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Experimental and numerical investigation of developing turbulent flow over a wavy wall in a horizontal channel

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HIGHLIGHTS

- PIV experimental data for turbulent flow over a channel with a lower wavy wall.
- CFD analysis of 2D cross section using 4 eddy viscosity models and 3 second moment closure RANS models.
- Results in the developing and fully periodic regions are presented.
- Mean flow, separation and re-attachment locations, and Reynolds shear stress are presented.
- Wall treatment significantly affected prediction of recirculation.

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ABSTRACT

Turbulent flow over a wavy bottom wall in a horizontal channel is investigated by experimental and numerical methods. The ratio between wave length and wave amplitude is 10. This work assesses the predictive accuracy of the seven turbulence models and provides an experimental benchmark dataset suitable for numerical validation in both the developing and fully periodic regions of the wavy wall flow. The experiments are conducted using a particle image velocimetry system at a Reynolds number of 10700. The influences of the recirculation region and the shear layer region on the flow mean quantities are studied experimentally. Three Reynolds stresses (streamwise, wall-normal, and shear) are examined to assess the development of the turbulence quantities along the wavy channel. There are significant differences between the flow characteristics at the first wave compared to others. Flow periodicity is found at Wave 8. Computational fluid dynamics simulations are performed to predict the turbulent flow using four eddy viscosity turbulence models: standard k-epsilon, Realizable k-epsilon, standard k-omega, and SST; and three Second Moment Closure (SMC) turbulence models: LRR-IP, LPS, and SMC-omega. The standard k-epsilon, Realizable k-epsilon, and LPS models have the best overall agreement compared to the experiments. The eddy viscosity models predict similar results for the mean velocity and recirculation location. The LPS and SMC-omega models are also in good agreement with experimental data for the mean velocity. The wall treatment is shown to be critically important in the capability of the model to predict the flow separation. The results indicate no notable benefit of the SMC models compared to the eddy viscosity models in capability of predicting the mean flow and the separation and re-attachment locations.

1. Introduction

Turbulent flow over structured surfaces occurs in many engineering systems. One common example is wavy surfaces in compact heat exchangers. The engineering interest is due to the increased transport of heat and mass that is usually associated with an increase in momentum transport. A thorough understanding of turbulent flow over structured surfaces is essential to the design and performance of heat exchangers. Computational Fluid Dynamics (CFD) simulations, which are extensively used to evaluate engineering system performance, rely on the turbulence model selection. Consequently, high quality experimental data and an assessment of commercially available turbulence models are important.

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Nomenclature

a	wave amplitude, [m]
h	half mean channel height, [m]
k	turbulence kinetic energy per unit mass, [$\mathrm{m^2 s^{-2}}$]
N	number of nodes
P	mean pressure, [$\mathrm{N\,m^{-2}}$]
Re	Reynolds number
u	velocity fluctuation in the x direction, [$\mathrm{m\,s^{-1}}$]
v	velocity fluctuation in the y direction, [$\mathrm{m\,s^{-1}}$]
$-\overline{uv}$	Reynolds shear stress per unit mass, [$\mathrm{m^2 s^{-2}}$]
U	mean velocity in the x direction, [$\mathrm{m\,s^{-1}}$]
u_*	friction velocity: $\sqrt{\tau/\rho}$, [$\mathrm{m\,s^{-1}}$]
U^+	dimensionless mean velocity in the x direction: U/u_*
U^*	dimensionless mean velocity in the x direction: U/U_b
V	mean velocity in the y direction, [$\mathrm{m\,s^{-1}}$]
V^*	dimensionless mean velocity in the y direction: V/U_b
W	channel width, [m]
x, y	Cartesian coordinate directions, [m]
$\tilde{x}$	dimensionless length: x/λ
y^*	dimensionless length: $y/2h$
y^+	dimensionless wall-normal distance: $\rho\, u_*\, y/\mu$

Greek Symbol

ϵ	turbulence dissipation rate, [$\mathrm{m^2 s^{-3}}$]
λ	wave length of wavy surface, [m]
μ	dynamic viscosity, [$\mathrm{kg\,m^{-1}\,s^{-1}}$]
ρ	density, [$\mathrm{kg\,m^{-3}}$]
τ	wall shear stress, [$\mathrm{N\,m^{-2}}$]
ω	specific turbulence dissipation, [$\mathrm{s^{-1}}$]

Subscripts

b	referring to bulk
h	referring to the half channel height
in	referring to the inlet region
r	referring to reattachment
rms	Root Mean Square
s	referring to separation
t	total
x	referring to the x direction
y	referring to the y direction
wall	referring to the wall

Superscripts

$*$	dimensionless quantities normalized using U_b or h

The geometry of interest in this study is shown in Fig. 1, where $2h$ is the mean channel height, $y_{\mathrm{wall}} = a\cos(2\pi\tilde{x})$ is the bottom surface position, λ is the wave length, and a is the wave amplitude. Note that y_{wall} is equal to zero at the mean wave level, equal to a at $\tilde{x} = 0.0$, and equal to $-a$ at $\tilde{x} = 0.5$, where $\tilde{x}$ is a local definition of dimensionless position along each wave.

The Reynolds number Re_h is defined in terms of the half channel height (h) and the bulk velocity (U_b), which is obtained from the local velocity profile, $U(y)$, where y varies from $y = y_{\mathrm{wall}} = a$ to $y = 2h$, as follows:

$$U_b = (2h - a)^{-1} \int_a^{2h} U(y)dy. \tag{1}$$

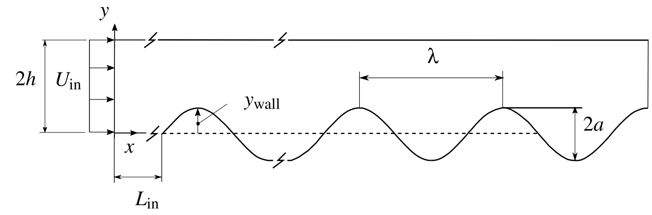

Fig. 1. Model domain.

Considerable research has been undertaken in the past to understand the turbulence characteristics of this flow, which are quite complicated compared to canonical turbulent flows over flat walls because of repeated flow separation and reattachment. Relevant experimental works are summarized in Table 1.

The flow development along the wavy section was discussed in Zilker et al. [1], where no significant changes in the wall shear stress were noted after the second wave, for a geometry with $\lambda/a = 64$. Buckles et al. [3] demonstrated the flow periodicity by comparing the streamwise mean velocities and turbulence intensities at $\tilde{x} = 0$ and $\tilde{x} = 1.0$, at the eighth wave. Martins Segunda et al. [10] confirmed the periodicity at the eighth wave when comparing mean velocities and turbulence intensities at the third, sixth, eighth, and ninth waves.

The studies for the fully periodic region in Zilker et al. [1], Zilker and Hanratty [2], and Kuzan et al. [4] demonstrated that the flow regime changes from a non-separated to a separated regime with a decrease in λ/a. Zilker and Hanratty [2] observed that reverse flow is possible for λ/a smaller than 60.6. They also concluded that the Reynolds number range where reverse flow exists increases with a decrease in λ/a. Kuzan et al. [4] demonstrated a modest decrease in the recirculation size with a Reynolds number increase from 4080 to 12 000. A subsequent increase to 30 000, however, showed a considerable decrease in the recirculation size for $\lambda/a = 10$.

Buckles et al. [3] and Kuzan et al. [4] studied the flow physics of a turbulent flow for a large amplitude wavy surface with flow separation, with $\lambda/a = 10$. Their velocity measurements revealed an inner boundary layer formation downstream from the reattachment location. This thin inner boundary layer moves away from the wall at the separation point and forms a free shear layer. Buckles et al. [3] identified a region of high vorticity associated with this free shear layer containing high velocity gradients. Martins Segunda et al. [10] also observed this high vorticity region in their studies. Hudson et al. [5] extended their previous work by studying the Reynolds shear stress and the turbulence kinetic energy production. Their studies concluded that the shear layer formed by the separation of the flow is responsible for large Reynolds shear stress values. Martins Segunda et al. [10] results for mean velocity and recirculation size in the fully periodic region agreed with previous experimental data [3].

Kruse et al. [6] investigated the dynamics of flow by analyzing the temporal flow behavior and stated that the large-scale flow structures provide a mechanism for momentum or scalar transport between the wavy wall and the bulk fluid. Kruse et al. [7] showed that Reynolds stresses, Reynolds stress correlations and turbulence kinetic energy in the outer flow are independent from those turbulence quantities generated at the wall. In Kruse et al. [8], particle image velocimetry (PIV) and liquid crystal thermometry (LCT) techniques were used to include heat flux studies of a wavy channel flow. They found that low-momentum high temperature fluid coming from the heated wall replaces high-momentum lower-temperature liquid, which advects towards the wall. This study reinforces the argument that such geometries are beneficial to heat exchangers applications, as they promote