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Momentum and mass transfer in developing liquid shear mixing layers

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ABSTRACT

Flow structure in developing mixing layers is experimentally investigated with an emphasis on the second moment terms. Instantaneous streamwise and vertical velocities and concentration are simultaneously measured using a combination of a laser-Doppler velocimeter and a laser-induced fluorescence technique. The results show that the turbulent momentum and mass transfer in developing mixing layers can be negative (counter-gradient flux) at middle and small eddy scales. As a result, the Reynolds shear stress in the developing mixing layer becomes smaller than that in the forcibly developed mixing layer, whereas the momentum production term in the developing mixing layer is larger than that in the developed mixing layer. As the mixing layer develops, the flow gradually becomes turbulent and turbulent momentum and mass transfer becomes positive at small scales. Consequently, the counter-gradient diffusion appears only at the middle scales before it fully develops. With respect to the streamwise mass transfer in the developing mixing layer, the fluid mass at large scales can also be transferred negatively in the off-central region of the mixing layer.

1. Introduction

Free shear flows such as jets and mixing layers appear in various industrial and environmental situations. Detailed flow structures including scalar transfer in turbulent shear mixing layers have been revealed in the past few decades [1–9]. There are also a number of studies on flow structures in developing laminar mixing layers [6,8,10–15]. It has been clarified that a mixing layer has a two-dimensional structure at the very early stage, and two side-by-side vortices merge into a single large vortex (pairing) according to the development. As the Reynolds number increases, streamwise rib vortices form and the flow becomes three dimensional, and, finally, it becomes a fully developed turbulent mixing layer. Developing mixing layers are often seen in low-Reynolds-number flows, and the developing region can significantly affect the following developed region. In addition, entrainment of a non-turbulent flow by a free turbulent jet has a structure similar to that in developing mixing layers [16,17]. It is, therefore, of great interest from a fundamental point of view to understand momentum and mass transfer mechanisms in developing mixing layers.

The primary focus of the present study is the second moment terms such as turbulent momentum and mass fluxes in shear mixing layers. Large eddy simulations (LES) and Reynolds-averaged Navier–Stokes (RANS) methods have become popular tools to investigate and predict a wide variety of fluid-dynamical phenomena. The creditability of these simulations strongly relies on the numerical models applied to compute the second moment terms. Clarification of the differences in momentum and mass transfer between developing and developed flows enables us to evaluate the applicability of the turbulence models to low-Reynolds-number flows that include nonturbulent regions.

In this study, flow structures in developing liquid shear mixing layers are experimentally investigated. The momentum and mass transfer in mixing layers at various transition stages is clarified and discussed by comparing with that in a developed sheared mixing layer.

2. Experimental

Fig. 1 shows a schematic of the experimental apparatus and measurement system. The test section is a polymethylemethacrylate (PMMA) rectangular water tunnel of 1.5 m in length and 0.1 × 0.1 m in cross section. The flow is completely separated by a splitter plate into upper and lower streams from the reservoir tanks until the entrance to the test section. The fluid used in this study is filtered water for both streams. A nonreacting fluorescence dye, uranine, was initially premixed in the upper stream at a concentration, C_0, of 5.0×10^{-5} mol/l. Table 1 lists the flow conditions of the mixing layers. The first flow (Run I) is a developing laminar mixinglayer and the second flow (Run II) is a turbulent mixing layer forcibly developed by trip wires. The initial streamwise velocities of the upper and lower streams, $\overline{U}_H$ and $\overline{U}_L$, were set to 1.65×10^{-1} and 8.5×10^{-2} m/s ($r = \overline{U}_L/\overline{U}_H = 0.52$ and

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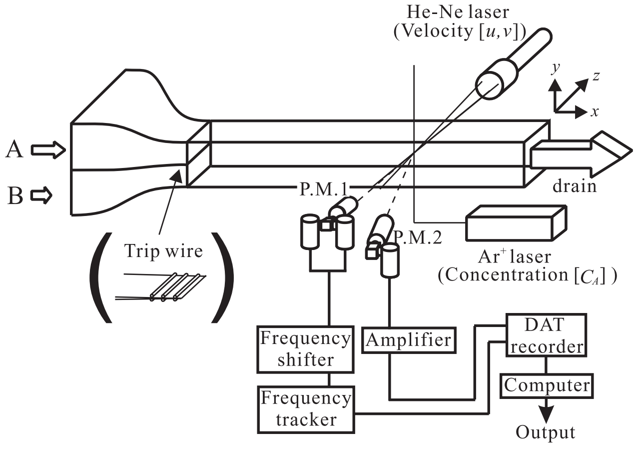

Fig. 1. Schematic of the experimental apparatus.

Table 1
Experimental conditions.

Run	$\overline{U}_H$ [m/s]	$\overline{U}_L$ [m/s]	$\overline{U}_{\langle v\rangle}$ [m/s]	ΔU [m/s]	r[-]	Trip wires
I	0.165	0.085	0.125	0.08	0.52	.No.
II	0.165	0.085	0.125	0.08	0.52	.Yes.
III	0.34	0.17	0.255	0.17	0.50	.No.
IV	0.145	0.105	0.125	0.04	0.72	.No.

$\Delta U = \overline{U}_H - \overline{U}_L = 8.0 \times 10^{-2}$ m/s), respectively, for both cases. The Reynolds number, Re, based on the average velocity and the side length of the channel (=0.1 m) is 12,500. Stainless wires were installed on both the upper and lower sides of the splitter plate in Run II. The wire diameter, d_w, was 1.2×10^{-3} m and the wires were placed at $x = -2.0 \times 10^{-2}$, -4.0×10^{-2}, and -6.0×10^{-2} m. The third flow (Run III) is also a developing mixing layer without trip wires but the mean velocity was set to twice the value of those in Runs I and II ($\overline{U}_H = 3.4 \times 10^{-1}$ m/s, $\overline{U}_L = 1.7 \times 10^{-1}$ m/s, and Re = 25,000). Note that the velocity ratio, r, is the same as that in Runs I and II. In the fourth mixing layer (Run IV), the velocity ratio, r, was set to 0.72 ($\overline{U}_H = 1.45 \times 10^{-1}$ m/s, $\overline{U}_L = 1.05 \times 10^{-1}$ m/s, and Re = 12,500).

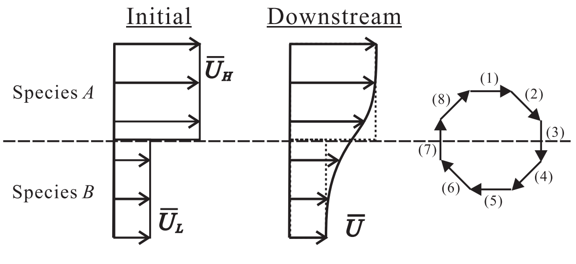

Fig. 2. Schematic of momentum and mass transfer. "+" means gradient flux and "−" means counter-gradient flux.

Table 2
Signs of the momentum and mass transfer.

Arrow no.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Reynolds shear stress (uv)		–		+		–		+
Streamwise turbulent mass flux (uc)	+	+		–	–	–		+
Vertical turbulent mass flux (vc)		–	–	–		+	+	+

Table 3
Directions of the momentum and mass transfer.

Sign	Positive (+)	Negative (−)
Reynolds shear stress (uv)	CGD	GD
Streamwise turbulent mass flux (uc)	GD	CGD
Vertical turbulent mass flux (vc)	CGD	GD

GD: Gradient diffusion.
CGD: Counter-gradient diffusion.

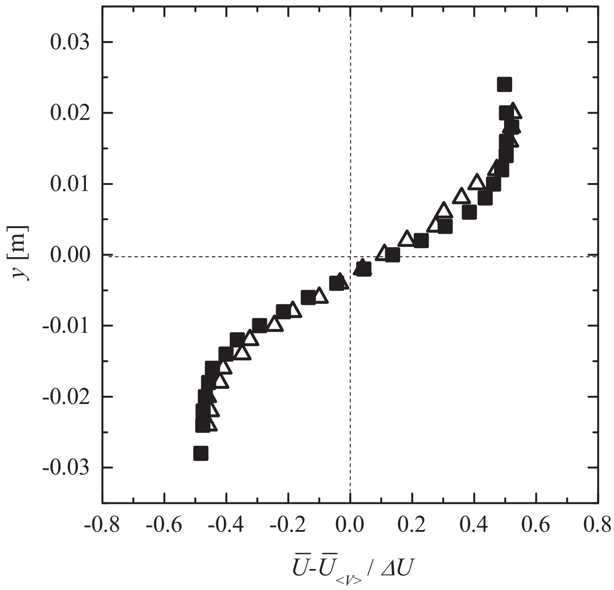

Fig. 3. Vertical distributions of the mean streamwise velocity at x = 0.32 m: ■, Run I; △, Run II.

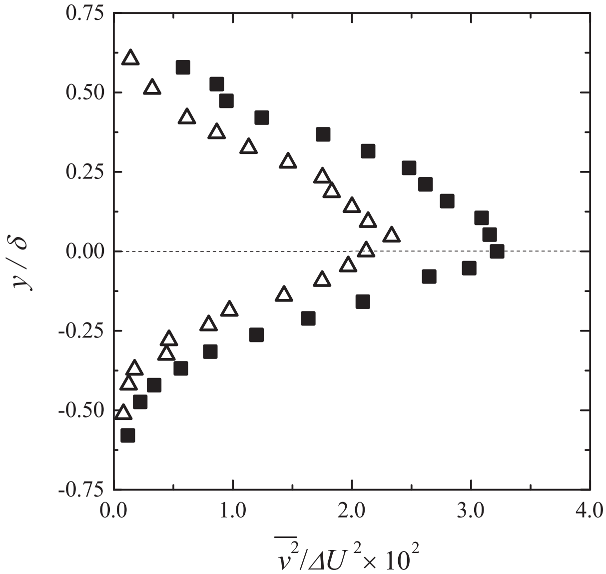

Fig. 4. Vertical distributions of the mean squared vertical velocity fluctuation at x = 0.32 m. Symbols as in Fig. 3.

Instantaneous streamwise and vertical velocities were measured by a two-component laser-Doppler velocimeter (LDV, DANTEC 55X Modular system) using a He–Ne laser (wavelength λ = 632 nm) [18]. The instantaneous concentration of species A was measured by a laser-induced fluorescence (LIF) technique