Available online at www.sciencedirect.com

ScienceDirect

International Journal of Heat and Fluid Flow 29 (2008) 774–782

International Journal of HEAT AND FLUID FLOW

www.elsevier.com/locate/ijhff

The effects of swell on turbulence over wavy walls

Ryoichi Kurose, Takanori Imashiro, Satoru Komori *

Department of Mechanical Engineering and Science, Advanced Research Institute of Fluid Science and Engineering, Kyoto University, Yoshida-honmachi, Sakyo-ku, Kyoto 606-8501, Japan

Received 26 October 2007; received in revised form 23 January 2008; accepted 24 January 2008
Available online 14 March 2008

Abstract

Three-dimensional direct numerical simulations (DNS) are applied to the turbulent air boundary layer over a wavy wall, which imitates the air–water interface consisting of both wind waves and swells, and the effects of the swells with various directions on the turbulence structure and drag over/on the wavy wall are investigated. The results show that parallel swell with the same direction as the wind increases the turbulence intensity and the Reynolds stress over the wavy wall. The swell also increases the pressure drag and decreases the friction drag on the wavy wall, and consequently increases the total drag because of remarkable increase of pressure drag. As the inclination angle of the swell against the wind increases from parallel to perpendicular, the swell effect on the drag becomes weak and finally vanishes. The reduction of friction drag due to swell supports our previous measurements that show reduction of the mass transfer velocity across the wind-driven wavy air–water interface due to the parallel swell.

Keywords: Turbulent flow; Boundary layer; Wavy wall; DNS; Swell

1. Introduction

Global warming, which has become one of the most serious environmental problems in recent decades, is known to be caused by emissions of greenhouse gasses such as carbon dioxide (CO_2) and methane (CH_4). In order to predict the increase of atmospheric temperature, it is of great importance to precisely estimate the global carbon cycle. One of the important issues is to precisely predict mass transfer velocity of greenhouse gases across the air–sea interface between atmosphere and oceans. In GCMs (general circulation models) for climate change simulations, the mass transfer velocity has been correlated with only wind speed observed over oceans (e.g. Wanninkhof, 1992). However, the relations between the mass transfer velocity and the wind speed are greatly scattered. One of the reasons why field measurements of mass transfer velocity are so scattered is that the air–sea mass transfer is affected by other factors besides wind speed. Generally, there exist two types of waves in oceans: wind waves generated by only wind shear acting on the air–sea interface, and swells propagated from afar with low frequency. Our previous measurements in a wind wave tank (Komori et al., 1993a; Tanno and Komori, 2004) showed that the swell decreases the mass transfer velocity across the air–water interface in a limited case where the phase velocities of the swell and wind wave are slower than the wind velocity. However, it has not been clarified why the swell reduces the mass transfer velocity. To explicitly understand the swell effect, the drag force acting on the interface should be carefully investigated, since mass transfer is promoted by turbulent motions (surface-renewal eddies) beneath the air–water interface, and the surface-renewal eddies are produced mainly by drag on the interface (Komori et al., 1989, 1993a,b).

Three-dimensional direct numerical simulation (DNS) and large-eddy simulation (LES), which solve air–water two phase flows, are useful tools for investigating the turbulence structure in both air and water flows, and also the drag on the interface (Lakehal et al., 2003; Fulgosi et al., 2003; Magnaudet and Calmet, 2006). However, these

* Corresponding author.
E-mail address: komori@mech.kyoto-u.ac.jp (S. Komori).

0142-727X/$ - see front matter © 2008 Elsevier Inc. All rights reserved.
doi:10.1016/j.ijheatfluidflow.2008.01.014

Notation

A	vertical projected area of wall
$\boldsymbol{e}_l$	wall tangential unit vector
$\boldsymbol{e}_n$	wall normal unit vector
$\boldsymbol{e}_x$	streamwise unit vector
$D_{F,f}$	friction drags on flat wall
$D_{F,w}$	friction drags on wavy wall
$D_{P,w}$	pressure drags on wavy wall
D_T	total of all drags ($=D_{F,f}+D_{P,w}+D_{F,w}$)
$D_{T,w}$	total of drags on wavy wall ($=D_{P,w}+D_{F,w}$)
$D_{F,case\,2}$	friction drags on wavy wall in case 2
P	pressure
p_w	pressure on wall
p_0	standard pressure on wavy wall
Re	Reynolds number based on half height of computational domain and streamwise maximum mean velocity, $Re=\frac{U_{max}\cdot\delta}{\nu}$
t	time
U_i	instantaneous velocity component in i direction (U, V, W)
u_*	friction velocity on wavy wall
u_{rms}, v_{rms}, w_{rms}	root mean square of U_i
x_i	coordinates in i direction (x, y, z)
x, y, z	streamwise, spanwise and vertical coordinates
z'	distance from wavy wall

Greeks

α	a constant to control the convergence of grid (=3.1)
δ	half height of the computational domain
θ	angle between wind and swell
λ	wave length of wind wave
ρ	density
τ_w	shear stress on wall
ν	kinematic viscosity
ς_i	coordinate of uniform grid

Superscripts

$\bar{()}$	ensemble average
$()^+$	normalization by wall variables (u_*, ν)

DNS and LES require huge computation time and big computational domain especially when wind waves and swells co-exist (referred to as swell wind wave, hereafter). To save computation time and to preserve the wide computational domain for the swell wind wave, it is practical to apply the DNS or LES to only air flow over a wavy rigid wall with similar shape to the air–water interface of the swell wind wave.

Turbulent flows over wavy rigid walls have been examined in many studies (e.g. Günther and von Rohr, 2003; Hudson et al., 1996; Krettenauer and Schumann, 1992; Poggi et al., 2003). Zilker et al. (1977) experimentally investigated the influence of the wave amplitude. Komori (1996) studied the turbulence structure over a three-dimensional wavy wall by DNS. Angelis et al. (1997) investigated the effect of wavelength on turbulence structure over a wavy wall by DNS. Nakagawa and Hanratty (2001) measured the turbulence structure over the wavy wall using PIV (particle image velocimetry). On the other hand, Sullivan et al. (2000, 2002) investigated the turbulence structure over the travelling wavy wall which emulates the real moving wind wave, and Belcher and Hunt (1998) reviewed the researches about the turbulent flow over the wavy terrain from theoretical aspects. However, these researches have not discussed the swell effect. Recently, Nakayama and Sakio (2003) applied the DNS to a turbulent flow over a complex wavy wall, which consisted of two types of waves with different wavelengths. In their studies, however, the drag on the wavy wall was not well investigated.

The purpose of this study is, therefore, to clarify the swell effects on the turbulence structure and drag (pressure and friction drag) on the air–water interface consisting of both wind waves and swells by applying a three-dimensional DNS to turbulent air flow over the wavy rigid wall with similar shape to the interface. Six types of wavy walls with shapes corresponding to pure wind wave and swell wind waves with five different angles to the wind direction are used here.

2. Direct numerical simulation

The three-dimensional continuity and Navier–Stokes equations for incompressible fluids:

$$\frac{\partial U_i}{\partial x_i}=0, \tag{1}$$

$$\frac{\partial U_i}{\partial t}+U_j\frac{\partial U_i}{\partial x_j}=-\frac{1}{\rho}\frac{\partial P}{\partial x_i}+\nu\frac{\partial^2 U_i}{\partial x_j\partial x_j}, \tag{2}$$

were directly solved using the finite difference method (Marker and Cell method). The details of the present numerical method and the accuracy are described in our previous paper (Komori et al., 1993b).

The computational domains and their details are shown in Fig. 1 and Table 1. Turbulent air flows over the six wavy walls: pure wind wave (case 1) and swell wind waves with five inclination angles with respect to the wind direction (cases 2–6), were computed. In Table 1, λ ($=1.0\times10^{-2}$ m) is the wavelength of the wind wave. The inclination angles of the swell to the wind direction, θ, in cases 2–6 were 0°, 27°, 48°, 70° and 90°, respectively. The swells with wind waves in cases 2 and 6 are referred to as "parallel-swell wind wave" and "perpendicular-swell wind wave", respectively, and swell wind waves in cases 3–5 are referred