In-silico experiments on characteristic time scale at a shear-free gas-liquid interface in fully developed turbulence

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Abstract. The purpose of this study is to model scalar transfer mechanisms in a fully developed turbulence for accurate predictions of the turbulent scalar flux across a shear-free gas-liquid interface. The concept of the surface-renewal approximation (Dankwerts, 1951) is introduced in this study to establish the predictive models for the interfacial scalar flux. Turbulent flow realizations obtained by a direct numerical simulation technique are employed to prepare details of three-dimensional information on turbulence in the region very close to the interface. Two characteristic time scales at the interface have been examined for exact prediction of the scalar transfer flux. One is the time scale which is reciprocal of the root-mean-square surface divergence, $T_\gamma = (\langle \gamma^2 \rangle)^{-1/2}$, where $\gamma$ is the surface divergence. The other time scale to be examined is $T_S = \Lambda/V$, where $\Lambda$ is the zero-correlation length of the surface divergence as the interfacial length scale, and $V$ is the root-mean-square velocity fluctuation in the streamwise direction as the interfacial velocity scale. The results of this study suggests that $T_\gamma$ is slightly unsatisfactory to correlate the turbulent scalar flux at the gas-liquid interface based on the surface-renewal approximation. It is also found that the proportionality constant appear to be 0.19, which is different with that observed in the laboratory experiments, 0.34 (Komori, Murakami, & Ueda, 1989). It is concluded that the time scale, $T_\gamma$, is considered a different kind of the time scale observed in the laboratory experiments. On the other hand, the present in-silico experiments indicate that $T_S$ predicts the turbulent scalar flux based on the surface-renewal approximation in a satisfactory manner. It is also elucidated that the proportionality constant for $T_S$ is approximately 0.36, which is very close to that found by the laboratory experiments. This fact shows that the time scale $T_S$ appears to be essentially the same as the time scale the laboratory experiments observed.

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1. Introduction

Understanding scalar transfer mechanisms at a gas-liquid interface contributes significantly to the establishment of predictive models for the turbulent scalar flux. These models are also applicable to chemical and nuclear engineering for design, management, and manipulation of industrial processes. Geophysics and ocean/marine engineering are other disciplines requiring the gas-liquid scalar transfer models for, e.g., prediction of gas and heat exchange mechanisms between the ocean and the atmosphere at an upper-ocean turbulent mixing layer (Enstad, Nagaosa & Alendal, 2006).

It is known widely that turbulence structures near the interface in water determine the turbulent scalar flux at a gas-liquid interface (hereafter we referred to as simply the “interface”). The surface-renewal approximation is expressed as (Dankwerts, 1951):

\[ K_0 = \alpha \left( \frac{D}{T} \right)^{1/2} = \alpha (Df)^{1/2}, \]

where \( K_0 \) is the scalar transfer coefficient, \( T \) is the characteristic time scale at the interface, or, reciprocal of the surface-renewal frequency \( f = 1/T \), \( D \) is the molecular diffusivity of scalar, and \( \alpha \) is the proportionality constant.

Komori, Murakami, & Ueda (1989) and Komori, Nagaosa, & Murakami (1990) showed that the surface-renewal approximation has been successful to predict the turbulent scalar flux at the interface by their laboratory experiments of measuring the hydrodynamics below the interface, and the scalar fluxes using carbon dioxide. They also revealed that turbulent vortical structures produced in the region close to a bottom boundary in an open-channel flume travel toward the interface, and interact with each other. They asserted that such interactions enhances replacement of the fluid elements between the interface and turbulent bulk, and are often referred to as surface-renewal events. The direct contributions of the surface-renewal events to enhancement of the interfacial scalar flux, nevertheless, had not been measured by their laboratory experiments because of difficulties of flow measurements in the region adjacent to the interface.

Rashidi, Hetsroni & Banerjee (1991) conducted laboratory experiments on the hydrodynamics near the interface of the turbulent open-channel. They introduced flow visualization techniques to identify turbulence structures which are responsible to turbulent scalar transfer at the interface. They also quantified turbulence statistics which are critical in modeling turbulent scalar transfer mechanisms. A predictive model for the turbulent scalar flux based on the surface-renewal approximation were proposed using the hydrodynamics at the interface they observed in their flow visualization experiments. Their experiments, however, did not measure the turbulent scalar flux directly in their experiments, and the results from the gas transfer experiments carried out by Komori, Murakami, & Ueda (1989) were used to establish their model.

Between the late 90’s to date, several researches have been conducted to investigate precise physics of turbulent scalar transfer between air and water phases based on laboratory and in-silico experiments, e.g., Pan & Banerjee (1995); Rashidi (1997); Kumar, Gupta & Banerjee (1998); Calmet & Magnaudet (2003); Turney, Smith, & Banerjee (2005); Magnaudet & Calmet (2006). Despite these continuous efforts, many aspects of the turbulent scalar transfer mechanisms have not been clarified comprehensively to reach consistent understanding on transport phenomena across the interface. One of the reasons for this is that scalar transport is governed by fluctuations of the three-dimensional velocity, vorticity and concentration in a very thin turbulent boundary layer underlying the interface. This has resulted in only very limited experimental data on turbulence near the interface.
The purpose of this study is to examine the relation between turbulent scalar transfer mechanisms and the hydrodynamics near the interface based on the surface-renewal approximation. We introduce in-silico experiments on turbulent scalar transfer problems at the shear-free gas-liquid interface of the three-dimensional open-channel flow to quantify physical mechanisms of transport phenomena at the interface. Turbulence and turbulent scalar transfer at the interface are realized by a direct numerical simulation (DNS) technique at low Reynolds numbers in the range $150 \leq Re_\tau \leq 600$, where $Re_\tau$ is the Reynolds number based on the wall shear velocity $u_\tau$, and water depth $\delta$. We evaluate the relation between the turbulent scalar flux at the interface and the hydrodynamics in the vicinity of the interface to explore optimum expression of the characteristic time scale of the surface-renewal at the interface. In addition, the predictions of the turbulent scalar flux by the proposed model are compared with those measured by the laboratory measurements (Komori, Murakami, & Ueda, 1989; Komori, Nagaosa, & Murakami, 1990).

### 2. Methodology of in-silico experiments

We consider a fully-developed turbulent flow in an open-channel flume, which is bounded by a solid wall and a flat gas-liquid interface. The domain sizes of this flow configuration are $L_x, L_y$ and $\delta$ in the streamwise ($x$), spanwise ($y$) and interface-normal ($z$) directions. The corresponding velocity components are expressed by $u, v,$ and $w$. The bottom and the interface of the open-channel are placed at $z = 0$ and $\delta$, respectively. The fluid flow considered here is periodic in $x$ and $y$ directions. The flow is driven by a well-controlled external force in the streamwise direction to maintain a constant flow rate. Fluid in this flow domain is considered incompressible, Newtonian, and isothermal with constant kinematic viscosity $\nu$, and density $\rho$. Scalar concentrations at the two vertical boundaries are kept constant, $C = C_{\text{int}}$ at the interface, and $C = C_0$ at the bottom. The scalar is transported from the interface toward turbulent bulk, because $C_{\text{int}} \geq C_0$ is assumed in this study. The effect of the buoyancy force caused by concentration difference of the scalar is ignored to avoid establishment of density stratification.

A DNS technique is used to obtain three-dimensional distributions of the fine-scale turbulence and the turbulent scalar field. The slightly modified version of the numerical code used for computing turbulent mixing at a shear-driven gas-liquid interface is adopted in this study (Enstad, Nagaosa & Alendal, 2006). All the spatial derivatives are approximated by a second-order central difference on a Cartesian staggered grid. A combination of a third-order Runge-Kutta method for nonlinear terms and a second-order Crank-Nicolson method for linear terms is used for the time integration of the governing equations. The time increment for integration of the governing equations is determined dynamically to keep the CFL number around $\sqrt{3}$.

The details of parameterization of the present in-silico experiments are given in table 1. Six numerical runs are carried out in this study by altering the Reynolds number $Re_\tau$ between 150 and 600. This Reynolds number region corresponds to about $2,300 < Re_m < 11,300$, where $Re_m$ is the Reynolds number defined by the bulk-mean velocity $U_m$ and water height $\delta$. These Reynolds numbers cover those of the laboratory experiments by Komori, Murakami, & Ueda (1989), and Komori, Nagaosa, & Murakami (1990). The Schmidt number, $Sc = \nu/D$, is assumed 1 in the all numerical runs.

### 3. Nondimensionalization of turbulent scalar flux

The scalar transfer equation is written as

$$\frac{\partial C}{\partial t} = \left\{ - \left( \frac{u}{\partial x} + \frac{v}{\partial y} + \frac{w}{\partial z} \right) + D \left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right) \right\} C. \quad (2)$$
The following equation is obtained by inserting \( C = \langle C \rangle + C' \), \( u = \langle u \rangle + u' \), \( v = v' \), and \( w = w' \), into equation 2, and taking time-space (or, ensemble) average,

\[
\frac{\partial}{\partial z} \left( -\langle w' C' \rangle + D \frac{\partial \langle C \rangle}{\partial z} \right) = 0, \tag{3}
\]

where \( \langle h \rangle \) and \( h' \) are the time-space (or, ensemble) average of \( h \), and fluctuation around \( \langle h \rangle \). Equation 3 shows that the following relation is satisfied

\[
\frac{\langle w' C' \rangle}{\text{Turbulent scalar flux}} + \frac{D \frac{\partial \langle C \rangle}{\partial z}}{\text{Viscous scalar flux}} = \frac{Q}{\text{Total scalar flux}}, \tag{4}
\]

where \( Q \) is the total scalar flux which should be constant without respect to \( z \). Equation 4 suggests that the total scalar flux can be separated into the turbulent and the viscous scalar fluxes. It is also understood that \( Q \) is equivalent to the interfacial scalar flux because of \( \langle w' C' \rangle = 0 \) at the interface.

The relation between \( Q \) and \( K_0 \) is written as

\[
Q = \langle K_0 \rangle (C_{\text{int}} - C_0). \tag{5}
\]

Inserting the Fick’s law of diffusion \( Q = D (\partial \langle C \rangle / \partial z)_{z=0} \) into equation 5, we obtain

\[
Sh = \frac{\langle K_0 \rangle \delta}{D} = \left( \frac{\partial \langle C \rangle}{\partial z} \right)_{z=0}, \tag{6}
\]

where \( Sh \) is the Sherwood number, which is a nondimensional version of the turbulent scalar flux at the interface. \( \bar{C} = C / (C_{\text{int}} - C_0) \), and \( \bar{z} = z/\delta \) are nondimensional concentration and \( z \) coordinate, respectively.

The surface-renewal approximation indicated in equation 1 is normalized as

\[
ShSc^{-1/2} = \alpha Re_T \langle T^+ \rangle^{-1/2}, \tag{7}
\]

or,

\[
\langle K_0^+ \rangle Sc^{-1/2} = \alpha \langle T^+ \rangle^{-1/2}, \tag{8}
\]

where \( T^+ = Tu^2_0 / \nu \) the characteristic time scale, and \( K_0^+ = K_0 / u_T = ShSc^{-1}Re_T^{-1} \) the nondimensional scalar transfer coefficient, respectively.

It should be stressed here that equations 7, or, 8 are convenient to compare the interfacial scalar fluxes of different Schmidt number experiments. While the present in-silico experiments assume \( Sc = 1 \), \( Sc \approx 600 \) was used in the laboratory experiments by Komori, Murakami, & Ueda (1989), and Komori, Nagaosa, & Murakami (1990), since carbon dioxide \( (D \approx 1.7 \times 10^{-9} \text{m}^2 \cdot \text{s}^{-1} \) at 101.3 kPa, and 298 K) was used to be transferred into turbulent water across the interface.
4. Results

4.1. Fully-developed turbulence statistics of scalar field

Figures 1(a) and 1(b) show the interface-normal profiles of mean concentration of scalar, and turbulent and total scalar fluxes, respectively, for the Reynolds numbers of $Re_\tau = 150, 400$, and $600$. In Figure 1(b), equation 4 are normalized by $C_\tau (\equiv Q/\bar{u}_\tau)$, $u_\tau$, and $\delta$, hence, the total scalar flux are scaled to be unity,

$$
\frac{1}{Re_\tau Sc} \frac{\partial (C^+)}{\partial z} = 1
$$

Figures 1(a) shows that the turbulent scalar flux at the interface increases with increasing the Reynolds number. Later in this report, the effect of the Reynolds number on the interfacial scalar flux is assessed by the results of the present in-silico experiments of turbulent scalar transfer. It is found in figure 1(b) that the scalar concentration field realized by the present study satisfies equation 4 in very satisfactory manner, showing that the present in-silico experiments provides very accurate realizations of the scalar concentration field in the turbulent open-channel, including the region very close to the interface.

4.2. Effect of the Reynolds number on the interfacial scalar flux

Figure 2 shows the effect of the Reynolds number $Re_m$ on the turbulent scalar flux obtained by the present study. The results from the laboratory experiments by Komori, Murakami, & Ueda (1989) are also plotted in the same figure. This comparison exhibits that the turbulent scalar fluxes predicted by the in-silico experiments are acceptable within possible margin of errors in the laboratory experiments. In-depth observation of figure 2 also suggests that the in-silico experiments underestimate the turbulent scalar flux slightly at about $Re_m > 7,000$ ($Re_\tau > 400$), whereas accuracy of the present predictions are satisfactory enough in the Reynolds number region $Re_m < 7,000$ ($Re_\tau < 400$). The reasons of the slight discrepancy between the numerical and laboratory measurements could be attributed to the effect of fine-scale fluctuations at the interface which are observed in the laboratory experiments but ignored in the present in-silico experiments. Indeed, the effect of both the Weber and Froude numbers should be involved in the present numerical study for more accurate predictions of the turbulent scalar flux (Tamburrino & Gulliver, 2002).

Despite the underestimation of the interfacial scalar flux at $Re_m > 7,000$, the present in-silico experiments provide practically acceptable predictions. This substantial agreement between the
results from both the in-silico and the laboratory experiments implies that the present prediction provide numerous information on three-dimensional velocity and scalar fluctuations including in the region very close to the interface. The implementation of the in-silico experiments is advantageous since laboratory experiments have been limited to measure details of three-dimensional turbulence structures in fluids, especially in the region below the interface.

4.3. Relation between the surface divergence and the turbulent scalar flux

Many researchers have tried to identify the turbulence structures responsible to the enhancement of the turbulent scalar transfer, since finding such structures is important to establish predictive models for obtaining exact turbulent scalar fluxes. Several references have pointed out two flow signatures, upwelling, and downdrafting of fluid at the interface, play an important role in determining turbulent scalar transfer mechanisms (Pan & Banerjee (1995); Rashidi (1997); Kumar, Gupta & Banerjee (1998); Handler, Saylor, Leighton, & Rovelstad (1999); Nagaosa & Handler (2003)). It is evident that predictions of the turbulent scalar flux will be successful if the effect of such interactions of turbulence with the interface is incorporated exactly into the framework of turbulent scalar transfer modeling.

This study introduces the surface divergence $\gamma$, defined by

$$\gamma = \left( \frac{\partial u'}{\partial x} + \frac{\partial v'}{\partial y} \right)_{z=\delta} = - \left( \frac{\partial w'}{\partial z} \right)_{z=\delta},$$

(10)

to establish an exact predictive model, as introduced by several studies (McCready, Vassiliadou & Hanratty, 1986; Tamburriano & Gulliver, 2002; McKenna & McGills, 2004; Turney, Smith, & Banerjee, 2005).

Definition of $\gamma$ shown in equation 10 indicates that positive surface divergence is produced by a fluid motion which rises toward the interface ($w' > 0$). The thickness of the turbulent boundary layer next to the interface will be reduced by the impinging motions, so that scalar transfer is intensified there. It is also understood from the definition of $\gamma$ that negative surface divergence occurs by a fluid motion which moves away from the interface ($w' < 0$), resulting in an increase of the turbulent boundary layer thickness. Turbulent scalar exchange between turbulent water and the above atmosphere across the interface should therefore be interfered at the regions of $\gamma < 0$. Introducing this quantity is, therefore, considered beneficial to analyze the physical relation between interface-normal velocity fluctuations, and the turbulent scalar flux at the interface.

Figure 2. Comparison of the turbulent scalar flux at the gas-liquid interface between the results of the present study and those in the laboratory experiments by Komori, Murakami, & Ueda (1989).
Figure 3. The joint probability density distribution between $\gamma$ and $G$ at the gas-liquid interface; (a) $Re_\tau = 150$; (b) $Re_\tau = 400$.

Figure 3 shows the joint probability density distributions of the surface divergence $\gamma$ and the local scalar gradient perpendicular to the interface, $G = (\partial C/\partial z)_{z=\delta}$ for $Re_\tau = 150$, and 400. Both $\gamma$ and $G$ are normalized by their root-mean-square (rms), as $\gamma^* = (\gamma - \langle \gamma \rangle) / \langle \gamma \gamma \rangle^{1/2}$, and $G^* = (G - \langle G \rangle) / \langle GG \rangle^{1/2}$. This statistical analysis demonstrates that the two parameters have very high positive correlation relation with each other. We also evaluated the correlation coefficient between the two parameters is given by

$$R_{\gamma G} = \frac{\langle \gamma(x, y, t) G(x, y, t) \rangle}{\langle \gamma \rangle^{1/2} \langle GG \rangle^{1/2}},$$

(11)

to quantify the correlation relation of the two parameters. The results of the present in-silico experiments exhibit that the correlation coefficient $R_{\gamma G}$ increases slightly from 0.73 for $Re_\tau = 150$, to 0.75 for $Re_\tau = 600$, as $Re_\tau$ increases. The statistical correlation is thought high enough to connect the two parameters based on physical insights of the hydrodynamics near the interface. It is expected that an employment of $\gamma$ will be profitable enough to model the turbulent scalar flux appropriately.

4.4. Characteristic time scale at the interface

The surface-renewal approximation, equation 1, requires the time scale of replacement of fluid elements between the interface and turbulent bulk. This study proposes two types of the time scale for the surface-renewal approximation. One is the time scale to be examined in the present study is derived from the surface divergence,

$$T_\gamma = \langle \gamma \gamma \rangle^{-1/2}.$$

(12)

This characteristic time scale is convenient to employ because of its simple parameterization using only the surface divergence, $\gamma$. The other is the time scale derived from the characteristic length and velocity scales as

$$T_S = \Lambda/V,$$

(13)

where, $\Lambda$ and $V$ are the characteristic length and velocity scales at the interface, respectively. The autocorrelation coefficient of the surface divergence in the streamwise $(x)$ direction,

$$C_x(\ell) = \frac{\langle \gamma(x, y, t) \gamma(x + \ell, y, t) \rangle}{\langle \gamma \gamma \rangle^{1/2}},$$

(14)
is used to evaluate the length scale, Λ. The zero-correlation length scales, \( C_x(\Lambda_0) = 0 \), can be interpreted as the mean radius of the turbulent spots which are formed numerously at the interface, as shown in the flow visualization indicating the plane distribution of the instantaneous surface divergence in figure 4. The characteristic length scale at the interface is, consequently, obtained by \( \Lambda = 2\Lambda_0 \), which represents the characteristic size of \( \gamma > 0 \) region found at the interface. The rms streamwise velocity fluctuation is employed as the characteristic velocity scale at the interface, i.e., \( \bar{V} = \langle u'u' \rangle^{1/2} / \delta \).

Figure 5 examines the relation between \( \langle K_0^+ \rangle Sc^{1/2} \) and \( T_\gamma^+ \) predicted by the present in-silico experiments, as plotted by closed circles. The results of the laboratory measurements by Komori, Murakami, & Ueda (1989) are also indicated in the same figure by open circles, under the assumption that the surface-renewal frequencies Komori, Murakami, & Ueda (1989) measured, \( f \), are assumed \( T_\gamma = 1/f \). The results of the present numerical predictions show that \( \langle K_0^+ \rangle Sc^{1/2} = \alpha \langle T_\gamma^+ \rangle^{-1/2} \) with \( \alpha \approx 0.19 \) correlates the turbulent scalar fluxes at the interface predicted by the present study, as demonstrated by the solid line. However, the time scale \( T_\gamma \) is different with the time scale Komori, Murakami, & Ueda (1989) measured in their laboratory experiments, since both the results from the in-silico and laboratory experiments exhibit different \( \alpha \). Indeed, the experimental results by Komori, Murakami, & Ueda (1989) are correlated by \( \langle K_0^+ \rangle Sc^{1/2} = \alpha \langle T_\gamma^+ \rangle^{-1/2} \) with the proportionality constant \( \alpha \approx 0.34 \), as indicated by the dashed line. It is also clarified by the least-square method that the turbulent scalar fluxes obtained by the present in-silico experiments exhibit that \( \langle K_0^+ \rangle Sc^{1/2} = \alpha \langle T_\gamma^+ \rangle^n \) with \( \alpha \approx 0.12 \), and \( n \approx -3/8 \), is the best-fit result, as illustrated by the solid-dashed line in figure 5. The least-square analysis implies that \( T_\gamma \) deviates slightly from the surface-renewal approximation, \( \langle K_0^+ \rangle Sc^{1/2} \propto \langle T_\gamma^+ \rangle^{-1/2} \).

Figure 6 shows the relation between \( ShSc^{-1/2} \) and \( Re^2_{\tau} / T_S^+ \) to examine the suitability of the surface-renewal approximation, equation 7, using the results of the present numerical experiments. The results of the laboratory measurements by Komori, Murakami, & Ueda (1989) are also indicated in the same figure by open circles. The results suggest that the Sherwood number obtained by the present study is correlated by the surface-renewal approximation with the proportionality constant of \( \alpha \approx 0.36 \) demonstrated by the solid line. This correlation relation agrees well with that obtained by Komori, Murakami, & Ueda (1989), and Komori, Nagaosa, & Murakami (1990) with the proportionality constant of \( \alpha \approx 0.34 \), as indicated by the dashed line. The time scale \( T_S \) proposed in this study appears to be equivalent to that Komori, Murakami, & Ueda (1989) measured in their open-channel experiments. It should be stressed here that
these time scales have been derived completely different treatment of the hydrodynamics under the interface. This study evaluates the time scale using its definition indicated in equation 13. The laboratory experiments introduced the variable interval time averaging technique to concentration signals of dye tracers to determine the characteristic time scale at the interface.

Comparison between figures 5 and 6 suggests strongly that the time scale $T_S$ is rather suitable as the surface-renewal time scale at the interface, and as the key hydrodynamics parameter for evaluating the turbulent scalar fluxes. The time scale, $T_\gamma$, appears to be acceptable to predict the interfacial scalar flux, nevertheless, the time scale is not equivalent to the time scale Komori, Murakami, & Ueda (1989) measured in their laboratory experiments. It should also be pointed out that the time scale $T_\gamma$ deviates slightly from the surface-renewal approximation. Careful considerations are necessary if the turbulent scalar flux is predicted by using the time scale $T_\gamma$, because of the reasons described above.

**Figure 5.** The relation between $K_0^{+}Sc^{1/2}$ and $T_\gamma^{+}$ predicted by the present in-silico experiments.

**Figure 6.** The relation between $ShSc^{1/2}$ and $Re_\tau^2/T_S^{+}$ predicted by the present in-silico experiments.

5. Conclusions

This study proposed a predictive model to predict the turbulent scalar flux at the shear-free gas-liquid interface in a fully developed turbulence. The concept of the surface-renewal approximation was introduced to establish the model. In-silico scalar transfer experiments based on a direct numerical simulation technique were applied in this study to obtain three-dimensional details of the hydrodynamics and the turbulent scalar transfer mechanisms in the region very close to the interface of the turbulent open-channel.

Two characteristic time scales at the interface have been proposed, and examined for exact predictions of the scalar transfer fluxes based on the surface-renewal approximation. One was the time scale which was derived directly from the surface divergence, $T_\gamma = \langle \gamma \gamma \rangle^{-1/2}$. The other was the time scale given by the characteristic velocity and length scales, $T_S = \Lambda / V$. The length scale, $\Lambda$, was evaluated by the zero-correlation length of the surface divergence. The velocity scale, $V$, was the rms velocity fluctuation in the streamwise direction.

The results of this study suggested that the characteristic time scale obtained by the surface divergence, $T_\gamma$, was slightly unsatisfactory to correlate the turbulent scalar flux at the interface based on the surface-renewal approximation. It was also found that the proportionality constant appear to be 0.19, which was different with that observed in the previous laboratory experiments.
On the other hand, $T_S$ predicted the turbulent scalar flux based the surface-renewal approximation in a satisfactory manner. It was also elucidated that the proportionality constant for $T_S$ was approximately 0.36, which was very close to that found by the laboratory experiments, $\alpha \approx 0.34$. The time scale $T_S$ is, therefore, appeared to be essentially the same as one the laboratory experiments measured. In conclusion, application of $T_S$ as the characteristic of the surface-renewal for predicting the turbulent scalar flux is acceptable for practical purposes, however, careful considerations are compulsory to derive mistaking predictions. The time scale $T_S$ is highly recommended to apply for predicting the interfacial scalar flux, since the time scale is considered essentially the same as the time scale Komori, Murakami, & Ueda (1989) measured in the laboratory experiments.

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