International Journal of Heat and Mass Transfer 104 (2017) 178–198

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

# Investigation of coherent structures in a turbulent channel with built-in longitudinal vortex generators

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ARTICLE INFO

*Article history:*
Received 10 January 2016
Received in revised form 21 July 2016
Accepted 29 July 2016

*Keywords:*
Turbulent channel flow
Vortex generators
Large eddy simulation (LES)
Proper orthogonal decomposition (POD)
Quadrant analysis
Vortical motion
Bursting events
Coherent structures

ABSTRACT

The present study discusses the results pertaining to eduction of coherent structures and assesses their contribution in promoting mixing between low and high momentum fluid streams to enhance thermal convection. The analysis has been carried out numerically in a periodic parallel-plate-channel containing built-in longitudinal vortex generators on the bottom wall. The Reynolds number of the investigation is 6000 based on the channel height and bulk mean velocity. The computational geometry resembles heat exchanger surfaces on which the vortex generators create strong longitudinal vortices that enhance heat transfer on the plane channel wall. At high Reynolds numbers, the enhancement of convective heat transfer near the wall largely depends on the large scale turbulent structures (coherent structures) that disappear and reappear frequently and exhibit typical correlated scales in time or space. Proper orthogonal decomposition (POD) is an efficient tool to identify these coherent turbulent structures from instantaneous flow field data. Despite geometrical simplicity, the complex swirling motion behind the vortex generators demands highly accurate computational method, like the large eddy simulation (LES) of turbulence for capturing the nuances of flow. The instantaneous velocity data at a cross-flow plane have been assembled over a long time-window and analyzed deploying POD technique to extract the large- and small-scale structures based on the turbulent kinetic energy of the structures. Reconstructions of the velocity field using different combinations of eigenmodes have yielded different patterns of the flow. Large-scale structures have been visualized using first few energetic modes, while remaining less energetic modes have provided small-scale structures. The technique enables us to identify coherent structures hidden in the random flow field by filtering the small scale effects. The analysis yields as large as 15 dominant POD modes to cumulatively capture as low as 25% of the total turbulent kinetic energy of the flow, indicating broad range of energy spectrum that shares a large number of POD modes and thereby concludes highly complex turbulent fields with numerous spatial and temporal turbulent scales. Reconstructed velocity fields considering the leading dominant modes reveal a cut-off of 43% turbulent kinetic energy to clearly expose the coherent structures, which are consistent with published literature on similar turbulent channel flows. Additionally, quadrant analysis on the reconstructed velocity fields has clearly revealed that sweep and ejection modes are the only dominating Reynolds-stress-producing events for the current flow of interest, where the vortices lift the low-momentum fluid away from wall through the ejection mechanism. The high-momentum fluid impinges on the wall in sweep mode.

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## 1. Introduction

It is of significant importance to analyze and interpret the spatial and temporal structures contained in the instantaneous velocity data to understand the nature of turbulence, and to decipher information related to formation and interaction of flow structures typical of the members of the ensemble in some sense. Despite random in nature, turbulent flows provide regular flow patterns ascribed as coherent structures. Since its inception [1], the study on coherent structures has become extremely useful in providing new insights related to kinematics, dynamics and scales of turbulence. In turbulent flow fields, coherent structures are characterized as distinguishable large-scale turbulent fluid mass that disappear and reappear in a repetitive manner. These structures

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.07.105
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**Nomenclature**

| | |
|---|---|
| t | time |
| u, v, w | velocities in streamwise, wall-normal and spanwise directions |
| $L_p$ | length of channel |
| $B_p$ | width of channel |
| H | half height of channel |
| l | length of winglet pair |
| h | height of winglet pair |
| $U_m$ | mean streamwise velocity |
| Re | Reynolds number |
| M | number of snapshots |
| N | number of spatial points |
| R(x,x′) | two-point correlation tensor |
| x | streamwise direction |
| y | wall-normal direction |
| z | spanwise direction |
| Q | second invariant |
| POD | proper orthogonal decomposition |
| TKE | turbulent kinetic energy |
| LES | large eddy simulation |
| SGS | subgrid-scale stress tensor |
| SISM | shear improved Smagorinsky model |
| $C_s$ | Smagorinsky constant |

*Greek*

| | |
|---|---|
| $\nu$ | kinematic viscosity |
| $\nu_T$ | Eddy viscosity |
| $\rho$ | density |
| $\beta$ | angle of attack of winglet pair |
| $\alpha$ | eigenvector |
| $\lambda$ | eigenvalue |
| $\Phi$ | eigenfunction |
| $\Delta$ | grid filter width |

*Symbols*

| | |
|---|---|
| $\langle\rangle$ | time averaging |
| (,) | inner product |
| $\|\| \ \|\|$ | norm |

*Superscripts and Subscripts*

| | |
|---|---|
| $()^+$ | normalized by $u_\tau$, $\delta$ and $\rho$ |
| $()'$ | fluctuation component |
| $(\bar{\ })$ | filtered quantity |
| $()^T$ | transpose vector |
| p | period |

also retain their shape for a relatively long time against dissipation, and thus exhibit typical correlated scales in time or space that are significantly larger compared to the smallest local scales of flow.

A wide class of coherent motions is documented in the literature [2]. Examples of some typical coherent motions include: streaks of high and low speed fluid motions in boundary layer [1], outward ejections of low speed fluid and sweeps of high speed fluid towards the wall [3] and vortical structures of different shape [4]. High and low velocity streaks, distributed randomly in space, are commonly found in the inner region of boundary layer. Ejection and sweep mechanisms, often found in the turbulent boundary layers, maintain turbulence production process. Similarly, relevance of the vortical coherent motions, such as, symmetric arch vortices, quasi-streamwise vortices and hairpin vortices, has been elucidated in the literature [1,5–7].

Since the characterization and interpretations of coherent motions solely depend on the method used to identify these structures, it is necessary to devise accurate methods for educing coherent structures. Using physically meaningful flow quantities, numerous identification techniques have been proposed and implemented to identify coherent structures. Reynolds decomposition and vorticity are traditional approaches. Unfortunately, Reynolds decomposition provides little information regarding the turbulent structures as illustrated by Adrian et al. [8]. Alternative procedures to Reynolds averaging are Galilean decomposition and low-pass filtering [8]. Some promising modern techniques include two-point correlation [9], critical-point analysis of local velocity gradient tensor [10], conditional sampling [11] and stochastic estimation [12]. The suitability of the method depends on the structures to be investigated for a particular purpose. Some methods are better suited for educing small scale vortices and some methods are appropriate for extracting large scale vortices.

The study of coherent structures thus calls for an accurate, unbiased and statistical method which can exploit the quantitative nature of the data to extract coherent patterns from multidimensional data sets. Proper orthogonal decomposition (POD) [13] is one such efficient method that takes advantage of the spatial information of the multipoint instantaneous velocity fields obtained either from experimental PIV measurement or numerical simulations. POD is a powerful mathematical tool that decomposes an ensemble of data into spatiotemporal modes or sets of optimal basis functions [14,15]. More specifically, the decomposition provides a set of time-independent orthogonal spatial components or eigenfunctions and time varying coefficients. The decomposition is unbiased because it does not look for prior information of the flow and the basis functions are obtained from the data set itself in contrast to other expansion techniques, such as, wavelet or Fourier transforms. The method is optimal in the sense that expansion with any arbitrary number of modes can converge faster and recover larger fraction of energy from the data compared to any other available expansion techniques (e.g. Fourier expansion). Therefore, the method is truly efficient for extracting the dominant energetic structures of a multi-dimensional process while employing only a few modes. Since POD acts as an inhomogeneous low-pass filter, it is highly effective for studying inhomogeneous turbulent flow fields [8]. The dominant structures obtained from this decomposition are found to represent coherent motions [15].

The POD procedure has been applied in many disciplines. Depending on the application, it was popularly known as Karhunen–Loeve (K–L) decomposition, singular value decomposition [15] or principal component analysis. In the context of turbulent flow, for the identification of coherent structures, the classical POD technique was first introduced by Lumley [16]. He suggested that the POD modes represent coherent structures if and only if it possess a dominant fraction of energy. Although, the implementation of classical POD has been restricted due to high computational power, snapshot POD technique as introduced by Sirovich [17], has been found to be an efficient method. Some notable works by Sirovich et al. [18], Berkooz et al. [13], Bakewell et al. [19] and Aubry et al. [20] have established the potential of this technique in fluid mechanics.

The method of interest has been adopted in many flow configurations, such as, in free shear flows by Kirby et al. [21], in separated flows by Alfonsi et al. [22], in transitional boundary layer [23], in motored engine flows [24] and so on. Moin et al. [25] and Ball et al. [26] have investigated coherent structures in turbulent channel flows using POD method. Alfonsi et al. [27] applied 3D snapshot POD to extract the coherent structures in

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