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Study of a free surface in open-channel water flows in the regime from "weak" to "strong" turbulence

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Abstract

A liquid–air interface in an inclined open-channel water flows was studied experimentally as the flow changes from "weak" to "strong" turbulence. In this regime, the interface is highly agitated by bulk eddies and waves, but not broken. The surface deformation statistics were obtained under a variety of conditions, including different inclination angles and flow rates. The parameter space is described in terms of Reynolds, Froude, and Weber numbers. The surface-normal displacements were obtained via the time series of the fluctuating flow depth with an ultrasound transducer. Independently, the in-plane changes in surface structures were acquired with a high-speed camera. These structures are seen as surface cells. By applying a newly developed image processing technique, the cell celerity was found to agree well with the mean flow velocity. This suggests that the cells appear when a turbulent surface-renewal eddy interacts with the interface. As the flow changes to strong turbulence, the turbulence–interface interactions become dominant over the wave phenomena, and the turbulent structures at the surface become more 3D (similar to those in the bulk flow), compared to quasi-2D structures in the weak turbulence.
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Keywords: Turbulence; Free surface; Water–air interface; Surface renewal; Image processing

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1. Introduction

1.1. Background

When a liquid flows over a solid surface, the liquid–gas interface is often not flat. Wave motions, including capillary or gravity waves, can produce deformations, or deformations can be caused by turbulent eddies in the liquid impinging upon the free surface. Both mechanisms have a strong effect on the scalar transfer rate across the interface. The importance of the wave motion was demonstrated by Frisk and Davis (1972), Kutateladze (1982), and Nakoryakov et al. (1987), indicating strong correlation between the scalar transport and surface waves. An increase in the heat transfer coefficient by 40–60% due to surface waves was reported by Frisk and Davis (1972), while mass transfer intensification in absorption of carbon dioxide by 100–170% in wavy water flows was observed by Kutateladze (1982) and Nakoryakov et al. (1987). Another strong evidence of the wave effect on mass transfer was shown by Saylor and Handler (1997) in their studies of gas transport across an air–water interface populated with capillary waves. Recently, an approximately 100% increase in heat transfer coefficient due to interface irregularities was observed by Freeze et al. (2003) in inclined water flows.

Recent discoveries in studies of turbulence in open-channel flows near the liquid–gas interface have shown that if large shear stresses are not applied to the free surface, the scalar (heat and mass) transport rate across the interface is mostly controlled by large turbulent eddies coming from the interior flow. Such eddies are formed as a result of bursting events in the near-wall region. The turbulent eddies reach the interface, and then gradually dissipate, and/or attach themselves to the surface before being dissipated. This process of delivering liquid from the flow interior to the free surface by turbulent eddies is known as "surface-renewal phenomenon" (Dankwerts, 1951). The importance of this phenomenon can be illustrated by the fact that the mass transfer coefficient across the interface is proportional to the square root of the surface-renewal frequency. Many characteristics of the surface-renewal eddies and associated surface phenomena were carefully studied both experimentally and numerically. As shown by Komori et al. (1989), the frequency of the surface-renewal eddies is slightly lower than the bursting frequency, indicating that almost all the wall ejections reach the interface. It was also observed (Komori et al., 1982, 1989) that at the free surface and in its vicinity, the surface-renewal eddies are about $2h_m$, $0.5h_m$, and h_m in the streamwise, vertical, and spanwise directions, respectively, where h_m is the mean flow thickness. Rashidi (1997) measured the average size of the interfacial patches associated with the upwelling eddy motion at the interface using oxygen bubble visualization technique. He observed that the patch size is comparable with the mean flow depth. The turbulent length scale near a free surface has also been calculated using DNS (e.g. Handler et al., 1993). Similar to the earlier experimental studies (Ueda et al., 1977), the DNS study showed significant turbulence redistribution near the interface. Namely, the streamwise and spanwise length scales associated with the streamwise and spanwise velocity fluctuations grow when approaching the free surface from the flow bulk, while the length scale normal to the free surface decreases. This indicates a more pancake-like eddy structure near the free surface compared with the structure in the bulk flow where turbulence is very similar to that in a closed channel flow. It was found that the increase in the streamwise length scale is by a factor of three and it is by a factor of two for the spanwise length scale, in comparison with the bulk values. Recent DNS studies by Naga-

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