

## EXPERIMENTAL INVESTIGATION OF EDDY DIFFUSIVITY IN A REACTIVE LIQUID JET

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**Abstract** A gradient diffusion model for reactive scalar is experimentally investigated in a planar liquid jet with a second-order chemical reaction  $A + B \rightarrow R$ . Reactant A is premixed into a jet flow, and reactant B is premixed into an ambient flow. Concentrations of reactive species and streamwise velocity are simultaneously measured by using an optical fiber probe based on the light absorption spectrometry and I-type hot-film anemometry. The eddy diffusivities of reactive species are calculated from the mean concentrations and the turbulent mass fluxes of reactive species. The results show that the eddy diffusivity of reactant A becomes small due to the chemical reaction. It is also found that the effects of the chemical reaction on the eddy diffusivity depend on the chemical reaction rate.

### INTRODUCTION

Reynolds-averaged approach is often used to predict turbulent flows with scalar transfer. In this approach, a turbulent model for a turbulent mass flux  $\langle u_i \gamma_\alpha \rangle$  is required to calculate averaged scalar fields, where  $\langle \rangle$  denotes an ensemble average,  $u_i$  and  $\gamma_\alpha$  are fluctuating components of instantaneous  $i$ -direction velocity,  $U_i$ , and instantaneous concentration of species  $\alpha$ ,  $\Gamma_\alpha$ . The gradient diffusion model<sup>[1]</sup> is often used to model  $\langle u_i \gamma_\alpha \rangle$ , and in the gradient diffusion model,  $\langle u_i \gamma_\alpha \rangle$  is given by

$$\langle u_i \gamma_\alpha \rangle = -D_{t\alpha} \frac{\partial \langle \Gamma_\alpha \rangle}{\partial x_i}, \quad (1)$$

where  $D_{t\alpha}$  is an eddy diffusivity of species  $\alpha$ , and is generally calculated from  $D_{t\alpha} = \nu_t / Sc_{t\alpha}$ . Here,  $\nu_t$  is a turbulent viscosity obtained from another turbulent model and  $Sc_{t\alpha}$  is a turbulent Schmidt number. In this study, we measure the eddy diffusivity in a reactive planar jet to investigate the gradient diffusion model for reactive scalars.

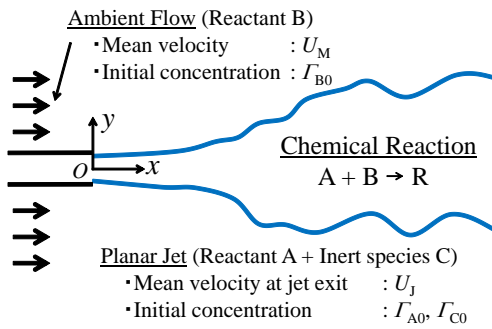
### EXPERIMENTS

Figure 1 shows the schematic diagram of planar jet with a second-order chemical reaction  $A$  (1-naphthol) +  $B$  (diazotized sulphanilic acid)  $\rightarrow R$  (monoazo dyestuff). The chemical reaction rate constant for this reaction is  $k = 12,000 \text{ m}^3/(\text{mol} \cdot \text{s})$ .<sup>[2]</sup> Reactant A is premixed into the jet flow and reactant B is premixed into the ambient flow. The jet flow also contains an inert species C (blue dyestuff), whose concentration can be considered as a conserved scalar. The initial concentration of species C is  $\Gamma_{C0} = 0.1 \text{ kg/m}^3$ . The jet is ejected through a rectangular slit with a width of  $d = 2 \text{ mm}$ . The mean velocity of jet flow at the nozzle is  $U_J = 1.29 \text{ m/s}$ , and the mean velocity of the ambient flow is  $0.073 \text{ m/s}$ . The Reynolds number is  $Re = (U_J - U_M)d/\nu = 2,200$ . Here,  $\nu$  is a kinematic viscosity. The initial concentrations of reactant A and B are  $\Gamma_{A0} = 0.4 \text{ mol/m}^3$  and  $\Gamma_{B0} = 0.2 \text{ mol/m}^3$ , respectively. Damköhler number, defined by  $Da = k(\Gamma_{A0} + \Gamma_{B0})d/(U_J - U_M)$ , is 11.8.

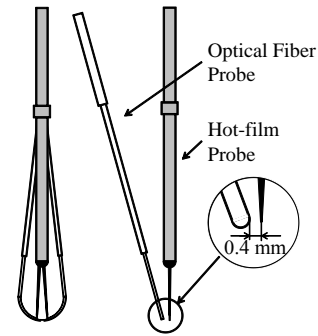
The instantaneous concentrations of product R and inert species C are measured by using an optical fiber probe based on the light absorption spectrometry. According to Bilger et. al.<sup>[3]</sup>, the instantaneous concentrations of reactant A and B can be obtained from  $\Gamma_A = \Gamma_{A0}\xi - \Gamma_R$  and  $\Gamma_B = \Gamma_{B0}(1 - \xi) - \Gamma_R$ . Here,  $\xi$  is the mixture fraction, and is defined by  $\xi = \Gamma_C/\Gamma_{C0}$ . The optical fiber probe is combined with the I-type hot-film probe as shown in Fig. 2, and these two probes are used to simultaneously measure the concentrations of reactive species and the streamwise velocity. The detail of the measurement methods can be referred to Watanabe et. al.<sup>[4]</sup>.

### RESULTS

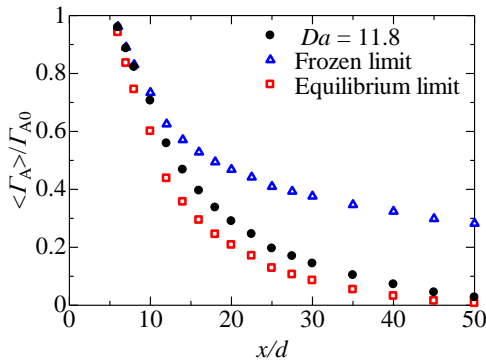
Figure 3 shows the mean concentration of reactant A,  $\langle \Gamma_A \rangle$ , on the jet centerline. The results for a frozen limit corresponding to  $k \rightarrow 0$  and an equilibrium limit corresponding to  $k \rightarrow \infty$  are also shown in Fig. 3. The frozen limit means that the chemical reaction does not occur, and the equilibrium limit means that the chemical reaction proceeds very fast. By comparison of  $\langle \Gamma_A \rangle$  for  $Da = 11.8$  with those for two limiting cases, it is found that the chemical reaction makes  $\langle \Gamma_A \rangle$  small, and  $\langle \Gamma_A \rangle$  for  $Da = 11.8$  lies between the frozen and the equilibrium limits. Figure 4 shows the eddy



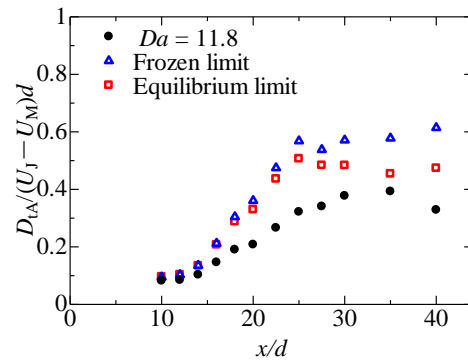
**Figure 1.** Schematic diagram of the reactive planar jet



**Figure 2.** The combined Probe



**Figure 3.** Mean concentration of reactant A on the jet centerline.



**Figure 4.** Eddy diffusivity of reactant A on the jet centerline.

diffusivity of reactant A,  $D_{tA}$ , on the jet centerline.  $D_{tA}$  for the reactive cases ( $Da = 11.8$  and the equilibrium limit) is small compared with  $D_{tA}$  for the frozen limit. The change of  $D_{tA}$  by the chemical reaction for  $Da = 11.8$  is larger than that for the equilibrium limit, and this result implies that the effects of the chemical reaction on the eddy diffusivity depend on the Damköhler number.

## CONCLUSION

In a planar liquid jet with a chemical reaction  $A + B \rightarrow R$ , concentrations of reactive species and the streamwise velocity are simultaneously measured to investigate the gradient diffusion model for reactive scalars. Reactant A is premixed into the jet flow, and reactant B is premixed into the ambient flow. The eddy diffusivity of reactant A,  $D_{tA}$ , is obtained from the mean concentration and the turbulent streamwise mass flux of reactant A. The results show that the  $D_{tA}$  becomes small due to the chemical reaction, and the effects of the chemical reaction on  $D_{tA}$  depend on the Damköhler number. It can be concluded that the effects of chemical reactions on the gradient diffusion model cannot be neglected, and should be taken into consideration through the eddy diffusivity or the turbulent Schmidt number to accurately predict the turbulent mass flux.

## ACKNOWLEDGEMENT

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## References

- [1] D. P. Combest, P. A. Ramachandran, and M. P. Dudukovic. On the gradient diffusion hypothesis and passive scalar transport in turbulent flows. *Industrial Engineering Chemistry Research* **50**: 8817–8823, 2011.
- [2] J. R. Bourne, C. Hilber, and G. Tovstiga. Kinetics of the azo coupling reactions between 1-naphthol and diazotised sulphanilic acid. *Chemical Engineering Communications* **37**: 293–314, 1985.
- [3] R. W. Bilger, L. R. Saetran, and L. V. Krishnamoorthy. Reaction in a scalar mixing layer. *Journal of Fluid Mechanics* **233**: 211–242, 1991.
- [4] T. Watanabe, Y. Sakai, K. Nagata, O. Terashima, and T. Kubo. Simultaneous measurements of reactive scalar and velocity in a planar liquid jet with a second-order chemical reaction. *Experiments in Fluids* **53**: 1369–1383, 2012.