean Reynolds stress with the velocity ratios \( r=0.5 \) and 0.25 at different cross sections to investigate the effects of velocity ratios on the distributions of Reynolds stress quantitatively. Previous researchers had investigated the Reynolds stress distribution along the stream-wise direction for a long time. However, there exists considerable scatter in the published data. Naka (2006) found that the Reynolds stress decreased along down stream-wise when the Reynolds numbers of high and low speed side of the wind tunnel are 610 and 260. But numerical simulation results of Cheng (2005) showed that the peak values of Reynolds shear stress

\[ \frac{\bar{u}'v'}{\mu_{s}c}\]

of the free shear layer (Mc=0.64) increased along the down stream-wise direction. The results of our experiments in Fig. 4 indicates that the mean Reynolds stress increases along the down streamwise at the same velocity ratio but decreases with the velocity ratio increasing at the same cross section. So not only the Reynolds number but also the the velocity ratios has important effects on the distribution of mean Reynolds stress.

\[ \text{Fig. 4 Distributions of Reynolds stress along the stream-wise direction under different velocity ratio} \]

### 3.3 Vorticity

Fig. 5 shows the distributions of mean vorticity on different cross-section under different velocity ratio along the stream-wise in mixing layer. It indicates that the mean vorticity will decrease with the development of mixing layer. There are deficits of the mean vorticity profiles in Fig. 5 a) and b) at the location \( x^*=0 \) of the low speed side because of the splitter wake. Compared Fig. 5 a) and b) we can find that the value of deficit at the plane edge is increasing with the velocity ratio. But the splitter wakes only have effects for a short distance downstream. The negative vorticity almost vanishes when the normalized \( x^* \) is equal and greater than 1 for both velocity ratios.

\[ \text{Fig 5. Distributions of vorticity on different cross-section} \]
The peak value of normalized statistics vorticity $\omega^*(\omega^* = \frac{\omega_{\text{max}}}{\langle \omega_{\text{max}} \rangle_{\text{max}}})$ is an important parameter for the development of mixing layer, which indicates the decreasing speed of the peak values of mean vorticity compared to the maximum mean vorticity at the place of the mixing layer merging. The distributions of dimensionless vorticity $\omega^*$ are plotted in the Fig. 6. This Figure shows that the dimensionless vorticity decreases along the stream wise according to an exponential law $\omega^* = 0.75\exp(-x^*/(4.2 - 4.4r)) + 0.23$. It is obviously that the decreasing speed of the dimensionless vorticity is faster when the velocity ratio is larger.

In order to investigate the role of wake vorticity in the mixing layer development, the dimensionless vorticity of plate wake $\omega_{wp}^* (\omega_{wp}^* = \frac{\omega_{\text{max,wp}}}{\langle \omega_{\text{max,wp}} \rangle_{\text{max}(0)}})$ along the streamwise is shown in Fig. 7. It is shown that the dimensionless vorticity of the wake decreases sharply in a short distance the mixing layer beginning and the decreasing speed is faster when the velocity ratio is smaller. The results of Fig. 7 also say that the dimensionless vorticity is increasing with the velocity ratio at the same crosssection.

### 4. CONCLUSION

With two different velocity ratios 0.25 and 0.5, our PIV experiments indicate that the mean Reynolds stress increases with the velocity ratio decreasing on the same cross section and with the distance increasing along the stream wise direction at the same velocity ratio.

The mean vorticity will decrease along the stream wise and the dimensionless mean vorticity $\omega^*$ also decreases along the stream wise according to an exponential law. The decreasing speed is faster when the velocity ratio is larger.

The plate wake makes the mean velocity and vorticity have deficits in a short distance where the mixing layer began merging. The peak value of dimensionless vorticity of plate wake is decreasing sharply to almost zero. The decreasing speed is faster when the velocity ratio is larger. However, the value of this dimensionless vorticity is increasing with the velocity ratio at the same Reynolds number.

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### REFERENCES

Azim M. Abdul et al. (2003). “Plane mixing layers from parallel and non-parallel merging of two streams,” Experiments in Fluids, 34(2), pp.220-226.
Bernal L.P., et al. (1986). “Streamwise vortex structure in plane mixing layer” J. Fluid Mech., 170, pp.499-525.

Brown G.L. et al. (1974). “On density effects and large structure in turbulent mixing layers,” J. Fluid Mech., 64, pp. 775-816.

Browand F.K. et al. (1976). “Large scales in the developing mixing layer,” J. Fluid Mech., 76(1), pp.127-144.

Chih-ming Ho et al. (1982). “Subharmonics and vortex merging in mixing layer,” J. Fluid Mech., 119, pp.443-473.

Dimotakis Paule et al. (1976). “The mixing layer at high Reynolds number: large-structure dynamics and entrainment,” J. Fluid Mech., 78(3), pp.535-560.

Ford B. et al. (2000). “Ellipsoidal Bubble Diffusion in a Turbulent Shear Layer,” Int. J. Multiphase Flow, 26(3), pp.503-516.

Guo Fude et al. (2007). “PIV Experimental Investigation of a Turbulent Mixing Layer (I): Single Phase Flow,” 13th China Symposium for Multiphase Flow, pp.164-171.

Lang Daniel Bernard (1985). “Laser Doppler velocity and vorticity measurements in turbulent shear layer,” PHD Thesis, California Institute of Technology Pasadena, California, USA.

Loth E. et al. (1995). “Modulation of shear layer thickness due to large bubbles. Int. J. Multiphase Flow,” 21(5), pp.919-927.

M. D. SLESSOR et al. (1998). “Turbulent shear-layer mixing at high Reynolds numbers: effects of inflow conditions”. Journal of Fluid Mechanics, 376, pp. 115-138.

Mehta R.D. (1991). “Effect of velocity ratio on plane mixing layer development: influence of the splitter plate wake,” Experiments in Fluids, 10, pp.194-204.

Naka Yoshitsugu, et al. (2006). “Simultaneous measurements of fluctuating velocity and pressure in a turbulent mixing layer”. International Journal of Heat and Fluid Flow, 27(4), pp737-746.

Plesniak M.W. et al. (1993). “Effects of small changes in initial conditions on mixing layer three-dimensionality,” Experiments in Fluids, 14(4), pp.286-288.

Wieck Kevin C. et al. (1998). “Effects of velocity ratio on mixing layer three-dimensionality,” Experimental Thermal and Fluid Science, 16, pp.165-176.