International Journal of Heat and Fluid Flow 50 (2014) 209–224

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

Large-eddy simulation of open channel flow with surface cooling

R. Walker [a,*], A.E. Tejada-Martínez [a], G. Martinat [b], C.E. Grosch [b]

[a] Civil and Environmental Engineering, University of South Florida, Tampa, FL 33620, USA
[b] Center for Coastal Physical Oceanography and Ocean, Earth and Atmospheric Science, Old Dominion University, Norfolk, VA 23509, USA

ARTICLE INFO

Article history:
Received 4 September 2013
Received in revised form 15 July 2014
Accepted 11 August 2014
Available online 10 September 2014

Keywords:
Open channel flow
Turbulent mixing
Unstable stratification
Surface cooling

ABSTRACT

Results are presented from large-eddy simulations of an unstably stratified open channel flow, driven by a uniform pressure gradient and with zero surface shear stress and a no-slip lower boundary. The unstable stratification is applied by a constant cooling flux at the surface and an adiabatic bottom wall, with a constant source term present to ensure the temperature reaches a statistically steady state. The structure of the turbulence and the turbulence statistics are analyzed with respect to the Rayleigh number (Ra_τ) representative of the surface buoyancy relative to shear. The impact of the surface cooling-induced buoyancy on mean and root mean square of velocity and temperature, budgets of turbulent kinetic energy (and components), Reynolds shear stress and vertical turbulent heat flux will be investigated. Additionally, colormaps of velocity fluctuations will aid the visualization of turbulent structures on both vertical and horizontal planes in the flow. Under neutrally stratified conditions the flow is characterized by weak, full-depth, streamwise cells similar to but less coherent than Couette cells in plane Couette flow. Increased Ra_τ and thus increased buoyancy effects due to surface cooling lead to full-depth convection cells of significantly greater spanwise size and coherence, thus termed convective supercells. Full-depth convective cell structures of this magnitude are seen for the first time in this open channel domain, and may have important implications for turbulence analysis in a comparable tidally-driven ocean boundary layer. As such, these results motivate further study of the effect of surface cooling on tidal boundary layers simulated via an oscillating pressure gradient. Such large-scale structures may also have an important impact on RANS-based (Reynolds-averaged Navier–Stokes equations-based) modeling of turbulence within tidal, convective flows.

1. Introduction

Open channel flow under various combinations of forcing mechanisms can act as an important model problem for tidal ocean flows. The flow patterns exhibited in existing computational simulations of simple channel flows share several significant characteristics with empirical findings from real world ocean flows undergoing turbulent mixing, and as such, clearer understanding of the factors influencing the simpler model problem can make an important contribution to the study of the more complex environmental phenomena.

Under certain flow conditions, large-scale, turbulent, counter-rotating cell structures aligned in the streamwise direction can be found, acting as a secondary motion to the mean flow and persisting in space and time. These structures can induce significant vertical mixing throughout the full depth of the channel and interact with the solid lower wall boundary layer. Li et al. (2004) observed that, in a tidal channel under an oscillating pressure gradient and without the influence of a surface temperature flux, large scale rotating cell structures were visible on horizontal and vertical planes of the flow. These cells increased in size and intensity to a maximum at peak and ebb tide, and the turbulence field was found to dissipate during the transition period without strong shear turbulence production at the solid lower boundary.

In a traditional turbulent Couette flow, caused by the constant motion of two parallel plates in opposite directions and simulated in recent years by Papavassiliou and Hanratty (1997) and Lee and Kim (1991), a streamwise, rotating cellular turbulent structure has also been found. In a typical turbulent flow an energy cascade process occurs whereby the larger, unstable eddies break down into smaller eddies, transferring their kinetic energy down the scale spectrum until it can be dissipated by viscosity. Papavassiliou and Hanratty (1997) noted that the large scale structures observed were actually capable of receiving energy from small scale motions, contrary to the common energy cascade process.

Under both constant and oscillating body forces representative of tidal forcing, the application of surface temperature gradients

* Corresponding author.
E-mail address: rachelwalker@mail.usf.edu (R. Walker).

http://dx.doi.org/10.1016/j.ijheatfluidflow.2014.08.005
0142-727X/

can inhibit or promote vertical mixing. Taylor et al. (2005) considered the case of an open channel with stable stratification imposed at the free surface by a constant heating flux. An adiabatic solid lower wall was used and a stably density stratified pycnocline was seen to develop throughout the channel, inhibiting the mixing induced by the turbulence generated by flow interaction with the solid wall at the lower boundary.

To date, LES applied to open channel flows has usually maintained focus on stably stratified density profiles through the application of surface heating (Taylor et al., 2005) or the application of bottom and surface Dirichlet boundary conditions such that the temperature difference across the channel is fixed (for example Armenio and Sarkar (2002)). Adapting the LES code of Tejada-Martínez and Grosch (2007) and using a pressure gradient driven channel flow with zero surface shear stress, we can apply a constant surface temperature flux to see the impact of a cooling induced buoyancy on the large scale turbulent structures described above. The constant pressure gradient or body force can be assumed to represent a tidal force at peak tide; the turbulent motions are considered on a time-scale significantly shorter than that of a full tidal cycle such that this can be assumed to be temporarily constant.

The structure of the rest of the paper is as follows. After a brief description of the governing equations, the major differences in the equilibrium dynamics between pressure gradient-driven flow both with and without cooling-induced buoyancy will be highlighted. This will include comparison of mean and root mean square of velocity and temperature profiles and budgets of important resolved turbulent quantities such as turbulent kinetic energy and its components, as well as colormaps of velocity fluctuations showing the large-scale turbulent structures on both vertical and horizontal planes in the flow domain.

2. Governing equations

The non-dimensional, spatially filtered governing continuity equation, Navier–Stokes equations for momentum, and advection–diffusion equation for temperature in our incompressible flow are, respectively,

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{1}{Re_\tau}\frac{\partial \bar{\tau}^v_{ij}}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j} + Ra_\tau \theta_f \delta_{i3} + f\delta_{i1} \quad (2)$$

$$\frac{\partial \bar{\theta}}{\partial t} + \bar{u}_j \frac{\partial \bar{\theta}}{\partial x_j} = \frac{1}{Re_\tau Pr}\frac{\partial^2 \bar{\theta}}{\partial x_j^2} + \frac{\partial \lambda_j}{\partial x_j} + s \quad (3)$$

An overbar denotes application of a homogeneous low-pass spatial filter. Streamwise, cross-stream and vertical directions are denoted by x_1, x_2 and x_3 respectively. $\bar{p}$ and $\bar{u}_i$ are the dimensionless, spatially filtered pressure and velocity.

The characteristic flow velocity is taken as the bottom friction velocity $u_\tau = (\tau_{wall}/\rho_0)^{1/2}$. Here, τ_{wall} is the mean viscous shear stress at the no-slip bottom boundary. Non-dimensionalizing the governing equations with characteristic flow velocity u_τ, characteristic length scale $\delta = H/2$ (the water column half depth) and characteristic temperature $\theta_* = \delta|d\theta/dx_3|_s$ (based on the absolute value of the imposed temperature gradient at the surface: $|d\theta/dx_3|_s$) gives rise to the constant Reynolds number, Rayleigh number and Prandtl number defined as

$$Re_\tau = \frac{u_\tau \delta}{\nu}$$
$$Ra_\tau = \frac{\beta g \delta^2}{u_\tau^2}\left|\frac{d\theta}{dx_3}\right|_s \quad (4)$$
$$Pr = \frac{\nu}{\kappa}$$

as seen in (2) and (3). Note that ν is the molecular kinematic viscosity, κ is the molecular diffusivity and β the coefficient of thermal expansion. The Prandtl number is set to 7. The setting of the Reynolds and Rayleigh numbers will be addressed in due course.

The sub-grid scale (SGS) stress and buoyancy flux, τ_{ij} and λ_j, generated by the spatial filtering are modeled using the dynamic Smagorinsky model (Smagorinsky, 1963) as follows:

$$\tau_{ij} = 2(C_s\bar{\Delta})^2|\bar{S}|\bar{S}_{ij}$$
$$\lambda_j = (C_{\bar{\theta}}\bar{\Delta})^2|\bar{S}|\frac{\partial \bar{\theta}}{\partial x_j} \quad (5)$$

where $\bar{\Delta}$ is the spatial filter width, C_s, and $C_{\bar{\theta}}$ are Smagorinsky coefficients, $\bar{S}_{ij} = (\bar{u}_{i,j} + \bar{u}_{j,i})/2$ is the filtered strain-rate tensor and $|\bar{S}_{ij}|$ its norm. Note that the model coefficients are computed dynamically (Germano et al., 1991; Lilly, 1992).

The fourth term on the right hand side of the momentum Eq. (2) represents buoyancy. In this buoyancy term θ_f is defined as $\bar{\theta} - \theta_b$ where bulk temperature θ_b is instantaneous $\bar{\theta}$ averaged over homogeneous directions of the flow, here taken to be the horizontal directions x_1 and x_2 (for further detail of this treatment of the buoyancy term the reader is directed to Tejada-Martínez et al. (2009) and Armenio and Sarkar (2002)).

The last term in the momentum Eq. (2) is the constant body force (or pressure gradient) in the x_1 direction representing tidal forcing. In this case the dimensionless body force is $f = 1/2$. Finally, the last term on the right hand side of Eq. (3) represents a source term used to make the temperature statistically steady (Leighton et al., 2003). This source term in dimensionless form is $s = 1/(2PrRe_\tau)$. Note that without this term the temperature would decay continuously throughout the domain due to the surface cooling boundary condition, which is to be described further in the next section.

3. Flow configuration

A sketch of the computational domain is provided in Fig. 1. The computational domain is of dimensions $4\pi\delta \times (8/3)\pi\delta \times 2\delta$ in the x_1 (downstream), x_2 (cross-stream) and x_3 (vertical) directions respectively, where again δ represents the channel half-depth. Periodic boundary conditions are applied in both the former two horizontal directions, zero shear stress and no-penetration ($\bar{u}_3 = 0$) are applied at the upper surface, and no-slip is applied at the bottom. The flow, characterized by a Reynolds number of 395, is driven by a constant, uniform pressure gradient aligned with the x_1-axis as described above.

The bottom wall is adiabatic and a cooling heat flux is applied at the surface. In dimensional form, the vertical gradient of temperature at the surface is prescribed as $(d\theta^d/dx_3^d)_s = -Q/k$ where $Q > 0$

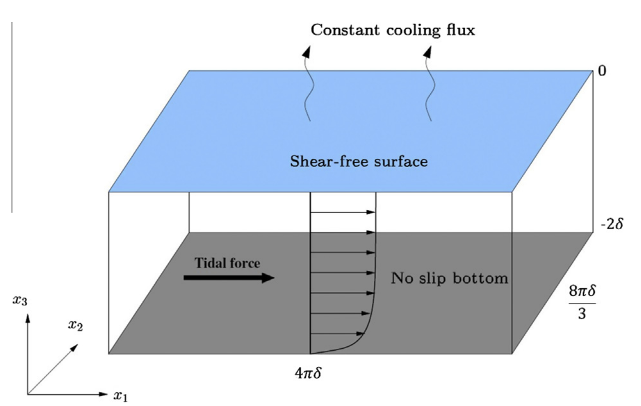

Fig. 1. Three dimensional LES domain featuring pressure-gradient driven flow and unstable stratification.