Large-eddy simulation for turbulent flow and gas dispersion over wavy walls

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A R T I C L E   I N F O

A B S T R A C T

Large-eddy simulation is implemented for turbulent flow and gas dispersion over wavy walls across a wide range of the wave amplitude to wavelength ratio (α = 1.0, 1.5, and 2.0). Two tracer gases are emitted from point sources located at a single crest and trough of the wavy wall. Because the values of α increase under the Reynolds number based on the bulk velocity and the wavelength is 6.67×10^4, the flow separates behind the crest and the standard deviations of the fluctuation in streamwise and spanwise velocity components become relatively large especially at the upslope of the wavy wall. The increase are related to the vortices linked to the Görtler instability mechanism. The change in the flow pattern with respect to the value of α significantly affects the gas dispersion within the valley. As the Reynolds number increases under the wavy wall with α = 2.0, the flow tends to follow the bottom surface of the wavy wall and the number of the vortices increases at the upslope, but the vortices do not significantly affect the gas dispersion over the wavy wall.

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1. Introduction

Turbulent flow and gas dispersion over a complex geometry are of interest in numerous environmental and engineering problems. In a chemical industry, the momentum and scalar transfer between a gas and liquid over a wavy wall is essential in several types of gas-liquid contactors. Under environmental flow, the turbulent flow and gas dispersion are significantly affected owing to complex terrain such as mountains, hills, and valleys. The wavy wall induces the alternation of favorable and adverse pressure gradients and a relatively large ratio of amplitude to wavelength generates a complex recirculating flow, which enhances scalar mixing.

A three-dimensional turbulent flow over a two-dimensional wavy wall is the simplest wavy wall, but the flow pattern is complicated. The two-dimensional wavy wall is normally characterized using the wave ratio $2a$, which is the ratio of the wave amplitude $2a$ to the wavelength λ. The pressure variation and velocity field outside the viscous wall region in the non-separated flow for relatively small values of α can be approximated using the linear theory, but the linear theory eventually becomes inappropriate as α is increased [1]. When α is larger than 0.03 and the Reynolds number Re_h, based on the half-width of the channel and the bulk velocity, which is smaller than 1.92×10^4, the flow separates over the wavy wall. Zilker and Hanratty [2] and Kuzan et al. [3] demonstrated the

border between the separated and non-separated flows spanned by α and Reynolds number Re_α (based on the friction velocity and wave amplitude). Buckles et al. [4] classified the detachment of the boundary layer from a wavy surface as three zones: a free shear layer formed by the detachment of the boundary layer from the wave surface, a separated region, and an attached boundary layer. Hudson et al. [5] incorporated another outer layer zone into the classification. The separated region is bounded by the streamwise function of zero. The separation point occurs where there is an unfavorable pressure gradient and the reattachment point occurs immediately upstream of the maximum pressure region [4]. Above the separated region, a shear layer is generated that contains an inflection point and exhibits a large velocity gradient [5]. Yoon et al. [6] implemented direct numerical simulation (DNS) and evidently observed velocity bursts, which they described as large eruptions from the trough. In an attached boundary layer, a thin accelerating boundary layer forms after reattachment of the flow downstream of the trough until the next crest, and in this layer exceedingly large velocity gradients are observed near the wall. In the outer layer above the shear layer, the flow is not affected by the wave-induced turbulence. The turbulent statistics are based on the friction velocity, as in a turbulent flow over a flat plate. As the Reynolds number increases, the recirculation zone decreases in size and finally disappears. For α = 0.05, a recirculation zone has been observed for $Re_h = 5.0 \times 10^3$ and 1.5×10^4 but not for $Re_h = 3.0 \times 10^4$ in the water-channel experiments [2]. Wagner

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et al. [7] indicated that for a relatively high Reynolds number, the recirculation zone decreases in size and the mean velocity gradient becomes larger than that for a lower Reynolds number. The existence of the recirculation zone depends significantly on the Reynolds number.

Several researchers [8–12] have focused on the heat transfer over a wavy wall, but the mass transfer has not been investigated in detail. Zilker and Hanratty [2] used traces of dye streamers originating from injection points on the downslope, near the separation point, downstream of the separation point, and in the trough, and observed the basic trajectories of the dyes for α = 0.125. Wagner et al. [7] measured the velocity and concentration of a trace dye for a turbulent flow over a wavy wall with α = 0.05 in a water channel. A point source was located at the crest of a wavy wall. The wavy wall was observed to enhance the spreading rate of a scalar plume, compared with plumes over the flat wall.

Rossi and Iaccarino [13] implemented DNS for scalar mixing from a point source over a wavy wall and Rossi [14] concluded that the algebraic models can predict the scalar field in complex flows when the mean velocities and the Reynolds stress tensor are accurately represented. Michioka et al. [15] investigated the Reynolds-number dependence of gas dispersion over a wavy wall with α = 0.1 using large-eddy simulation (LES) and indicated that gas advection increasingly follows the bottom surface of the wavy wall as the Reynolds number increases. However, this study was limited to a wavy wall with α = 0.1. The relationship between turbulent flow and gas dispersion over a wavy wall with different values of α is still unclear.

DeAngelis et al. [16] indicated that large spanwise fluctuations occur at the upslope of the wavy wall. These are related to vortices linked to the Görtler instability mechanism, which are observed in boundary-layer flow over a concave surface [17,18]. The formation, development, and destruction of the vortices were visualized using LES by Tseng and Ferzier [19]. However, these previous studies have provided less attention to the effect of the vortices on the gas dispersion over a wavy wall.

The paper is organized as follows. First, the LES is implemented for three types of wavy walls with α = 0.1, 0.15, and 0.2 for $Re = 6.67 \times 10^4$ to investigate the change in turbulent flow and gas dispersion over wavy walls. Under $Re = 6.67 \times 10^4$, the mean recirculation flow was not observed for α = 0.1 [15]. Subsequently, the effect of the vortices linked to the Görtler instability mechanism on the gas dispersion and the Reynolds-number dependence of the scalar dispersion over a wavy wall with α = 0.2 for $2.40 \times 10^4 \leq Re \leq 2.67 \times 10^5$ is investigated. Point sources are located at a single crest and a trough of the wave. The computational conditions and numerical set-up are described in Section 2 and using the LES results, we subsequently discuss the mechanism of gas dispersion over a wavy wall in Section 3.
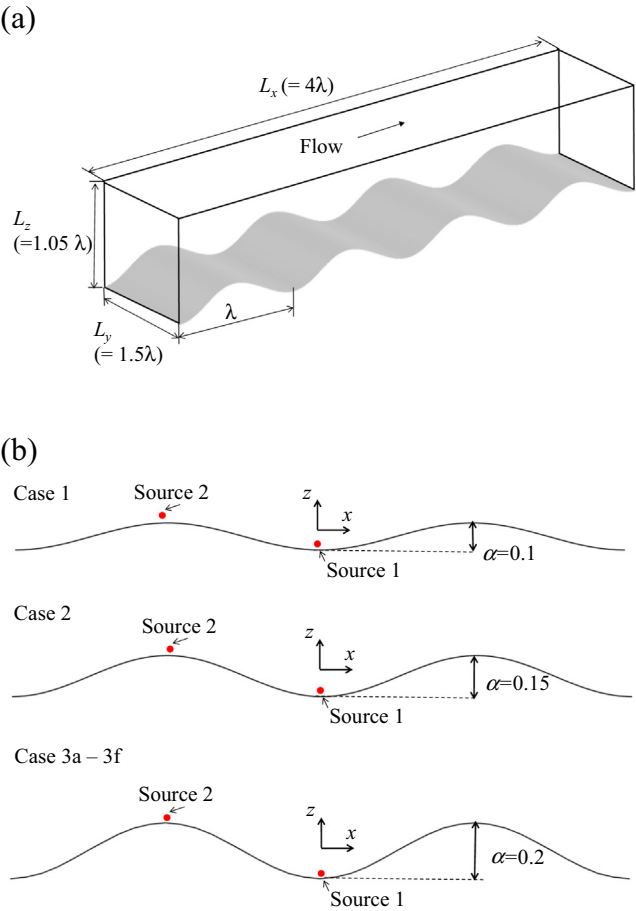

Fig. 1. Schematic of (a) computational domain in Case 1, (b) geometry of a wavy wall.
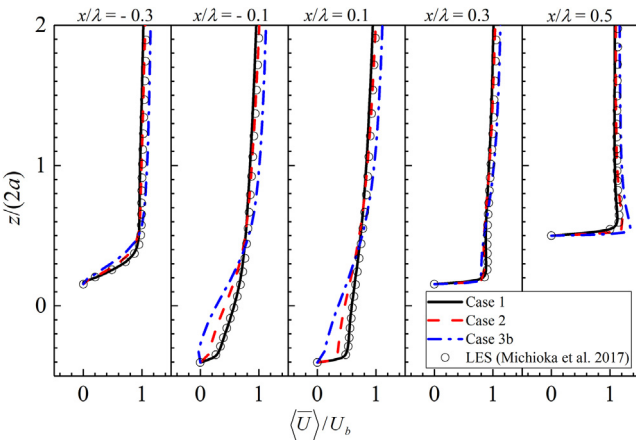

Fig. 2. Vertical distributions of the mean streamwise velocity component at x/λ = −0.3, −0.1, 0.1, 0.3 and 0.5.

Table 1
Computational conditions.

	$2a/\lambda$	$L_x \times L_y \times L_z$	$N_x \times N_y \times N_z$	Re	U_b (m/s)
Case 1	0.1	$4\lambda \times 1.5\lambda \times 1.05\lambda$	$170 \times 128 \times 128$	6.67×10^4	1.0
Case 2	0.15	$4\lambda \times 1.5\lambda \times 1.075\lambda$	$170 \times 128 \times 128$	6.67×10^4	1.0
Case 3a	0.2	$4\lambda \times 1.5\lambda \times 1.1\lambda$	$170 \times 128 \times 128$	2.40×10^4	0.36
Case 3b	0.2	$4\lambda \times 1.5\lambda \times 1.1\lambda$	$170 \times 128 \times 128$	6.67×10^4	1.0
Case 3c	0.2	$4\lambda \times 1.5\lambda \times 1.1\lambda$	$170 \times 128 \times 128$	1.33×10^5	2.0
Case 3d	0.2	$4\lambda \times 1.5\lambda \times 1.1\lambda$	$170 \times 128 \times 128$	2.00×10^5	3.0
Case 3e	0.2	$4\lambda \times 1.5\lambda \times 1.1\lambda$	$170 \times 128 \times 128$	2.67×10^5	4.0
Case 3f	0.2	$4\lambda \times 1.5\lambda \times 1.1\lambda$	$170 \times 128 \times 172$	2.67×10^5	4.0