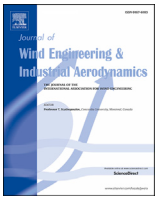
Journal of Wind Engineering & Industrial Aerodynamics 170 (2017) 214–225

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

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



Large-eddy simulation of stably stratified flow past a rectangular cylinder in a channel of finite depth

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ARTICLE INFO

Keywords:
Aerodynamic force
Large-eddy simulation
Rectangular cylinder
Stationary internal wave
Stratified flow

ABSTRACT

Large-eddy simulation is performed to investigate an incompressible stratified flow with a linear temperature gradient past a rectangular cylinder with side ratio $b/h = 0.6$, where b and h are its breadth and depth, respectively. Simulations are performed for Reynolds number $\mathrm{Re} = 8,400$ with respect to a series of stratification numbers K. Results show that transition of stratification effect occurs at around $K = 2$ due to the occurrence of second-order stationary internal waves. Both Strouhal number St and drag coefficient C_D decrease with stratification number K when $K < 2$ due to suppression of vertical motion, but increase with K when $K > 2$ because of the stationary internal waves. The relationship between the fields of temperature and other flow parameters are studied and a coincidence of temperature field with internal wave is observed at high stratification number. Finally the stratification effect on the vortex street is discussed.

1. Introduction

Stratified flow past a bluff body is of fundamental importance to many wind-related engineering issues such as wind loads on structures, urban air pollutant dispersion, pedestrian wind environment and wind-induced structural vibration. Generally, flow stratification in the atmospheric boundary layer is the state in which heavier air is found below lighter air (Cushman-Roisin and Beckers, 2011). In the present study, however, simplifications were introduced to define the flow stratification as the condition in which inflow temperature rises linearly in the vertical direction while the inflow velocity is uniform, which is equivalent to a linear density gradient according to Boussinesq approximation. Currently, wind resistant design of structures is performed with respect to strong winds under neutral conditions, neglecting the influence of flow stratification that is often encountered in natural atmospheric surface layers (Cushman-Roisin and Beckers, 2011). However, flow stratification may influence wind loads on structures in various ways. In a stably stratified atmospheric surface layer the vertical and horizontal distributions of wind speed are affected by buoyancy and gravity waves and the flow-structure interaction process may exhibit different behaviors as in neutral flow, creating different wake formations and different aerodynamic forces acting on the structure. In addition, this complicated flow-structure interaction process may be influenced by micro-scale turbulence accompanying stratified atmospheric flow. The differences between wind load on structures under neutral and non-neutral conditions are of great interest, so a stratified flow past a rectangular cylinder is systematically investigated in the present study, aiming to shed light on wind loads on structures caused by stratified wind and the mechanisms behind them. Note that a channel of finite depth is considered in the present study, by which wave energy is trapped between the upper and ground rigid boundaries. According to linear theory, internal waves in a channel of finite depth have discrete vertical modes and continuous horizontal modes (Wei et al., 1975), making it easier to recognize stationary internal waves and to study stratification effects on flow around obstacles through experimental or numerical studies.

There has been less research on finite-depth stratified flow than on neutral flow. Most has focused on basic theory of internal waves or atmospheric surface layer flow over ground-mounted obstacles, idealized or real hills, urban terrains and ocean surfaces (e.g. Ding et al., 2003; Leo et al., 2016). Flow patterns over objects are mainly affected by the geometric shape and Reynolds number $\mathrm{Re} = \rho_0 Uh/\mu$ (ρ_0: reference density; U: inflow velocity; h: height of object; μ: viscosity coefficient) among others. However, in a stably stratified fluid, flow motions are modulated by stratification also. The stratification strength can be defined by internal Froude number $\mathrm{Fr} = U/Nh$ based on bluff body size h or stratification number K based on channel depth H:

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http://dx.doi.org/10.1016/j.jweia.2017.08.019
Received 10 January 2017; Received in revised form 28 June 2017; Accepted 27 August 2017

List of symbols (unless otherwise defined in the text)

U	Inflow velocity
b, h	Breadth and depth of rectangular cylinder
H	Channel depth
y	Height from ground
Re	Reynolds number
T	Temperature
N	Brunt-Väisälä frequency
α	Thermal expansion coefficient
n	Vertical mode number
λ	Longitudinal wavelength
K	Stratification number
St	Strouhal number
x_1	Roll-up distance
x_r	Longitudinal length of recirculation zone
C_D	Mean drag coefficient
C_{pb}	Mean base-pressure coefficient
C_p	Mean pressure coefficient
C_{Lf}	Fluctuating lift coefficient

$$K = \frac{NH}{\pi U} \tag{1}$$

$$N^2 = -\frac{g}{\rho_0}\frac{\partial \rho}{\partial y} = \frac{g}{\theta_0}\frac{\partial \theta}{\partial y} \tag{2}$$

where Brunt-Väisälä frequency N, namely the buoyancy-driven oscillation frequency of a fluid parcel, is constant for a linearly-stably-stratified air; ρ is the flow density, θ and θ_0 are the potential temperature and its reference value, y is the height from ground and g is the gravity acceleration. The physical meaning of K is the ratio of the fastest linearly vertical internal-wave speed to the inflow speed (Ozono et al., 1997). Regarding stratified flow over bluff bodies, Honji (1988) reported that the Strouhal number $\mathrm{St} = f_v h/U$ (f_v: vortex shedding frequency) of a horizontal circular cylinder in the Reynolds number range $150 < \mathrm{Re} < 450$ is smaller than in a neutral fluid, and vortex shedding is suppressed in the vertical direction. Lofquist and Purtell (1984) measured the drag on a sphere moving horizontally through stably stratified fluid in the Reynolds number range 150 to 5,000 and found that lee-wave drag and suppression of turbulence in the wake contributed positively and negatively individually to the amount of drag. Hanazaki (1988) reported that stratified flow past a sphere for $\mathrm{Re} = 200$ becomes approximately two-dimensional when stratification increases to $\mathrm{Fr} < 0.4$. Ohya and Nakamura (1990) and Ohya et al. (2013) utilized a density-stratified wind tunnel to study the near wakes of a circular cylinder and rectangular cylinders for $5,000 \le \mathrm{Re} \le 10,000$. They reported a critical change of vortex shedding pattern at around $K = 1$, which was caused by asymmetric stationary internal waves. Meanwhile, Ozono et al. (1997) performed two-dimensional numerical and experimental studies on rectangular cylinders for $\mathrm{Re} = 1,000$ and found that if the rectangular cylinder was symmetrically placed in a stratified flow, only symmetric stationary waves with vertical mode number $n = 2$ would occur and the critical change of drag coefficient and Strouhal number took place at around $K = 2$. However, if there was a geometric asymmetry in the flow configuration, an asymmetric wave with $n = 1$ appeared, resulting in a critical change of flow pattern at about $K = 1$.

As shown above, previous research efforts have not led to consistent conclusions on stratification effects on flow around a cylinder. In addition, most previous experimental and numerical studies were conducted at low Reynolds number or high blockage ratio (Honji, 1988; Ohya et al., 2013). Some numerical studies were even two-dimensional. Furthermore, the relationship between the temperature field and velocity field was seldom discussed in the past. The mechanism and flow structure of stratified flow are not fully understood. Many unknowns remain, and further detailed study is necessary on this flow configuration. To accurately simulate the interaction between a rectangular cylinder and surrounding stratified flow and to then gain reliable prediction of wind load, three-dimensional large-eddy simulation (LES) at a higher Reynolds number and a low blockage ratio is considered essential, which promoted the present study. In addition, the present study considers a rectangular cylinder with side ratio $b/h = 0.6$, which is the 'Golden Section' (Norberg, 1993) for studying neutral flow around a rectangular cylinder. At this side ratio, vortex shedding is very powerful, accompanied by strong roll-up of separating shear layers at near wake and, as a result, drag coefficient reaches a maximum value (Nakaguchi et al., 1968; Bearman and Trueman, 1972). The stratification effect on vortex shedding is considered easier to recognize at this section, since no reattachment happens and vortices are strong.

This paper presents a three-dimensional LES study of stratification effect on flow around a rectangular cylinder of side ratio $b/h = 0.6$ placed at the center height of a channel with a channel depth $H = 20h$. In order to clarify the stratification effect, the simulations were carried out for 16 stratification numbers, $K = 0$, 0.3, 0.5, 0.8, 1, 1.2, 1.4, 1.5, 1.6, 1.8, 2, 2.2, 2.4, 2.5, 2.8 and 3, in which $K = 0$ corresponds to neutral flow. The simulations were performed under a relatively high Reynolds number $\mathrm{Re} = 8,400$ and a low blockage ratio $h/H = 5\%$. Detailed analyses of aerodynamic parameters, near wake pattern and stationary internal waves are presented, in order to depict a clear picture of the stratification effect and its variation with stratification strength. In addition, the relationships between the fields of temperature and other flow parameters, including pressure, velocity and vorticity, which were seldom discussed in the previous researches, were investigated in order to enhance the understanding of stratification effects.

2. Problem formation and numerical details

2.1. Filtered Boussinesq function for LES

In the present study, the linearly-stably-stratified flow is treated as an incompressible fluid simplified by Boussinesq approximation, where flow density $\rho = \rho_0$ is constant in all solved equations, except for the buoyancy term in the momentum equation,

$$(\rho - \rho_0)g \approx -\rho_0(\alpha T - \alpha T_0)g \tag{3}$$

where T and T_0 are the local and reference temperature and α is the thermal expansion coefficient. By Boussinesq approximation, the constant density gradient is equivalently replaced by a linear gradient of temperature. The accuracy of the Boussinesq approximation is sufficient as long as changes in actual density are small, namely

$$\alpha T - \alpha T_0 < < 1 \tag{4}$$

In the simulation, a high-Rayleigh-number condition is assumed, so the heat transfer is primarily in the form of convection, corresponding to a condition of buoyancy-force-driven natural convection. In addition, changes of fluid thermal properties are neglected, which means that viscosity coefficient, thermal conductivity and specific heat are treated as constant. Eqs. (5)–(7) present the filtered Boussinesq equations for LES:

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0 \tag{5}$$

$$\frac{\partial \overline{u}_i}{\partial t} + \overline{u}_j\frac{\partial \overline{u}_i}{\partial x_j} = -\frac{1}{\rho_0}\frac{\partial \overline{P}}{\partial x_i} + \frac{\mu}{\rho_0}\frac{\partial^2 \overline{u}_i}{\partial x_i \partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} - \alpha g_i(T - T_0) \tag{6}$$