Concentration measurement in a planar liquid jet with a chemical reaction by using the improved concentration measurement system based on the light absorption spectrometric method

Takahiro NAITO*, Tomoaki WATANABE**, Yasuhiko SAKAI*, Kouji NAGATA* and Yasumasa ITO*
* Department of Mechanical Science and Engineering, Nagoya University
  Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan
  E-mail: naitou.takahiro@b.mbox.nagoya-u.ac.jp
** Research Fellow of Japan Society for the Promotion of Science
  Kojimachi business center, 5-3-1 Kojimachi, Chiyoda-ku, Tokyo 102-0083, Japan

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Abstract
We improve a spatial resolution of concentration measurement system based on the light absorption spectrometric method, which is used to measure instantaneous concentrations of multiple absorptive species. Light-emitting diodes (LEDs), which have a higher light intensity than a halogen lamp used in the former concentration measurement system, are used as light sources of the new concentration measurement system. We also develop a new optical fiber probe with a higher spatial resolution than the former one. The diameter of the optical fiber bundle and the length of the sampling volume of the new optical fiber probe are 0.1 mm and 0.5 mm, respectively. The sampling volume of the new optical fiber probe is 35 times smaller than that of the former one. In a turbulent planar liquid jet with a second-order chemical reaction $A + B \rightarrow R$, concentrations of all reactive species are measured by using the new concentration measurement system, and we validate the new concentration measurement system by comparing the measurement results obtained by the new system with those obtained by the former system. The results show that the mean concentrations of reactive species measured by the new system are consistent with those measured by the former system. The power spectra of concentration fluctuations of reactive species show that the new system is able to measure the concentration fluctuations up to higher frequency ranges than the former system.

Key words: Turbulent flow, Jet, Mixing, Chemical reaction, Concentration measurement

1. Introduction
Turbulent diffusion with chemical reactions is seen in various engineering fields. For example, we are concerned about predictions of pollution emission and efficiency of chemical reactors. Therefore, it is important to elucidate the mechanism of diffusion and reactions of chemical species in turbulent flows. Mixing in turbulent flows depends on the Schmidt number. The Schmidt number is defined as $S_c = \nu / D$, where $\nu$ and $D$ are the kinematic viscosity and the molecular diffusivity, respectively. Because of high Schmidt number, the smallest scale of concentration fluctuation, the Batchelor scale, in a liquid flow is smaller than that in a gaseous flow. Therefore, a higher spatiotemporal resolution is required to measure concentrations of diffusive species in a liquid flow.

In reacting liquid flows, measurements of instantaneous concentrations of reactive species have been carried out in a grid turbulence (Bennani, et al., 1985; Komori, et al., 1993 and 1994), a planar jet (Kubo, et al., 2009; Watanabe, et al., 2012 and 2013), and a confined jet (Chorny and Zhdanov, 2010 and 2012; Zhdanov and Chorny, 2011). Komori et al. (1993 and 1994) used an electrode-conductivity technique and a laser induced fluorescence (LIF) method for measuring concentrations of reactive species in a grid turbulence. Chorny and Zhdanov (2010 and 2012) used a two-color planar-LIF method for measuring concentrations of reactive species in a confined jet. These measuring methods have been used for...
measurements in reacting flows with a neutralization reaction, which is an infinitely fast reaction. Because a chemical reaction rate has a great influence on turbulent mixing of reactive species, it is valuable to measure concentrations in several reacting flows with different reaction rate constants in investigating the effect of turbulent mixing on chemical reactions. Komori et al. (1994) used the electrode-conductivity technique and LIF to investigate a moderately fast reaction. Kubo et al. (2009) and Watanabe et al. (2012 and 2013) used an optical fiber probe based on the light absorption spectrometric method for measuring concentrations of reacting species in a planar jet with a moderately fast reaction. However, the spatial resolutions of the measuring method used by these studies are much larger than the Batchelor scale. Thus, the concentration measurement system with a high spatiotemporal resolution is required to be developed for investigating reacting flows with a moderately fast reaction.

The purpose of this study is to develop a concentration measurement system for investigating turbulent liquid flows with a moderately fast reaction. We improve a spatial resolution of the concentration measurement system based on the light absorption spectrometric method used by Kubo et al. (2009) and Watanabe et al. (2012 and 2013). This concentration measurement system was originally developed by Nakamura et al. (1987). The new system is applied to a turbulent planar liquid jet with a moderately fast reaction, and is validated by comparing the concentration statistics between the experiments using the new and former concentration measurement systems (Kubo, et al., 2009; Watanabe, et al., 2012 and 2013).

2. Experiments

2.1. Chemical reaction

The chemical reaction investigated in this study is given by

\[ A + B \rightarrow R. \]  

Here, reactant A is 1-naphthol, and reactant B is diazotized sulfanilic acid. The water solutions of these reactants are transparent. Product R is the red monoazo dyestuff. The reaction rate constant for this chemical reaction is \( k = 12,000 \text{ m}^3/(\text{mol-s}) \) (Bourne, et al. 1985).

Figure 1 shows a snapshot of a planar liquid jet investigated in this study. The reactants A and B are premixed into the jet flow and the ambient flow, respectively. The blue dyestuff C (Acid Blue 9) is also premixed into the jet flow. The species C is independent of the above chemical reaction given by Eq. (1). The product R and the non-reactive species C have light absorption characteristics. Therefore, the instantaneous concentrations of these two species can be simultaneously measured by the light absorption spectrometric method, which is described in Sec. 2.3.

2.2. Experimental apparatus and conditions

Figure 2 shows the schematic of the experimental apparatus. The jet flow and the ambient flow are supplied to the test section through the head tanks. The fluid overflows from the end of the test section. The detail of the test section are shown in Fig. 2 (b). The shape of the cross section of the test section is rectangular with a width of 160 mm and a spanwise length of 40 mm, and the height of the test section is 300 mm. The jet flow is ejected into the ambient flow.
through a rectangular slit with a width of \( d = 2 \) mm and a spanwise length of \( l_S = 40 \) mm (the aspect ratio \( l_S/d = 20 \)). The mean bulk velocity of the jet flow at the jet exit is \( U_J = 1.29 \) m/s, and the mean bulk velocity of the ambient flow is \( U_A = 0.061 \) m/s. The Reynolds number is \( Re = (U_J - U_A)d/\nu = 2,200 \). The streamwise velocity was measured close to the jet exit \((x/d = 0.25)\) using the I-type hot-film probe (TSI 1210-20W). Figure 3 shows the lateral profiles of the mean streamwise velocity and the rms value of streamwise velocity fluctuation at \( x/d = 0.25 \). These profiles are close to those observed in the channel flow (Abe, et al., 2001) The initial concentrations of reactants A and B are \( A_0 = 0.4 \) mol/m\(^3\) and \( B_0 = 0.2 \) mol/m\(^3\), respectively. The initial concentration of species C is \( C_0 = 0.1 \) kg/m\(^3\). The Damköhler number is \( Da = k(\Gamma_{A0} + \Gamma_{B0})d/(U_J - U_A) = 11.7 \). The origin of coordinates is located at the center of the jet exit as shown in Fig. 2 (b). The streamwise, cross-streamwise, and spanwise directions are represented by \( x, y, \) and \( z \), respectively. Further details of the experimental setup can be referred to Watanabe et al. (2012).

2.3. Concentration measurement method

The instantaneous concentrations of light absorptive species R and C are measured by the light absorption spectrometric method (Lee and Brodley, 1964; Nakamura, et al., 1987). The light absorption spectrometric method is briefly described below. Here, as shown in Fig. 4, the light of wavelength \( \lambda \) passing a solution containing an absorptive species \( \alpha \) is considered. \( \Gamma_{\alpha} \) is the instantaneous concentration of the absorptive species \( \alpha \). We define \( P(\lambda) \) and \( k_\alpha(\lambda) \) as follows:

\[
P(\lambda) = -\ln \frac{I_0(\lambda)}{I(\lambda)}, \quad k_\alpha(\lambda) = \beta_\alpha(\lambda)l,
\]

where \( I_0(\lambda) \) is the intensity of incident light into the sampling volume, \( I(\lambda) \) is the intensity of transmitted light, \( l \) is the length of sampling volume, and \( \beta_\alpha \) is the function of \( \lambda \) which is dependent on the light absorption characteristics of absorptive species \( \alpha \). Using the Beer’s absorption law, we can relate \( P(\lambda) \) and \( k_\alpha(\lambda) \) by

\[
P(\lambda) = k_\alpha(\lambda)\Gamma_\alpha.
\]
For a solution of multiple absorptive species, \( P(\lambda) \) is equal to the sum of each \( P(\lambda) \) for the solution of single absorptive species. Therefore, for the solution of species R and C, \( P(\lambda_1) \) and \( P(\lambda_2) \) can be written as follows:

\[
P(\lambda_1) = k_R(\lambda_1)I_R + k_C(\lambda_1)I_C, \quad (4)\\
P(\lambda_2) = k_R(\lambda_2)I_R + k_C(\lambda_2)I_C. \quad (5)
\]

Our concentration measurement system can measure \( P(\lambda) \) for two wavelengths \( \lambda_1 \) and \( \lambda_2 \). \( k_R(\lambda_1), k_R(\lambda_2), k_C(\lambda_1), \) and \( k_C(\lambda_2) \) are obtained by the prior calibration experiments. Hence, we can measure the instantaneous concentrations of two species from Eqs. (4) and (5) by measuring \( P_{\lambda_1} \) and \( P_{\lambda_2} \).

According to the conserved scalar theory (Bilger, et al., 1991), the instantaneous concentrations of reactants A and B can be related to the instantaneous concentrations for product R and non-reactive species C as follows:

\[
\begin{align*}
\Gamma_A &= \xi \Gamma_{A0} - \Gamma_R, \\
\Gamma_B &= (1 - \xi) \Gamma_{B0} - \Gamma_R,
\end{align*}
\]

where \( \xi \) is called the mixture fraction, which is a conserved scalar and defined as \( \xi = \Gamma_C/\Gamma_{C0} \). Thus, the instantaneous concentrations of reactants A and B can be obtained from \( \Gamma_R \) and \( \Gamma_C \) by using Eqs. (6) and (7).

From Eqs. (6) and (7), the mass conservation law is derived as follows:

\[
\frac{\Gamma_A}{\Gamma_{A0}} + \frac{\Gamma_B}{\Gamma_{B0}} + \frac{\Gamma_R}{\Gamma_{R0}} = 1, \quad (8)
\]

where \( \Gamma_{R0} \) is defined as,

\[
\Gamma_{R0} = \frac{\Gamma_{A0}\Gamma_{B0}}{\Gamma_{A0} + \Gamma_{B0}}. \quad (9)
\]

In the present experimental conditions, \( \Gamma_{R0} = 0.133 \text{mol/m}^3 \) which is calculated by substituting the initial concentrations \( (\Gamma_{A0} = 0.4 \text{mol/m}^3, \Gamma_{B0} = 0.2 \text{mol/m}^3) \) into Eq. (9).

For the second-order chemical reaction \( A + B \rightarrow R \), we can define the frozen limit, which is the limiting case of no reaction \( (Da \rightarrow 0) \), and the equilibrium limit, which is the limiting case of infinitely fast reaction \( (Da \rightarrow \infty) \). The equilibrium limit corresponds to the case that the deficient reactant A or B is consumed completely by the chemical reaction. From Eqs. (6) and (7), the instantaneous concentrations in the frozen limit, \( \Gamma^0_\alpha \) \( (\alpha = A, B, \) and R), are derived as follows:

\[
\begin{align*}
\Gamma^0_A &= \lim_{Da \rightarrow 0} \Gamma_A = \xi \Gamma_{A0}, \\
\Gamma^0_B &= \lim_{Da \rightarrow 0} \Gamma_B = (1 - \xi) \Gamma_{B0}, \\
\Gamma^0_R &= \lim_{Da \rightarrow 0} \Gamma_R = 0.
\end{align*}
\]

Likewise, the instantaneous concentrations in the equilibrium limit, \( \Gamma^{\infty}_\alpha \), are derived as follows:

\[
\begin{align*}
\Gamma^{\infty}_A &= \lim_{Da \rightarrow \infty} \Gamma_A = (\Gamma_{A0} + \Gamma_{B0})(\xi - \xi_S)H(\xi - \xi_S), \\
\Gamma^{\infty}_B &= \lim_{Da \rightarrow \infty} \Gamma_B = (\Gamma_{A0} + \Gamma_{B0})(\xi_S - \xi)H(\xi_S - \xi), \\
\Gamma^{\infty}_R &= \lim_{Da \rightarrow \infty} \Gamma_R = \begin{cases} 
\frac{\Gamma_{A0}\xi}{\Gamma_{B0}(1 - \xi)} & (\xi < \xi_S) \\
\frac{\Gamma_{A0}\xi_S}{\Gamma_{B0}(1 - \xi_S)} & (\xi \geq \xi_S)
\end{cases}.
\end{align*}
\]
Here, \( H(z) = 0 \) for \( z < 0 \) or \( H(z) = 1 \) for \( z \geq 0 \). \( \xi_S \) is the stoichiometric value of the mixture fraction and is given by \( \xi_S = \Gamma_{B_0}/(\Gamma_{A_0} + \Gamma_{B_0}) = 0.333 \). The concentration statistics for the frozen limit and the equilibrium limit are compared with the measurement results of concentration of reactive species for the moderately fast reaction \( (Da = 11.7) \). \( \Gamma_{A_0}^{A} \) and \( \Gamma_{B_0}^{B} \) \( (\Gamma_{A_0}^{A} \) and \( \Gamma_{B_0}^{B} \) ) are the higher and lower bounds for \( \Gamma_{A} \) \( \Gamma_{B} \). We have confirmed that this relationship is always satisfied by the measured instantaneous concentrations. This indicates that the experiments were properly conducted.

3. Measurement System

3.1. Concentration measurement system

Here, we describe the concentration measurement system based on the light absorption spectrometric method, which is developed in this study. Light-emitting diodes (LEDs), which have a higher light intensity than a halogen lamp used in the former system (Sakai, et al., 1997; Kubo, et al., 2009; Watanabe, et al., 2012 and 2013), are used as light sources of the new system. Figure 5 shows the schematic of the new system. The lights emitted by two different LEDs are collected by the optical collector. The collected light is led to the sampling volume at the tip of the optical fiber probe, detail of which is described in Sec. 3.2. As shown in Eq. (3), the light passing the sampling volume decays depending on the light absorptive characteristics and the concentrations of absorptive species in the sampling volume. The light passing the sampling volume is separated into two monochromatic lights by the monochromator. The wavelengths of two monochromatic lights are the same as those at which each LED has a peak value. The light intensities of separated lights are transformed into voltage signals by the photomultiplier, and are processed by the A/D converter and the personal computer.

The concentration measurement system is designed for the concentration measurement of absorptive species R and
C. Therefore, the light absorptive characteristics of these two species are important for the concentration measurement. Figure 6 shows the light absorption spectra for species R and C. The light absorption spectra for species R and C have a peak value at \( \lambda = 515 \text{ nm} \) and \( \lambda = 628 \text{ nm} \), respectively. Because the light absorption spectra for species R and C have a peak value at different wavelengths, the light absorption spectrometric method is suitable for measuring the concentrations of species R and C. The wavelengths used in the light absorption spectrometric method described in Sec. 2.3 should be chosen from the wavelength around 515 nm and 628 nm. In this study, green and red LEDs which have the maximum light intensity at \( \lambda = 525 \text{ nm} \) (green) and \( \lambda = 625 \text{ nm} \) (red), respectively, are used as the light sources. The output powers of LEDs are 120 mW. Note that the halogen lamp produces white light, whose power spectrum is almost flat for all wavelengths. In contrast, the light emitted from the LEDs exhibits a power spectrum with a large peak at a particular wavelength. Therefore, although the total powers of LEDs are lower than the halogen lamp, at \( \lambda = 525 \text{ nm} \) and \( \lambda = 625 \text{ nm} \), the light intensities of LEDs are higher than those of halogen lamp.

3.2. Optical fiber probe

Figure 7 shows the optical fiber probe used in the former system (Sakai, et al., 1997) used by Kubo et al. (2009) and Watanabe et al. (2012 and 2013). The diameter of the optical fiber bundle and the length of the sampling volume of the optical fiber probe used in the former system are 0.5 mm and 0.7 mm, respectively, and its sampling volume is \( V_{FP} = 0.14 \text{ mm}^3 \). Here, the shape of the sampling volume is considered as a circular cylinder. In order to develop the concentration measurement system which can measure concentration fluctuations at smaller scales than the former one, we develop the new optical fiber probe whose sampling volume is much smaller than the former one. Figure 8 shows the new optical fiber probe developed in this study. The shape of the new probe is different from the former one. The shape of the new probe is designed to be easily combined with another probe, such as a hot-film probe, for simultaneous measurements of velocities and concentrations. The diameter of the optical fiber bundle and the length of the sampling volume of the new probe are 0.1 mm and 0.5 mm, respectively. The sampling volume of this probe is \( V_{NP} = 0.0039 \text{ mm}^3 \), which is 35 times smaller than that of the former one. When the new probe is used instead of the former one, the amount of the light passing through the optical fiber decreases because of the small diameter of optical fiber bundle used in the new probe. However, in the new system, the decrement of the amount of the light is compensated by using the LEDs, which have a higher light...
We measure concentrations of product R and non-reactive species C in the reactive planar jet using the new system. Figure 10 shows the lateral profiles of the mean concentrations of product R, \( \langle R \rangle \), and non-reactive species C, \( \langle C \rangle \), at \( x/d = 20 \). To validate the new system, the mean concentrations obtained by the new system are compared with those obtained by the former system in Fig. 10. \( \langle R \rangle \) and \( \langle C \rangle \) are normalized by \( R_0 \) and \( C_0 \), respectively, and \( y \) is normalized by the slit width of the nozzle \( d \). The lateral profiles of \( \langle R \rangle/R_0 \) and \( \langle C \rangle/C_0 \) measured by the new system are almost consistent with those measured by the former system. Thus, the mean concentration is accurately measured by the new system. The product R is often produced in the interfacial region between the two reactants. This region is related to the interfacial region between the jet and the ambient flow, and exists away from the jet centerline. Therefore, \( \langle R \rangle \) is large intensity than the halogen lamp used in the former system.

To estimate the noise level of concentration measurement, the concentration of species C is measured in a static liquid solution of species C, whose concentration is 0.08 kg/m³. Because the concentration of species C is constant in the solution, the concentration fluctuation measured by the concentration measurement system can be considered as the noise of concentration measurement. So, here we estimate the Noise / Signal \( (N/S) \) ratio from \( N/S = \gamma C^2/\langle C \rangle \) for the static liquid solution of species C, where \( \gamma C \) is the rms value of concentration fluctuation of species C and \( \langle C \rangle \) is the mean concentration of species C. Here, \( \langle \cdot \rangle \) is the time averaged value. \( N/S \) of the new concentration measurement system and the former system are obtained as follows:

\[
N/S \approx 0.70\% \quad \text{(new system),} \quad N/S \approx 0.25\% \quad \text{(former system).} \tag{12}
\]

It is found that \( N/S \) of the new system is larger than that of the former system. Because the concentration fluctuation measured in the static solution is related to the random fluctuation in the light intensity of the light source, we can consider that the different light sources cause the difference in \( N/S \). Although the noise of the new system is larger than that of the former system, it is smaller than 1% of signal. Therefore, the noise of the new system is expected not to affect the concentration measurement.

The new system is used for the concentration measurement in the planar liquid jet with the chemical reaction. The optical fiber probe is inserted in the test section as shown in Fig. 2 (b). It is important to compare the spatial resolution of the measurement with the characteristic length scales in the planar jet. Figure 9 shows the Taylor microscale \( \lambda \), the Kolmogorov scale \( \eta_K \), and the Batchelor scale \( \eta_B \) on the jet centerline (Watanabe et al., 2012). We can consider \( V_{FP}^{1/3} \) and \( V_{NP}^{1/3} \) as the length scale corresponding to the spatial resolution of the optical fiber probe. \( V_{FP}^{1/3} \) and \( V_{NP}^{1/3} \) are also shown in Fig. 9. It is found that \( V_{NP}^{1/3} \) lies between the Kolmogorov scale and the Batchelor scale, whereas \( V_{FP}^{1/3} \) lies just above the Kolmogorov scale. Thus, it is thought that the new probe can measure the concentration fluctuations of the order of the Kolmogorov scale more accurately than the former one.

4. Result

4.1. Concentrations of product R and non-reactive species C

We measure concentrations of product R and non-reactive species C in the reactive planar jet using the new system. Figure 10 shows the lateral profiles of the mean concentrations of product R, \( \langle R \rangle \), and non-reactive species C, \( \langle C \rangle \), at \( x/d = 20 \). To validate the new system, the mean concentrations obtained by the new system are compared with those obtained by the former system in Fig. 10. \( \langle R \rangle \) and \( \langle C \rangle \) are normalized by \( R_0 \) and \( C_0 \), respectively, and \( y \) is normalized by the slit width of the nozzle \( d \). The lateral profiles of \( \langle R \rangle/R_0 \) and \( \langle C \rangle/C_0 \) measured by the new system are almost consistent with those measured by the former system. Thus, the mean concentration is accurately measured by the new system. The product R is often produced in the interfacial region between the two reactants. This region is related to the interfacial region between the jet and the ambient flow, and exists away from the jet centerline. Therefore, \( \langle R \rangle \) is large
Fig. 10 The lateral profiles of the normalized mean concentrations of product R, \( \langle \Gamma_R \rangle / \Gamma_{R0} \), and non-reactive species C, \( \langle \Gamma_C \rangle / \Gamma_{C0} \), obtained by the new system (●) and the former system (▲) at \( x/d = 20 \).

Fig. 11 The lateral profiles of the normalized rms values of concentration fluctuations of product R, \( \gamma_R'/\Gamma_{R0} \), and non-reactive species C, \( \gamma_C'/\Gamma_{C0} \), obtained by the new system (●) and the former system (▲) at \( x/d = 20 \).

Fig. 12 The normalized power spectra of concentration fluctuations of product R, \( E_R(f) / \gamma_R'^2 \), and non-reactive species C, \( E_C(f) / \gamma_C'^2 \), obtained by the new system (black lines) and the former system (orange lines) at \( x/d = 20 \) and \( y/b_y = 1.0 \). The wavenumber \( 2\pi f / \langle U \rangle \) is normalized by the Kolmogorov wavenumber \( 1/\eta_K \).
even away from the jet centerline unlike \( \langle I_C \rangle \). The jet flow entrains the ambient flow, which does not contain the reactant A and the product R with the jet development. The ambient flow is entrained through the interface of the two flows, which appears in the outer region of the jet. Therefore, \( \langle I_R \rangle \) near the edge of the jet decreases in the outer and downstream direction. Figure 11 shows the lateral profiles of the rms values of concentration fluctuations of product R, \( \gamma_R' \) and species C, \( \gamma_C' \), at \( x/d = 20 \). \( \gamma_R' \) and \( \gamma_C' \) are normalized by \( I_{R0} \) and \( I_{C0} \), respectively. \( \gamma_R' / I_{R0} \) and \( \gamma_C' / I_{C0} \) measured by the new system are larger than those measured by the former system. However, the tendencies of the lateral profiles of \( \gamma_R' \) and \( \gamma_C' \) are similar between the new and former systems.

Figure 12 shows the power spectra of concentration fluctuations of product R and non-reactive species C at \( x/d = 20 \) and \( y/b_2 = 1.0 \). The spectra of product R and species C are normalized by the rms values of concentration fluctuations of product R and species C, respectively, and the wavenumber \( 2\pi f / \langle U \rangle \) is normalized by the Kolmogorov wavenumber \( 1/\eta_K \). Here, \( \langle U \rangle \) is the streamwise mean velocity measured by the I-type hot-film probe. When concentrations are measured by the former system, the power spectrum of product R, \( E_R \), exhibits the power laws with an exponent close to \( -5/3 \) for \( 2\pi f \eta_K / \langle U \rangle < 0.6 \), and the power spectrum damps around \( 2\pi f \eta_K / \langle U \rangle = 0.6 \). On the other hand, the frequency range where \( E_R \) obtained by the new system exhibits the power laws extends to the higher frequencies than \( 2\pi f \eta_K / \langle U \rangle = 0.6 \). Thus, the concentration fluctuations up to \( 2\pi f \eta_K / \langle U \rangle = 1 \) \((f \approx 800 \text{ Hz})\) measured by the new system are considered more accurate than those measured by the former system.

4.2. Concentrations of reactant A and B

We investigate the statistical properties of concentrations of reactants A and B. Figure 13 shows the lateral profiles of the mean concentrations of reactants A, \( \langle I_A \rangle \), and B, \( \langle I_B \rangle \), at \( x/d = 20 \) and \( x/d = 40 \). \( \langle I_A \rangle \) and \( \langle I_B \rangle \) are normalized by \( I_{A0} \) and \( I_{B0} \), respectively, and \( y/b_2 \) is normalized by the jet half width \( b_2 \) based on \( \langle I_C \rangle \). Figure 13 also shows the lateral profiles of the mean concentrations in the frozen limit and the equilibrium limit. \( \langle I_A \rangle \) and \( \langle I_B \rangle \) are smaller than those in the frozen limit because of consumption by the chemical reaction. The differences in \( \langle I_A \rangle \) and \( \langle I_B \rangle \) between the frozen limit and the equilibrium limit are larger than those between the frozen limit and the moderately fast reaction case \((D_a = 11.7)\). The mean concentrations of reactants for \( D_a = 11.7 \) at \( x/d = 40 \) are more far from the frozen limit values and closer to the equilibrium limit values than those at \( x/d = 20 \) because the chemical reaction progresses toward the downstream region.

Figure 14 shows the lateral profiles of the rms values of concentration fluctuations of reactants A, \( \gamma_A' \) and B, \( \gamma_B' \), at \( x/d = 20 \) and \( x/d = 40 \). \( \gamma_A' \) and \( \gamma_B' \) are normalized by \( I_{A0} \) and \( I_{B0} \), respectively. Figure 14 also shows the lateral profiles of the rms values of concentration fluctuations in the frozen limit and the equilibrium limit. \( \gamma_A' \) in the frozen limit has peaks at \( |y/b_2| \approx 1.0 \), whereas the profiles of \( \gamma_A' \) with the chemical reaction (the moderately fast reaction case and the equilibrium limit) have no clear peaks. The values of \( \gamma_A' \) in the equilibrium limit is smaller in the outer region \((|y/b_2| \geq 0.7 \text{ at } x/d = 20 \text{ and } |y/b_2| \geq 0.5 \text{ at } x/d = 40) \) and larger in the inner region \(|y/b_2| < 0.7 \text{ at } x/d = 20 \text{ and } |y/b_2| < 0.5 \text{ at } x/d = 40 \) than those for \( D_a = 11.7 \). On the other hand, the profiles of \( \gamma_B' \) with the chemical reaction have larger peaks at \( |y/b_2| \approx 1.0 \) than those in the frozen limit. The values of \( \gamma_B' \) in the equilibrium limit are larger in the outer region \(|y/b_2| \geq 0.7 \text{ at } x/d = 20 \text{ and } |y/b_2| \geq 0.5 \text{ at } x/d = 40) \) and smaller in the inner region \(|y/b_2| < 0.7 \text{ at } x/d = 20 \text{ and } |y/b_2| < 0.5 \text{ at } x/d = 40 \) than those for \( D_a = 11.7 \). Thus, it is found that the chemical reaction affect the concentration fluctuation around \( |y/b_2| \approx 1.0 \) to decrease the concentration fluctuation of reactant A, which is contained in the jet flow, and to increase that of reactant B, which is contained in the ambient flow. From Fig. 14, it is found that \( \gamma_A' \) for \( D_a = 11.7 \) decreases from \( x/d = 20 \) to \( x/d = 40 \), whereas \( \gamma_B' \) for \( D_a = 11.7 \) is almost independent of the streamwise location. In the nonreactive case, \( \gamma_A' \) decreases in the streamwise direction. For \( D_a = 11.7 \), the chemical reaction also decreases \( \gamma_A' \). In contrast, \( \gamma_B' \) is increased by the chemical reaction although in the nonreactive case \( \gamma_B' / I_{B0} \) is equal to \( \gamma_A' / I_{A0} \), which decreases in the streamwise direction. The opposite effects of the reaction on \( \gamma_A' \) and \( \gamma_B' \) cause the difference in the streamwise evolution between \( \gamma_A' \) and \( \gamma_B' \).

Figure 15 shows the normalized power spectrum of concentration fluctuation of reactant A, \( E_A(f)/\gamma_A'^2 \), at \( x/d = 20 \) and \( y/b_2 = 1.0 \). From Fig. 15, it is found that \( E_A(f)/\gamma_A'^2 \) for \( D_a = 11.7 \) is slightly smaller in the low-frequency range \((f < 50 \text{ Hz})\) and slightly larger in the high-frequency range \((f > 100 \text{ Hz})\) than those in the frozen limit. The changes in the spectrum in the equilibrium limit are more noticeable than those for \( D_a = 11.7 \). It is thought that because of the chemical reaction, the contribution of large-scale fluctuations to the rms values of the concentration fluctuation decreases, and that of small-scale fluctuations increases.
Fig. 13 The lateral profiles of the normalized mean concentrations of reactant A, $\langle A \rangle / \Gamma_{A0}$, and reactant B, $\langle B \rangle / \Gamma_{B0}$, obtained by the new system (●) for $Da = 11.7$ at $x/d = 20$ and $x/d = 40$. The lateral profiles of the mean concentrations in the frozen limit (blue dashed lines) and the equilibrium limit (red solid lines) are shown together.

Fig. 14 The lateral profiles of the normalized rms values of concentration fluctuation of reactant A, $\gamma_A' / \Gamma_{A0}$, and reactant B, $\gamma_B' / \Gamma_{B0}$, obtained by the new system (●) for $Da = 11.7$ at $x/d = 20$ and $x/d = 40$. The lateral profiles of the rms values of concentration fluctuations in the frozen limit (blue dashed lines) and the equilibrium limit (red solid lines) are shown together.
Fig. 15  The normalized power spectrum of concentration fluctuations of reactant A, $E_A(f)/\nu_A^2 f^2$, for $D_{Ae} = 11.7$, obtained by the new system at $x/d = 20$ and $y/b_j = 1.0$ (black line). The power spectra of concentration fluctuations in the frozen limit (blue dashed line) and the equilibrium limit (red line) are shown together.

5. Conclusion

We improved a spatial resolution of the concentration measurement system based on the light absorption spectrometric method. We used the LEDs, which have a higher light intensity than a halogen lamp used in the former system, as the light sources of the new system. The new optical fiber probe developed in this study has a 35 times smaller sampling volume than that used in the former system. In a turbulent planar liquid jet with a second-order chemical reaction, concentrations of light absorptive species (product R and non-reactive species C) are measured by using the new system. Then, by using the conserved scalar theory, concentrations of reactants A and B are obtained from concentrations of species R and C. We validated the new concentration measurement system by comparing the measurement results obtained by the new system with those obtained by the former system. The conclusions of this study are summarized as follows.

(1) The mean concentrations of product R and non-reactive species C measured by the new system are consistent with those measured by the former system. Thus, the mean concentration is accurately measured by the new system.

(2) The new system is able to resolve the small concentration fluctuations, which cannot be resolved by the former system. Slopes of the power spectra of product R and species C obtained by the new system suggest that concentration fluctuations up to $2\pi f \eta_k \langle U \rangle \approx 1$ ($f \approx 800$ Hz) can be accurately measured.

(3) The mean concentrations of reactants A and B with the chemical reaction are smaller than those in the frozen limit. The differences from the frozen limit increase with increasing the reaction rate.

(4) The rms values of concentration fluctuations of reactant A with the chemical reaction have no clear peaks at $|y/b_j| \approx 1.0$, whereas those in the frozen limit have peaks at $|y/b_j| \approx 1.0$. In contrast to reactant A, The rms values of concentration fluctuations of reactant B with the chemical reaction have larger peaks at $|y/b_j| \approx 1.0$ than those in the frozen limit.

(5) The power spectrum of concentration fluctuation of reactant A at $x/d = 20$ and $y/b_j = 1.0$ is smaller in the low-frequency range and larger in the high-frequency range than that in the frozen limit. Because of the chemical reaction, the contribution of large-scale fluctuations to the rms values of the concentration fluctuation decreases, and that of small-scale fluctuations increases.

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References


