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The effects of inflow conditions on reactive–diffusive mechanism in a shear mixing layer at low Reynolds number

Yasumasa Ito [*], Kouji Nagata, Yasuhiko Sakai, Osamu Terashima

Department of Mechanical Science and Engineering, Nagoya University, Japan

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ABSTRACT

The effects of inflow conditions on the reactive–diffusive mechanism in a liquid shear mixing layer are experimentally investigated. Trip wires and a turbulence-generating grid are installed at the entrance to the test section not only to develop the mixing layer but also to promote scalar mixing and chemical reaction. 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 both the trip wires and the grid increase disturbances at small scales, and scalar mixing and chemical reaction are significantly enhanced. The grid promotes chemical production more effectively than the trip wires under the condition that the mass diffusion is at the same level between the two flows. This is attributed to the fact that the grid enhances both mass diffusion and substitution of the unreacted reactant with the reacted reactant at the fluid interfaces, whereas the chemical product is entrained by the coherent eddies and stays in the interfacial region in the mixing layer with the trip wires.

1. Introduction

Turbulent shear flow phenomena involving chemical reactions are seen in a wide variety of situations in industry and the environment [1]. When reactive fluids are introduced to a reaction field under a non-premixed condition as in mixing layers and jets, fluid mixing plays an important role in the progress of the chemical reactions because it proceeds through molecular diffusion at the interface between the reactive fluids [2,3]. More specifically, the productivity of the chemical reactions is mainly dominated by the following two factors: how complicatedly the interfaces of the reactive fluids are deformed and how the chemical product produced at the interfaces is replaced by the unreacted reactants until the reactants are perfectly mixed [2–4].

From an engineering point of view, it is often desirable to develop techniques to promote scalar mixing and chemical reaction efficiently. The use of mean fluid shear based on the velocity gradient of fluids is a conventional method for such purposes. However, mean fluid shear mostly enhances mixing at large scales, especially in low-Reynolds-number flows [2,3,5]. This indicates that it does not promote chemical reaction significantly since small-scale mixing is required for efficient chemical production. Therefore, it is important to propose methods to create small-scale disturbances in a mixing layer, preferably with a simple technique. Here, trip wires have been often used to accelerate development of mixing layer flows in past studies [6–11]. Given that the trip wires transform a laminar mixing layer into a turbulent mixing layer, this method forcibly creates small-scale disturbances. However, most of the studies have referred to only their effects on momentum and mass transfer, and the effects on chemical reaction have rarely been investigated [7,9] despite their frequent uses. In addition, a turbulence-generating grid, which is a common tool to generate isotropic homogeneous turbulence, is also expected to promote mixing and reaction in mixing layers because it also makes the flow turbulent. However, no research has focused on such effects. Inflow conditions significantly affect the flow [5,12] and it is of great interest to investigate the effects of inflow conditions on the reactive–diffusive mechanism in free turbulence. In particular, considering that the progress of chemical reaction strongly depends on flow structure, chemical productivity can vary even though the fluid mixing is promoted to the same level by such methods.

We therefore experimentally investigated scalar mixing with a chemical reaction in the following types of liquid shear mixing layers: a laminar plane mixing layer, a mixing layer with trip wires, a mixing layer with a grid, and a mixing layer using both trip wires

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[*] Corresponding author. Address: Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8603, Japan. Tel./fax: +81 52 789 4488.

E-mail address: yito@nagoya-u.jp (Y. Ito).

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and a grid. The purpose of this study is to clarify the reactive–diffusive mechanism in the mixing layer affected by the trip wires and the grid and evaluate their efficiency as passive promoters for scalar mixing and chemical reaction. The mixing level of the non-reacting chemical species were set to the same between the flows with the trip wires and the grid.

Table 1
Experimental conditions.

Run	$\overline{U}_1$ (m/s)	$\overline{U}_2$ (m/s)	ΔU (m/s)	r (–)	Trip wires	Grid
I	0.165	0.085	0.08	0.52	×	×
II	0.165	0.085	0.08	0.52	○	×
III	0.165	0.085	0.08	0.52	×	○
IV	0.165	0.085	0.08	0.52	○	○

2. Experimental

Fig. 1 shows a schematic of the experimental apparatus and measuring system. The test section is a rectangular water tunnel made of polymethylemethacrylate (PMMA), and its size is 1.5 m in length with a 0.1 m × 0.1 m cross section. The upper and lower streams are completely separated from reservoir tanks until the entrance to the test section. The tip thickness of the splitter plate in the contraction section is 5.0×10^{-4} m and the inclined angle is 2°. The initial streamwise velocities of the upper and lower streams, $\overline{U}_H$ and $\overline{U}_L$, were set to 1.65×10^{-1} m/s and 8.5×10^{-2} m/s ($r = \overline{U}_L/\overline{U}_H = 0.52, \Delta U = \overline{U}_H - \overline{U}_L = 8.0 \times 10^{-2}$ m/s), respectively. The Reynolds number based on the mean velocity at the center of the mixing layer, $\overline{U}_{\langle V \rangle}(= (\overline{U}_H + \overline{U}_L)/2)$, and the boundary layer thickness, δ_V, at $x = 0.32$ m is about 5×10^3.

The flow condition is listed in Table 1. The experiments were carried out in the following four types of non-reacting and reacting flows. The first type (Run I) is a laminar plane mixing layer in which neither trip wires nor a turbulence-generating grid is installed. The second type (Run II) is a mixing layer with trip wires. Stainless wires were installed on both the high- and low-speed sides of the splitter plate. The wire diameter, d_w, was 1.2×10^{-3} m, and the wires were placed at $x = -2.0 \times 10^{-2}$ m, -4.0×10^{-2} m, and -6.0×10^{-2} m. The third type (Run III) is a mixing layer with a turbulence-generating grid. The grid had a round-rod, square-mesh, single-biplane construction. The mesh size, M, and diameter of the rod, d, were 2.0×10^{-2} m and 3.0×10^{-3} m, respectively. The grid was installed at the entrance to the test section ($x = 0$). The configurations of the trip wires and the grid were determined to make the vertical gradient of the non-reacting species A the same in the central area of the mixing layers at $x = 0.32$ m so that we can clearly see the effects of flow structure on the chemical reaction at the same level of mixing. The fourth flow (Run IV) is a mixing layer with both trip wires and a turbulence-generating grid. The configurations of the wires and the grid are the same as those in Runs II and III.

The combinations of chemical species A and B are listed in Table 2. For a non-reacting flow, filtered tap water without any chemical species was used as species A in the lower stream. Sodium fluorescein in the form of uranine ($C_{20}H_{10}Na_2O_5$) was premixed at a concentration, C_0, of 5.0×10^{-5} mol/l, as species B in the upper stream. The concentration of species B was measured by a laser-induced fluorescence (LIF) technique using a linear relationship between the fluorescence intensity and the concentration [2,3,5,14]. The concentration of species A, C_A, is calculated by

$$C_A/C_0 = 1 - C_B/C_0. \tag{1}$$

For a reacting flow, acetic acid (CH_3COOH) and ammonium hydroxide (NH_4OH) were used as species A and B, respectively. They were premixed at the same concentration, C_0^*, of 1.0×10^{-2} mol/m^3 in the lower and upper streams, respectively. The neutralization between the weak acid and base is expressed as an irreversible rapid reaction:

$$CH_3COOH + NH_4OH \rightarrow CH_3COONH_4 + H_2O.$$

The uranine was also premixed into both streams at a concentration of 5.0×10^{-5} mol/l to measure the concentration of species A, C_A, by the LIF technique using the dependence of fluorescence intensity on the pH of the solution [2,3,14]. This technique is similar to the technique applied in Mueschke et al.'s work [15] but weak base and acid solutions were used in the present study to measure the concentration of the reacted species in the measurement volume. The differences in molecular diffusivity, density, viscosity, and reaction rate constant between the reacting and non-reacting flows were neglected because the concentrations of reacting species were extremely low.

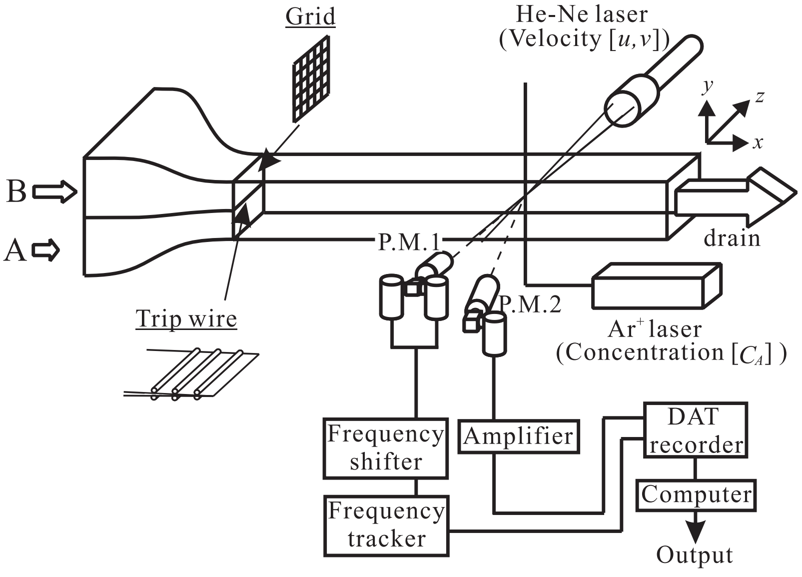

Fig. 1. Schematic of the experimental apparatus.