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EFFECTS OF SURFACE TENSION REDUCTION ON MOMENTUM AND SCALAR TRANSFER IN WIND-WAVE TWO-PHASE TURBULENT FLOW

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ABSTRACT

Effects of surface tension reduction on the momentum and scalar transfers across the wind-wave air-water interface are investigated by using a direct numerical simulation (DNS) of gas-liquid two-phase turbulent flow. The incompressible Navier-Stokes equations for both gas and liquid phases are solved using an arbitrary Lagrangian-Eulerian (ALE) method with boundary-fitted moving grids. The DNS is performed for the cases of the surface tension of water and half of it. The results show that the significant wave height for the small surface tension case becomes larger than that for the large surface tension case. The enhancement of wind wave development can be explained by increase of the form drag due to surface tension reduction. In contrast, the scalar transfer rate becomes smaller due to the surface tension reduction.

INTRODUCTION

Momentum and scalar transfers across wind-wave air-water interface are important to understand interactions between the atmosphere and ocean because wind-wave turbulent flows enhance the momentum and scalar transfers. A recent study reported that prediction of tropical cyclone intensity is significantly influenced by the momentum and heat transfer rates (Komori et al., 2018). Matthews et al. (2017) reported that suppression of wind waves due to surfactants was observed around floating objects in the Pacific Ocean. The suppression of wind wave development due to surfactants in water was reported by several papers (Scott, 1972; Mitsuyasu and Honda, 1986). This fact implies that surface tension plays an important role for the momentum and scalar transfers across wind-wave interface because surface tension decreases as the concentration of surfactants increases. Thus, this study aims to investigate the effects of surface tension reduction on the momentum and scalar transfers across the wind-wave air-water interface by using a direct numerical simulation (DNS) of gas-liquid two-phase turbulent flow.

COMPUTATIONAL METHOD

The governing equations for gas and liquid flows are the incompressible Navier-Stokes equation and the continuity equation:

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 U_i}{\partial x_j \partial x_j} - \frac{1}{Fr}\delta_{i3} \qquad (1)$$

$$\frac{\partial U_i}{\partial x_i} = 0 \qquad (2)$$

where U_i and p are the velocity and pressure normalized by the representative velocity and density, U_0 and ρ_0. Re and Fr are the Reynolds number and the Froude number, respectively. The air-water interface was tracked by using the transport equation of the height function η:

$$\frac{\partial \eta}{\partial t} + U_1 \frac{\partial \eta}{\partial x_1} + U_2 \frac{\partial \eta}{\partial x_2} = U_3 \qquad (3)$$

The dynamical balance at the interface is given by the following equations:

$$p_{\rm w} + \tau_{\rm nw} + p_{\rm s} = p_{\rm a} + \tau_{\rm na} \qquad (4)$$

$$\tau_{\rm tw} = \tau_{\rm ta} \qquad (5)$$

where the subscripts a and w indicate the quantities for the gas and liquid phases, respectively, and $\tau_{\rm n}$ and $\tau_{\rm t}$ are the viscous stress normal and tangential to the interface, respectively. $p_{\rm s}$ denotes the pressure gap due to the surface tension, given by $p_{\rm s} = We^{-1}\kappa$, where κ is the curvature of the interface. We is the Weber number, $We \equiv \rho_0 L_0 U_0^2/\sigma$, where σ is the surface tension and L_0 is the representative length. The transport equation of scalar concentration C is given by

$$\frac{\partial C}{\partial t} + U_j \frac{\partial C}{\partial x_j} = \frac{1}{Re \cdot Sc}\frac{\partial^2 C}{\partial x_j \partial x_j} \qquad (6)$$

where Sc is the Schmidt number of the scalar.

We have adopted boundary-fitted moving grids: The grid points move vertically following the vertical displacement of the interface. The governing equations for the flow and the scalar transport were solved using an arbitrary Lagrangian-Eulerian (ALE) method (Hirt et al., 1997; Komori et al., 2010; Takagaki et al., 2015; Kurose et al., 2016). The advection and viscous terms were calculated by the fifth-order upstream difference and forth-order central difference schemes, respectively. The velocity and pressure were coupled by using the Marker and Cell

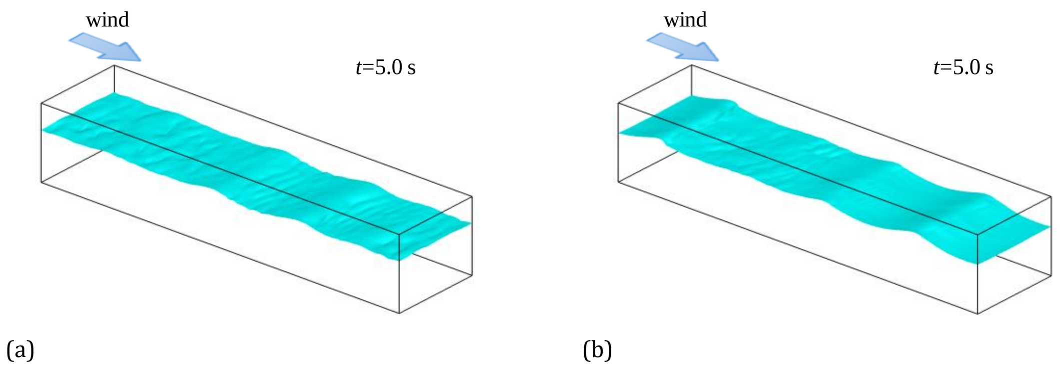

Figure 1. The air-water interface at t = 5.0 s for the cases of (a) $\sigma = 1.0\sigma_{\mathrm{w}}$ and (b) $\sigma = 0.5\sigma_{\mathrm{w}}$.

(MAC) method. The first-order implicit Euler method was used for the time integration.

COMPUTATIONAL SETTING

The computational domain size was set to $L_x = 0.200$, $L_y = 0.048$, and $L_z = 0.0375$ m in streamwise (x), spanwise (y), and vertical (z) directions, respectively. The flat interface was initially located at 0.025 m above the bottom of the domain. The domain was discretized to $400 \times 96 \times 180$ grid points. The grid points were located uniformly in horizontal directions. In the vertical direction, nonuniform grids were adopted to both gas (upper 60 points) and liquid layers (lower 120 points) so that fine grids were located near the interface. The periodic boundary condition was applied to the horizontal directions and the Neumann condition was applied to the vertical direction. The density and the kinematic viscosity were set to typical values of air and water. The gravitational acceleration was set to $g = 9.8$ m/s^2. We have examined two cases of the surface tension σ: The normal surface tension case, where the surface tension of water was used ($\sigma = 1.0\sigma_{\mathrm{w}}$), and the half surface tension case, where the surface tension was reduced to half of water ($\sigma = 0.5\sigma_{\mathrm{w}}$).

A developed wall-bounded turbulent flow was imposed initially in the gas layer, whereas the liquid layer was static. The initial speed at the top of the domain was $U_{\mathrm{top}} = 4.7$ m/s. A steady streamwise pressure gradient was applied as a driving force to the flow in the gas phase. The wind wave development in 7 seconds was simulated.

The scalar C represents the gas concentration absorbed in the liquid phase, and the scalar transport in the liquid phase was calculated. The initial scalar concentration in the liquid phase was set to 0. The scalar concentration on the interface was fixed to 1. The Schmidt number was set to $Sc = 1$. The calculation of scalar transport was started at t = 4.0 s.

RESULTS AND DISCUSSIONS

Figure 1 shows the interface shape at t = 5.0 s. For the case of $\sigma = 0.5\sigma_{\mathrm{w}}$, the ripple waves are less significant, and the wave height looks higher. In order to compare them quantitatively, the significant wave height has been calculated by using the zero-up-cross method. Figure 2 shows the significant wave height H for the cases of $\sigma = 1.0\sigma_{\mathrm{w}}$ and $\sigma = 0.5\sigma_{\mathrm{w}}$. For both cases, the development of wind waves becomes slower at t = 2.0 or 2.5 s. After this period, the wave height for $\sigma = 0.5\sigma_{\mathrm{w}}$ is higher than that for $\sigma = 1.0\sigma_{\mathrm{w}}$. Reliability of this results has been confirmed by our laboratory experiments using ethanol solutions. This result indicates that the effect of surface tension reduction is contradicted to the effect of surfactants. That is, the suppression of wind waves due to surfactants would be attributed to spatial variance of surface tension; i.e., the Marangoni stress.

The momentum transfer across the interface is evaluated by the friction and form drags, D_{f} and D_{p} respectively. These drags were calculated by

$$D_{\mathrm{f}} = \frac{1}{L_x L_y}\int_\Gamma \tau_{\mathrm{ta}} t_1 dS,$$
$$D_{\mathrm{p}} = \frac{1}{L_x L_y}\int_\Gamma \{p_{\mathrm{a}} + g\eta\} n_1 dS,$$

where t_1 and n_1 are the streamwise components of the tangential and normal vectors, and Γ represents the interface area. Figure 3 shows the temporal variation of D_{f} and D_{p}. As the wind waves develop, the form drag D_{p} increases, while the friction drag D_{f} decreases. At $t > 3$ s, D_{f} for $\sigma = 0.5\sigma_{\mathrm{w}}$ becomes smaller than that for $\sigma = 1.0\sigma_{\mathrm{w}}$, while D_{p} for $\sigma = 0.5\sigma_{\mathrm{w}}$ becomes larger. Since the wave energy growth rate is related to the form drag (Melville and Fedorov 2015), the larger form drag for $\sigma = 0.5\sigma_{\mathrm{w}}$ explains the faster development.

To evaluate the scalar transfer across the interface, we have calculated the scalar transfer rate k_{L}, which is defined as

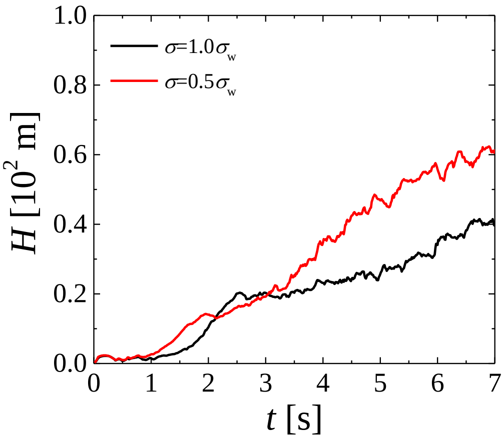

Figure 2. Effect of σ on the significant wave height H.

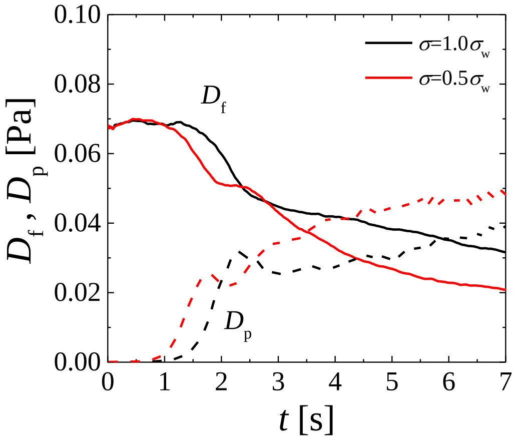

Figure 3. Effect of σ on the friction drag D_f and form drag D_p.

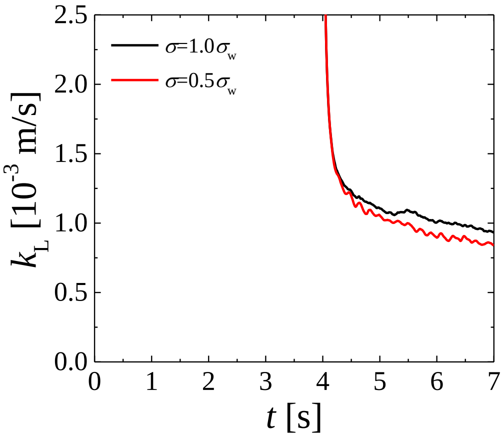

Figure 4. Effect of σ on the scalar transfer rate k_L.

$$F = k_L(C_i - C_b),$$

where C_i is the scalar concentration on the interface ($C_i = 1$), C_b is the bulk scalar concentration ($C_b = 0$), and F is the mean scalar flux, defined as

$$F \equiv \frac{1}{L_x L_y}\int_\Gamma D\frac{\partial C}{\partial n}dS,$$

where D is the diffusive coefficient, and n is the normal distance from the interface. Figure 4 shows the temporal variation of the scalar transfer rate k_L in the liquid side for the cases of $\sigma = 1.0\sigma_w$ and $\sigma = 0.5\sigma_w$. As the scalar concentration boundary layer develops, the difference in k_L becomes remarkable. At t = 7.0 s, k_L for $\sigma = 0.5\sigma_w$ is approximately 10% smaller than that for $\sigma = 1.0\sigma_w$. Note that the reduction of k_L cannot be explained by the difference in the surface area of interface because the surface area for $\sigma = 0.5\sigma_w$ is slightly larger than that for $\sigma = 1.0\sigma_w$. Previous studies (e.g., Komori et al. 2010) reported that the scalar transfer rate k_L is strongly influenced by the turbulence structure below the interface. In figure 3, the smaller values of D_f for the smaller surface tension implies that the surface tension reduction weakens turbulence below the interface. We have also confirmed that the variance of the surface divergence of surface velocity decreases due to the surface tension reduction. Thus, the reduction of k_L is caused by the difference of the vortex structure near the interface.

CONCLUSION

Effects of surface tension reduction on the momentum and scalar transfers across the wind-wave air-water interface have been investigated by using a direct numerical simulation (DNS) of gas-liquid two-phase turbulent flow. The incompressible Navier-Stokes equations for both gas and liquid flows were solved using an arbitrary Lagrangian-Eulerian (ALE) method with boundary-fitted moving grids. The DNS has been performed for the cases of the surface tension of water and half of it. The results show that the significant wave height for the small surface tension case increases faster than that for the large surface tension case. The enhancement of the wave development is explained by the increase of the form drag for the small surface tension case. In contrast, the scalar transfer rate becomes smaller due to the surface tension reduction: The scalar transfer rate for the half surface tension case is about 10% smaller than that for the standard surface tension case. This is attributed to weakening of vortices near the interface.

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