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LES of turbulent flow in a cubical cavity with two parallel lids moving in opposite direction

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ABSTRACT

Large-eddy simulation (LES) of the incompressible turbulent flow in a two-sided lid-driven cubical cavity with lids moving in anti-parallel direction has been carried out at a Reynolds number of 12,000. The transient behaviour of the corner eddies have been discussed on the statistically symmetric plane. Time averaged solutions have been obtained by performing a long-lasting simulations using multiprocessing. The presence of four more eddies except the well known two corner eddies have been found in the transverse plane of the main core flow direction. The extent of the main average recirculating flow in the central core region in the x–z and y–z plane has been reported. The specific features of turbulent flow inside the cavity such as inhomogeneity of turbulence, small-scales localisation, second order turbulent statistics, cross-correlation of vorticity component and coherent structure of flow have been investigated.

1. Introduction

In the field of computational fluid dynamics the lid-driven cavity problem is commonly used as a benchmark problem similar as backward facing step problem. The complex flow inside the cavity offers the study of flow separation, recirculation, impingement, formation of eddies and many other phenomena. The simplicity in geometry of lid-driven cavity allows ease of formulation and implementation of boundary condition. A large number of numerical and few number of experimental studies on lid driven cavity flow for variety of configurations are present in literature. The experimental study of three-dimensional lid driven cavity for the ratio $1:1$ (depth to width) and $3:1, 2:1$, and $1:1$ (span to width) has been presented by Koseff and Street [1–3]. They have used thymol blue technique and rheoscopic liquid illuminated by laser-light sheets flow visualization, two-component laser-Doppler-anemometer for velocity measurements, and flush mounted sensors to the heat flux on the lower boundary of the cavity. The Reynolds number chosen in the range of 1000 to 10,000. They found that the flow becomes turbulent in the range of Reynolds numbers between 6000 to 8000. The numerical solution of turbulent flow in a single-sided lid-driven cubic cavity for a wide range of Reynolds number has been presented by Iwatsu et al. [4]. They concluded that the flow become unsteady when Reynolds number exceeds approximately 2000. The flow in a one-sided lid-driven cubic cavity is mainly laminar but unsteady in the range of Reynolds number between 10,000 to 18,000 as concluded by Leriche and Gavrilakis [5]. The direct numerical simulation (DNS) using Chebyshev spectral method for the incompressible flow in a single-sided lid-driven cubic cavity has been achieved at the Reynolds number of 12,000, 18,000 and 22,000 by Leriche [6]. The first and second order velocity statistics have been reported at the statistical symmetry plane. The large eddy simulation (LES) in a one sided cubic lid-driven cavity at the Reynolds number of 12,000 have been presented by Bouffanais et al. [7]. The spectral element method (SEM) using the dynamic model have been used and the results were compared with the DNS results of Leriche and Gavrilakis [5]. The results were in very good agreement with DNS results; it shows that the LES can provide a very close solution to DNS and is computationally cheaper. The LES with dynamic Smagorinsky model (DSM) and dynamic mixed model (DMM) using spectral element method (SEM) of flow inside the cavity have been presented by Bouffanais et al. [8] at the Reynolds number of 12,000. The specific features of flow in the turbulent regime, such as turbulence production, inhomogeneity of turbulence, small-scales localisation, time histories of total turbulent kinetic energy etc. have been presented. It shows that the flow inside the lid-driven cavity is transient and turbulent at high Reynolds number, and LES can provide similar results as DNS.

The experimental and numerical investigation of steady flow (low Reynolds number) in a two-sided lid-driven rectangular cavity with the aspect ratio of 1.96 have been presented by Kuhlmann et al. [9,10]. The experimental study for the same aspect ratio with

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Nomenclature

Variables

C	Smagorinsky coefficient
C^*	Smagorinsky coefficient at previous iteration
D	control volume of grid-filter
$\bar{f}(x,y,z,t)$	filtering function
l	dimensional length of a side of the cubical cavity
L_{ij}	resolved turbulent stresses
$\bar{P}$	filtered modified pressure
$\bar{p}'$	pressure correction term
P_t	turbulent production
Re	Reynolds number
$\bar{S}_{ij}$	large-scale strain rate tensor for grid-filter
$\hat{\bar{S}}_{ij}$	large-scale strain rate tensor for test-filter
t	time
T_{ij}	subtest-scale stresses tensor
TKE	total kinetic energy
$\bar{u}_i$	filtered velocities $\bar{u}$, $\bar{v}$, $\bar{w}$ for $i = 1, 2, 3$ respectively
$\bar{u}_i^*$	provisional velocity field
$U_\tau(x_1, x_2)$	dimensional velocity of moving lid
V_{mag}	velocity magnitude $\left(\sqrt{(\bar{u}^2 + \bar{v}^2 + \bar{w}^2)}\right)$
x_i	co-ordinates x, y, z for $i = 1, 2, 3$ respectively

Greeks

$\langle\varepsilon\rangle$	average turbulent energy dissipation rate
δ_{ij}	Kronecker's delta
$\bar{\Delta}$	grid-filter width
$\bar{\Delta}_x$, $\bar{\Delta}_y$ and $\bar{\Delta}_z$	mesh spacing for grid-filter in x, y and z direction respectively
$\hat{\bar{\Delta}}$	test-filter width
$\hat{\bar{\Delta}}_x$, $\hat{\bar{\Delta}}_y$ and $\hat{\bar{\Delta}}_z$	mesh spacing for test-filter in x, y and z direction respectively
ν	kinematic viscosity
ν_{sgs}	subgrid-scale (SGS) viscosity
ω_i	magnitude of vorticity $\omega_x, \omega_y, \omega_z$ for i = 1, 2, 3.
τ_{ij}	subgrid-scale (SGS) stress tensor
τ_{ij}^{turb}	turbulent shear stress tensor

Please note that all variables listed above are dimensionless unless stated otherwise.

some higher Reynolds number about 1200 have been presented by Blohm and Kuhlmann [11]. In the literature there are very few studies for three-dimensional flow field inside a cavity with multiple moving lid. The numerical study of the three-dimensional flow field in a two-sided non-facing lid-driven cubical cavity for low Reynolds number (≤ 700) has been presented by Ben Beya and Lili [12]. They have concluded beyond a certain Reynolds number (540 ± 2) the flow becomes unstable and bifurcates. To the best of our knowledge, the unsteady flow field in a two-sided lid-driven cubic cavity with high Reynolds number has not been studied.

In the present paper, two-sided cubic lid-driven cavity with two parallel lids moving in opposite direction has been studied numerically at 12,000 Reynolds number. The mathematical formulation (Section 2) is based on LES-DSM and the filtered Navier–Stokes equations are discretized using finite difference method. The grid size required for LES should be small enough compared to the integral scale of motion, but need not match the very small Kolmogorov scales, which makes LES significantly computationally cheaper than Direct Numerical Simulation (DNS). The details of computational parameters like velocity distribution on the lids, time step, post processing of data etc. are described in Section 3. As there were no numerical and experimental results found for the comparison, the present code has been validated with the results of one-sided lid-driven cavity flow obtained by Bouffanais et al. [8], Leriche and Gavrilakis [5] at Reynolds number 12,000 (Section 4). After validation of numerical calculation the code has been modified for study of the two-sided lid-driven cavity with parallel lids moving in opposite directions. The present work is a continuation of earlier study of two-sided cubic lid-driven cavity by Patel et al. [13]. In the previous work the one dimensional profiles of averaged velocity ($\langle\bar{u}\rangle$ and $\langle\bar{w}\rangle$) and second order turbulent statistics $\left(\langle\bar{u}'\bar{w}'\rangle, \sqrt{\langle\bar{u}'^2\rangle} \text{ and } \sqrt{\langle\bar{w}'^2\rangle}\right)$ on the mid-line $x = 0.5$ and $z = 0.5$ at statistical symmetry plane ($y = 0.5$) have been presented. Furthermore, the study of two dimensional contour plot of the averaged turbulent production ($\langle P_t\rangle$) and the rate of turbulent dissipation ($\langle\varepsilon\rangle$) for each impingement region of the cavity flow have been included, and the shearing and swirling structures involved in the cavity flow have been discussed at the statistical symmetry plane ($y = 0.5$) as well. In addition,the time histories and power spectra of various primitive variables, turbulent kinetic energy and turbulent production have been plotted for the location of maximum turbulent production zone, and the three dimensional iso-surface of averaged turbulent production ($\langle P_t\rangle$) have been discussed as well. In the present numerical study, the presentation and discussion of results (Section 5) have been divided into four sub-sections 5.1, 5.2, 5.3,5.4. Where the self-similar profiles of wall-jet near the left and right side wall, unsteady behaviour of first corner eddy, second order turbulent statistics $\left(\langle\bar{u}'\bar{w}'\rangle, \sqrt{\langle\bar{u}'^2\rangle} \text{ and } \sqrt{\langle\bar{w}'^2\rangle}\right)$ and coherent structures involved in the cavity flow using proper orthogonal decomposition (POD) analysis have been studied at statistical symmetry plane ($y = 0.5$) in Section 5.1. In addition, the contour plot of the averaged turbulent production ($\langle P_t\rangle$) and the rate of turbulent dissipation ($\langle\varepsilon\rangle$) have been presented at the three locations ($y = 0.25, 0.5$ and 0.75) of x–z plane (Section 5.1). The presence of four more eddies except the two well known corner eddies (first and second corner eddies) have been shown using the study of flow field at the three locations (x=0.19, 0.5 and 0.81) of y–z planes in Section 5.2. The three dimensional profiles of inhomogeneity ofturbulence and the rate of turbulent energy dissipation have been discussed in Section 5.3. Furthermore, the cross correlation between the first and the second corner eddy have been achieved using the time histories of vorticity component (ω_y) at the centre of those eddies, and power spectra of time histories have been presented as well in Section 5.4.

2. Mathematical formulation

In LES the filtered variables or large scale variables (denoted by over-bar) are defined as

$$\bar{f}(x,y,z,t) = \frac{1}{\bar{\Delta}_x\bar{\Delta}_y\bar{\Delta}_z}\int_D f(x,y,z,t)dxdydz. \tag{1}$$

The filtered Navier–Stokes and the continuity equations for an incompressible flow can be obtained by applying the filtering function (Eq. (1)) to the Navier–Stokes and continuity equations. The dimensionless form of the filtered Navier–Stokes (Eq. (2)) and the continuity equations (Eq. (3)) are obtained by using the length of