

Prediction of Turbulent Scalar Fluxes at Shear-free Gas-Liquid Interface Based on Surface Divergence

Ryuichi Nagaosa

Research Institute of Science for Safety and Sustainability (RISS)
National Institute of Advanced Industrial Science and Technology (AIST)
Tsukuba, Ibaraki, Japan

The purpose of this study is to establish a predictive model for evaluating the scalar exchange rate between turbulent water and the atmosphere across a shear-free, flat gas-liquid interface. A direct numerical simulation technique is used to quantify turbulent scalar flux at the interface, and the interfacial hydrodynamics. A concept of the surface-renewal approximation is employed to explore the relation between turbulence near the interface and turbulent scalar flux. The surface divergence is chosen to represent the characteristic time scale of the surface-renewal motions at the interface. The results of this study indicate that turbulent scalar flux at the interface is proportional to the square of the root-mean-square of the surface divergence, indicating that the surface-renewal approximation is suitable to model scalar exchange rate at the interface.

INTRODUCTION

Understanding scalar transfer mechanisms at a gas-liquid interface contributes significantly to the establishment of a predictive model for turbulent scalar flux. These models are applicable to evaluations of global heat and mass balances, and to predictions of the scalar exchange rate at the sea surface between the ocean and the atmosphere. This study proposes a simple and predictive model for turbulent scalar flux into turbulent liquid across a gas-liquid interface. A shear-free, flat gas-liquid interface, which corresponds to the zero-Froude (or Weber) number turbulence, is considered. This type of turbulent flow with the interface is one of the simple flow configurations to be investigated in the relation between the interfacial hydrodynamics and turbulence scalar transfer mechanisms.

It is widely known that turbulence quantities beneath the interface of turbulent water determine critically turbulent scalar flux at the interface, since the molecular diffusivity of scalar in water is much smaller than in air. The author has studied turbulence scalar transfer mechanisms in a turbulent open-channel flow based on laboratory and numerical experiments (Komori et al., 1989, 1990; Nagaosa, 1999; Nagaosa and Handler, 2003). The results of these studies have revealed that turbulent vortical structures produced in the turbulent boundary layer travel toward the interface and interact with each other. These interactions are known as an agent of replacement of fluid elements between the interface and turbulent bulk; for this reason, they are often referred to as surface-renewal events. The laboratory measurements show that turbulent scalar flux is predictable by the surface-renewal approximation, $K \propto f_s^{1/2}$, where K is the scalar transfer coefficient, and f_s is the surface-renewal frequency, or, the reciprocal of the characteristic time scale of the surface-renewal events, $T_s = 1/f_s$ (Dankwerts, 1951). The hydrodynamically close relation between the vortical structures under the interface and turbulence scalar transfer mechanisms at the interface has been disclosed by means of a direct

numerical simulation (DNS) technique, (Nagaosa, 1999; Nagaosa and Handler, 2003). Suitability of the surface-renewal approximation has also been verified by a series of our numerical studies.

An estimation of the characteristic time scale of the surface-renewal is crucial to establishing a predictive model for turbulent scalar transfer at the interface. The variable-interval time-average (VITA) method is applied to a time series of dye-tracer signals measured in the region close to the interface so as to evaluate the frequency of the surface-renewal in the previous laboratory measurements (Komori et al., 1989, 1990). This approach was designed to detect all the surface-renewal eddies at the interface by optimizing several parameters, such as the time duration for time average, and the threshold level to identify the surface-renewal eddies. While these experiments have been successful in quantifying the surface-renewal time scales, the parameter optimization procedures were complicated. Hence, an application of the VITA technique to various kinds of turbulent flows is not thought to be practical for this reason.

This study introduces surface divergence to quantify the characteristic time scale at the interface, instead of applying the VITA technique. One of the major advantages of this choice is that the surface divergence is measurable directly using only the plane distribution of the velocity fluctuations at the interface. Measurements of 2D information of the velocity fluctuations at the interface can be achieved by introducing a flow visualization technique, such as a particle-image velocimetry (PIV) in a laboratory experiment (e.g., McKenna and McGillis, 2004) and a remote sensing technique in a field measurement. In addition, the surface divergence has a dimension of $[T^{-1}]$, hence, the reciprocal of the surface divergence is regarded as a characteristic time scale at the interface. Indeed, many researchers have introduced the surface divergence to model turbulent scalar flux at the interface, e.g., Banerjee et al., 2004; Calmet and Magnaudet, 1998, 2003; Law and Khoo, 2002; Magnaudet and Calmet, 2006. A quantification of the characteristic time scale based on the surface divergence will be a key to developing a simple and predictive model for turbulent scalar flux.

The purpose of this study is to establish a simple model for predicting turbulent scalar flux at the gas-liquid interface of a fully developed turbulent flow. The concept of the surface-renewal approximation is employed to explore the relation between the

Received March 15, 2010; revised manuscript received by the editors October 11, 2010. The original version (prior to the final revised manuscript) was presented at the 20th International Offshore and Polar Engineering Conference (ISOPE-2010), Beijing, June 20–25, 2010.

KEY WORDS: Turbulence scalar transfer, gas-liquid interface, surface renewal, surface divergence, direct numerical simulation (DNS).