EFFECTS OF INTERFACIAL WAVE ON TURBULENT MASS TRANSFER IN OPEN CHANNEL FLOW

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Summary We carry out numerical simulation of a turbulent open channel flow and associated interfacial mass transfer in a flow regime where the interface is substantially disturbed, but not broken. Particular attention is paid to wave effects on the interfacial mass transfer. It is shown that the local mass transfer rates at both flat and wavy interfaces can be predicted fairly well from the surface divergence by the stagnation flow model. By decomposing the surface divergence into two contributions of turbulence and waves, the impact of waves on the mass transfer is discussed. It is found that the surface divergence is induced at the downstream of prominent wave crests, and that the contribution of waves is comparable with that of turbulence. These results suggest the interfacial wave significantly influences the local mass transport phenomena.

INTRODUCTION

Turbulent mass transfer across an air-water interface plays a critical role in geophysical and industrial processes. Since the Schmidt numbers *Sc* of slightly soluble gases such as carbon dioxide and oxygen are generally high and $Sc \sim O(10^3)$ in water, the most mass transfer resistance exists in a thin concentration boundary layer just beneath the interface. It is particularly important to understand the microscopic transport mechanisms inside this thin concentration boundary layer, which should be controlled by complex interaction between bulk turbulence, a free surface and waves. However, due to various obstacles in the measurement of velocity and concentration close to a moving interface, the detailed mass transfer mechanisms have not been fully explored. In addition, since most previous DNS studies were performed for a flat interface, keeping the normal velocity fluctuation vanish at the interface, very little is known about how the interfacial waves influence the mass transfer.

In general, the interfacial deformation is governed by the stabilizing effects of capillary tension and gravitational forces against the disrupting effect by turbulence. Correspondingly, Brocchini and Peregrine [1] introduced two dimensionless parameters, i.e., the Weber *We* and Froude *Fr* numbers, with which they classified the turbulent regimes into four typical cases. The flat interface corresponds to a "weak" turbulence, where both *We* and *Fr* are small, i.e., $We \ll 1$ and $Fr \ll 1$. In contrast, in the case of "strong" turbulence, i.e., $We \gg 1$ and $Fr \gg 1$, neither capillary nor gravitational forces sustain the turbulent dynamic motion, so that the flow breaks up into droplets. In the present study, we consider a transitional regime between the "weak" and "strong" turbulence, where the interface is substantially disturbed, but not broken up. In this regime, experimental observation [2] shows that the interfacial waves significantly influence the turbulent structures as well as heat/mass transfer characteristics.

Recently, Hasegawa and Kasagi [3] carried out numerical simulation of high Schmidt number turbulent mass transfer across a flat interface, and showed that the surface divergence β plays a critical role in controlling the local mass transfer rate. They analyzed a simplified concentration transport equation, and derived the following relationship between the local mass transfer rate *k* and β:

$$k = \frac{q^*}{u_\tau \Delta C_B^*} = \sqrt{\frac{2\beta^+}{\pi Sc}}\text{, when } \beta > 0. \tag{1}$$

This model holds fairly well at a flat air-water interface. The general expression of β is given by:

$$\beta = \left\{ -\left(\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} \right) + 2\kappa v \right\}_{y=0}. \tag{2}$$

Here, *x* and *z* denote the interface-tangential directions, while *y* is the distance from the interface, with *u*, *v*, *w* being velocity components in *x*, *y* and *z* directions, respectively. The local curvature of the interface is denoted by κ. The first term of Eq. (2) represents the surface divergence of tangential velocity induced by free-surface turbulence, while the second term is the rate of surface dilation or compression due to movement of a curved interface. The former is named as the turbulence contribution β_t, while the latter the wave contribution β_w, which vanishes at a flat interface.

In the present study, our main objectives are threefolds:

I. Verification of the surface divergence model, Eq. (1), at wavy interface,
II. Evaluation of the wave contribution to the surface divergence,
III. Clarification of mechanisms of the surface divergence generation at wavy interface.

NUMERICAL PROCEDURES

We use an algebraic mapping to transform the physical space (t, x, y, z) to the computational space (τ, ξ, ψ, ζ) with the following relation as $(\tau, \xi, \psi, \zeta) = (t, x, y/\eta, z)$, where η is the height of the interface. The transformed Navier-Stokes, continuity and concentration transport equations are solved by a pseudo-spectral method. By applying a fractional step method, the intermediate velocity field is first calculated, and then the pressure is determined so as to satisfy the continuity equation by solving the Poisson equation. The atmospheric pressure is assumed to be constant, and free-slip conditions are used for the tangential velocity components at the interface. No-slip conditions are imposed at the bottom boundary. Dimensionless parameters which govern the flow field are the Reynolds number $Re_\tau = u_\tau \delta / \nu$, the Weber number $We = \rho u_\tau^2 \delta / \sigma$, the Froude number $Fr = u_\tau / \sqrt{g\delta}$, where u_τ, ρ, δ, σ, g are the friction velocity, fluid density, mean depth, surface tension and gravity acceleration, respectively. In order to simulate the transitional regime mentioned above, these parameters are set to be $Re_\tau = 150$, $We = 0.16$, $Fr = 0.2$. A flat interface is also calculated for comparison. The Schmidt number in the concentration transport equation is $Sc = 1.0$.

RESULTS

The instantaneous velocity field is shown in Figure 1. The root-mean-square interfacial deformation is around 7 % of the mean depth δ, and cell-type structures at the interface can also be seen in accordance with the previous experiments, e.g., [2]. We compare the local mass transfer rate k and the surface divergence model of Eq. (1). In brief, good agreement is confirmed at both flat and wavy interfaces (not shown here). This means that the surface divergence can be used as an indicator of the interfacial mass transfer even at a wavy interface.

In order to highlight the impacts of interfacial waves, the time traces of the surface divergence β at flat and wavy interfaces, and interfacial deformation η are presented in Figure 2. Note that identical velocity and concentration fields are used as initial conditions for both cases. As time passes, the interfacial waves develop and the intensity of the surface divergence at the wavy interface (black solid line) clearly exceeds the value at the flat interface (red solid line). It is also observed that the contribution of interfacial waves β_w (dotted line) is comparable with the turbulence contribution β_t (broken line).

In Figure 3, the instantaneous distributions of the surface divergence are shown. The wave contribution of β_w has a large magnitude downstream of prominent crests, indicating the surface renewal is enhanced in these regions. As a result, the interfacial wave increases the surface divergence by about 30 % beyond the value at the flat interface. According to the surface divergence model, this corresponds to about 14 % increase in the mass transfer rate.

CONCLUSIONS AND FUTURE WORK

The present numerical results indicate that the interfacial waves significantly influence the surface divergence, and associated the interfacial mass transfer. In the final presentation, we will report on the effects of *We* and *Fr* on the turbulent structures, and also the detailed mechanisms of surface divergence generation due to the interfacial waves.

References

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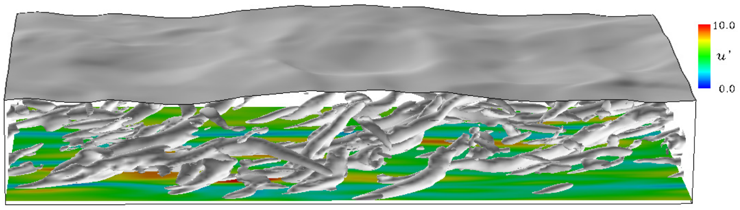

Figure 1. Instantaneous velocity field
White: contour of second invariant of deformation tensor $Q^+ = -0.1$
Red and Blue: high and low speed regions at $y^+ = 5$

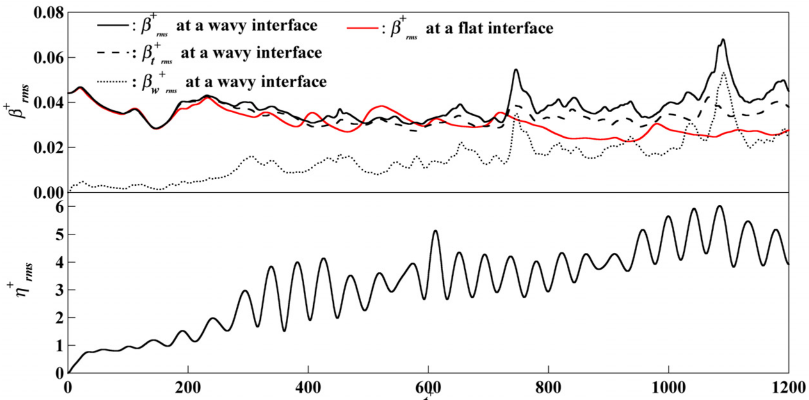

Figure 2. Time traces of surface divergence β (upper) and surface deformation η (lower).

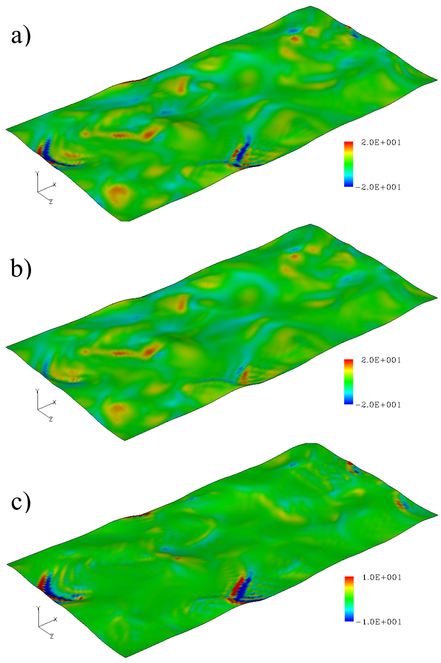

Figure 3. Instantaneous distribution of the surface divergence β at wavy interface,
a): total $\beta_t + \beta_w$, b): turbulence contribution β_t,
c) wave contribution β_w.