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Investigation of fundamental flow mechanisms over a corrugated waveform using proper orthogonal decomposition and spectral analyses

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ABSTRACT

This study investigates the interactions between the underlying turbulent features that together make up the complex flow behaviour observed in corrugated channel flows. Higher order analyses using proper orthogonal decomposition (POD) and wavenumber spectra were conducted on the turbulent velocity data for heated and unheated air flow through the channel. Results showed that at a given flow rate, the turbulent flow energy was produced by the corrugation and transported into the bulk flow at both heated and unheated conditions. At low flow rates, the heated wall increased the total turbulent energy and affected its distribution across the modes. Strong energies were seen close to the corrugations, which contributed to sustaining structures at higher modes, while the flow energy was more evenly distributed for the unheated condition. At the highest flow rate, the energy strength and distribution was very similar at low modes ($n \leq 20$) and heating effects were most prominent at high modes with higher energies associated with small-scale flow patterns. It is observed that the corrugation waveform has a larger impact on the turbulence generation compared to heating. The addition of heat primarily increased and maintained the strength of turbulent structures.

1. Introduction

Increasing the efficiency of heat exchangers is a desirable mean to reduce the energy consumption. A corrugated surface is a passive method suggested to increase thermal performance in channel flows by increasing turbulence and hence mixing [1]. Turbulence is generated over a wavy surface differently than that over a smooth wall because of the flow separation off the waveform crest and the generation of the shear layer. A common observation in studies conducted on the flow over a waveform is an asymmetric mean velocity profile, with a peak shifted away from the waveform surface, and an increase in the turbulent velocities, Reynolds stress, and turbulent kinetic energy production in the vicinity of one wave height [2–8].

Breuer et al. [2] conducted a numerical and experimental study to characterize the flow behaviour over a series of hills for a range of Reynolds numbers. They observed the flow reattachment position varied non-monotonically with the Reynolds number, which was considered to be due to the flow recirculation on the windward side of each hill. Their results provided an insight into the expected flow behaviour from shedding after flow separation and reattachment over a range of Reynolds numbers.

Kruse et al. [3] studied the turbulent flow over sinusoidal waves of three different amplitude-wavelength ratios in a channel using particle image velocimetry (PIV) technique. They found that the surface roughness does not have a significant impact on Reynolds stress and energy production approximately one wavelength away from the mean corrugation height. They also conducted a proper orthogonal decomposition (POD) analysis and observed that the large scales of structures were independent of the waveform amplitude and wavelength. They also suggested that at higher modes the local wall curvature could influence spanwise structures. The qualitative and quantitative data obtain using PIV allowed better understanding of the turbulent energy transfer mechanism over corrugated surfaces.

There are very few studies that examined the relationship between the flow structure and the heat transfer over the waveform. Eiamsa-ard and Promvonge [4] studied the effectiveness of heat

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transfer over a square waveform with variable spacing. Their results indicate that at sufficiently high Reynolds numbers, the Nusselt number becomes almost independent of the spacing to wave height ratio. Additionally, at a given Reynolds number, as the spacing between crests increases, the turbulent kinetic energy becomes stronger and spreads wider. Yang and Chen [9] conducted a numerical analysis on the heat transfer effectiveness in a channel flow between two saw-tooth corrugated surfaces. By varying the saw-tooth angle, they observed that an increase in the corrugation angle increased flow recirculation in the corrugation troughs which resulted in an increased Nusselt number. These studies enabled an improved understanding of the effects of heat transfer and Reynolds number, and the associated variation in the Nusselt number, for corrugated flows.

The mean velocities and turbulent properties of the flow within a corrugated transpired air collector channel for an unheated collector have been examined by Greig et al. [7]. For the unheated flow, the maximum mean velocity was shifted towards the plane construction wall and peaks of turbulent properties for an unheated flow were located at a height of one corrugation waveform. The turbulence produced by the waveform was found to advect and dominate the whole channel, especially at high flow rates. Relatively large turbulent velocity magnitudes were observed at the lowest flow rate (Reynolds number corresponding to the laminar regime) within the trough sections, which were attributed to strong instabilities that were generated by the corrugation waveform [7]. Greig et al. [8] investigated the influence of heat transfer from the corrugation wall on the mean and turbulent flow structure. It was found that the mean velocity and turbulent property magnitudes were largely enhanced at low flow rates compared to an unheated flow. At the lowest flow rate, the flow over the heated corrugated wall was primarily buoyancy driven and turbulent instabilities in the trough section were large. As the flow rate was increased, the magnitudes of mean velocity and turbulent properties became comparable to those observed for the unheated flow as forced convection became the dominant heat transfer mode. The results reported by Greig et al. [7,8] suggest that there are mechanisms involved at different scales within the corrugated channel flow that are not fully understood, especially the instabilities induced by the corrugation waveform.

There is a scarcity of studies on the detailed investigation of the underlying flow mechanisms above a wavy surface, particularly above a heated waveform. The present study investigates the energies and scales associated with turbulent flow features and how they are influenced by wall heating. The characterization of these energies and scales is important not only to improve the efficiency of the heat transfer in a corrugated channel but also contributes to the improved understanding of different features that comprise the turbulent corrugated flow.

2. Experimental setup

Experiments were conducted to measure the air flow in a two-dimensional channel bounded between a rough corrugation waveform and a plane wall. The channel was 1.83 m long (L), 1.22 m wide and the height of the channel based on the mean corrugation height (H) was 10.95 cm. The corrugation amplitude (h) and wavelength (l) were 3.5 cm and 15 cm, respectively. Radiation heat was supplied to the exterior of the corrugation wall by a 6×6 array of 60 W Sylvania halogen light bulbs spaced evenly 20 cm apart. The experiments were conducted for two heating cases and a non-heating case at five flow rates. Two dimensional instantaneous velocity fields over a complete waveform were obtained at three locations along the channel length, $X/L = 0.41$, 0.57, 0.80, where X was measured from the inlet of the channel (see Fig. 1). However, the results presented in this paper are for non-heating and high heating (793 W) cases and at the middle channel location ($X/L = 0.57$). The field of view of the camera was about 15.3 cm $\times$ 11.5 cm. For each measurement, 3000 eight bit images were acquired, using an image acquisition system (CoreView, IO Industries), to obtain 1500 velocity fields. Images were captured for the crest and trough regions separately to maintain high resolution, consequently there was about a 20% overlap of these measurement domains. For each position, measurements were taken in the mid cross plane where the flow was two-dimensional. Since the air density and viscosity varies with temperature, the Reynolds number for each flow rate could not be used as the reference parameter when comparing cases. The five flow rates will be referred to as Cases, I, II, III, IV and V; where Case I represents the lowest flow rate while Case V represents the highest flow rate. For reference, the corresponding Reynolds numbers for the unheated condition are 530, 2030, 2675, 4140, and 6650, respectively.

The uncertainly in the PIV velocity measurements was computed at the highest flow rate and the high heat case, which has the largest velocity gradients of all cases. It was estimated based on the criteria and data presented in Cowen and Monismith [10] and Prasad et al. [11] which was produced an error of ± 0.29 cm/s which was less than 1% of the bulk flow velocity.

In the present study high order analyses were utilized to conduct an in-depth investigation of the underlying physical mechanisms associated with the dynamical flow structures and their interactions. These include spectral analysis in the wavenumber domain and proper orthogonal decomposition (POD) analysis. The turbulent velocity data from Greig et al. [7,8] were used for these analyses.

2.1. Proper orthogonal decomposition scheme

A POD analysis in fluid dynamics represents the distribution of flow energy content at different orthogonal modes, thus one is able to determine the locations and energy associated with different turbulent structures. The first mode contains the largest mode energy and the most dominant and energetic structures within the flow. As the mode increases the total mode energy decreases and the size and energy of structures in general, tend to decrease. The primary mode is first determined as the component with the largest variance, and each subsequent mode is determined based on the eigenvectors of the turbulent velocities [12]. POD decomposes the turbulent flow from a data set to derive the orthogonal modes or basis functions, $\phi(\overline{x})$. These modes can be combined to describe different turbulent coherent structures as they are highly correlated with the turbulent flow field [13]. For the present study, the snapshot method was used with planar PIV turbulent velocity data using the algorithm developed by Doddipatla [14]. In this algorithm, the velocity is first expanded into a sum of spatial and temporal components given by eq. (1) [15]:

$$\overline{u}(\overline{x}, t) = \sum_{n=1}^{N} a^n(t)\phi^n(\overline{x}) \tag{1}$$

where $\phi^n(\overline{x})$ is the spatial component known as the basis function and $a^n(t)$ is the temporal coefficient. The eigenvalues can then be obtained from eq. (2) [15].

$$\int \left\langle \overline{u}(\overline{x}, t)\overline{u}^*(\overline{x}', t) \right\rangle \cdot \phi^n(\overline{x}')d\overline{x}' = \lambda^n \phi(\overline{x}) \tag{2}$$