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Modal analysis of confined square and rectangular cavity flows

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ABSTRACT

Particle image velocimetry (PIV) and common-base proper orthogonal decomposition (CPOD) were used to quantify the velocity field within the separated region of confined square and rectangular cavities with streamwise aspect ratios of one and two, respectively. For a constant Reynolds number of 60,000, the flow structure within the entire domain of the square cavity is dominated by a nominally two-dimensional primary vortex. The flow unsteadiness here is manifested in the rms distributions, which reveal significant contributions from the pseudo-fluctuations due to the meandering of the primary vortex core and from random unsteadiness. Comparisons were made to the backward-facing step geometry, and in contrast, for the rectangular cavity and backward-facing step, large-scale unsteady flow patterns, three-dimensional in character, are present in the velocity field. The formation of these unsteady events was identified through the realization of instantaneous velocity fields. In contrast to the square cavity, the CPOD analysis reveals the presence of a "shift mode" for the rectangular cavity, which results in spanwise variation throughout the entire flow field. As a conclusion, the unsteady behavior observed for both the rectangular-cavity and backward-facing-step flows is absent for the square cavity, which can be attributed to the strong coupling effect of the two vertical cavity boundaries at low streamwise aspect ratios. Furthermore, the spatio-temporal character of the rectangular cavity is shown to be more closely related to the backward-facing step than the square cavity.

1. Introduction

Flow separation resulting from a sudden expansion in geometry, as is encountered in cavities and backward-facing steps, occurs in a large array of engineering applications. Although these geometries are considered as canonical test cases for separated flows commonly encountered in aerodynamic and hydrodynamic problems, the flow-separation characteristics of these base flows can readily be extended to more complex geometries such as in high angle-of-attack or bluff-body flows. The velocity field immediately downstream of the separation point is often characterized by flow phenomena such as corner eddies, flow bifurcations, instabilities, and transition to turbulence. The simplicity of these geometries also readily lend themselves to the validation of turbulence closures since the fundamental topology of these geometries is known. Despite their physical resemblance listed above, the two geometries are often studied independently.

The principle feature of the backward-facing step (BFS) geometry, as observed in both two- and three-dimensional investigations, is the recirculation bubble that forms downstream of the stepped wall. This recirculation zone is characterized by flow reversals and vortical structures, as investigated by Le et al. (1997), Nie and Armaly (2002) and Tylli et al. (2002). Specifically, the flow phenomenon responsible for vortical structures in the shear layer is the Kelvin–Helmholtz instability, which is caused by the interaction between the shear layer and recirculating flow near the stepped wall, as recently described by Rani et al. (2007). In addition to the Reynolds number, the key variables associated with the backward-facing step problem are the expansion ratio (ER) and spanwise aspect ratio (SAR), defined as the ratios of downstream to upstream channel height and channel width to step height, respectively. The SAR is relevant only for three-dimensional geometries, whereas the ER is applicable to both two- and three-dimensional geometries. Tylli et al. (2002) reported the formation of complex flow structures for confined (three-dimensional) channels. Furthermore, they demonstrated that for laminar flow, these structures intensify with increasing Reynolds number for an ER and SAR of two and twenty, respectively. Existing literature on the backward-facing step geometry is rich and encompasses a wide range of topics, including quantification of the reattachment line as performed by Nie and Armaly (2002), turbulent energy budgeting beneath the separated shear layer and topological analyses of the flow by Le et al. (1997). However, studies performed on this

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geometry at high Reynolds numbers in the turbulent regime and with three-dimensional geometries are scarce due to obvious computational and experimental limitations.

Much like the backward-facing step geometry, the cavity has received similar attention over the past few decades ever since the pioneering work of Burggraf (1966). The majority of published studies in this area have been performed on cavities with a streamwise aspect ratio (StAR) of one, which is defined as the ratio of cavity length to height. The flow structure inside the square cavity is characterized by a main stationary/captive primary vortex, secondary vortices in the bottom two corners and Taylor–Görtler-like (TGL) vortices along the bottom of the cavity as investigated in detail by Prasad and Koseff (1989), as sketched in Fig. 1.

Rockwell and Knisely (1979) investigated the effect of the downstream cavity wall on evolution of the shear layer for Reynolds numbers of 106 and 324. The influence on the shear layer was found to be global, extending throughout the entire length of the shear layer, confirming the presence of feedback mechanisms within the cavity. Many studies have been conducted within laminar or transitional regimes, such as the work of Migeon (2002) and Sheu and Tsai (2002). However, comparatively few studies exist for Reynolds numbers above 10,000. Prasad and Koseff (1989) investigated the effect of Reynolds number ($3200 \leqslant \mathrm{Re} \leqslant 10{,}000$) and end-walls on square cavity flow through a series of experiments while varying the SAR between 0.5 and 1. A reduction in the SAR increased the viscous drag from the side-walls, which in turn decreased the velocity of the fluid over most of the domain. This reduction in the SAR also eliminated meandering of the TGL vortices, which were found to no longer have a dominant role on the flow field at higher Reynolds numbers (10,000 and above). Flow past two-dimensional rectangular cavities was investigated by Rowley et al. (2002) through numerical simulations. For small aspect ratios, the flow was found to be steady, but as the aspect ratio was increased the flow transitioned to a shear-layer mode characterized by self-sustained oscillations. For even longer cavities, the flow transitioned further to a "wake-mode" and contained a region of significant backflow in the cavity, which was hypothesized to be the cause of the feedback mechanism leading to the wake-mode. Several shortcomings in the numerical modeling were identified which could not be resolved without the assistance of more detailed three-dimensional simulations and experiments. Bouffanais et al. (2007) tested two LES models, namely the dynamic Smagorinsky and dynamic mixed models, for the three-dimensional cavity geometry at a Reynolds number of 12,000. These simulations were compared with the experimental results from Prasad and Koseff (1989) and were found to be in good agreement based on the cavity topology and velocity distributions despite small Reynolds number discrepancies. The flow was found to be highly inhomogeneous near the downstream wall, where turbulence production was found to be a maximum. In a similar set of simulations, Habisreutinger et al. (2007) investigated the accuracy of an LES simulation using the Legendre spectral element method for the lid-driven cavity problem. They used a DNS reference solution which utilized a Chebyshev collocation method at a Reynolds number of 12,000. Subgrid modeling of flows which contain coexistent laminar, transitional and turbulent flow regions, as is the case for the lid-driven cavity, is a challenging undertaking. Such numerical validations necessitate the presence of large experimental databases for these canonical geometries. Faure et al. (2007) performed flow visualizations in rectangular cavities with aspect ratios between 0.5 and 2 for a Reynolds number ranging between 1150 and 10,670. The aspect ratio, rather than the Reynolds number, was found to influence the vortex structure in the cavity. Aspect ratios of 1.5 and 2 were accompanied by an unsteady main vortex and a secondary vortex near the bottom of the upstream wall. For an aspect ratio of 1 the vortex occupied the entire cavity, with the secondary vortex reducing to a corner vortex. Two superimposed vortices with low velocities were observed for an aspect ratio of 0.5.

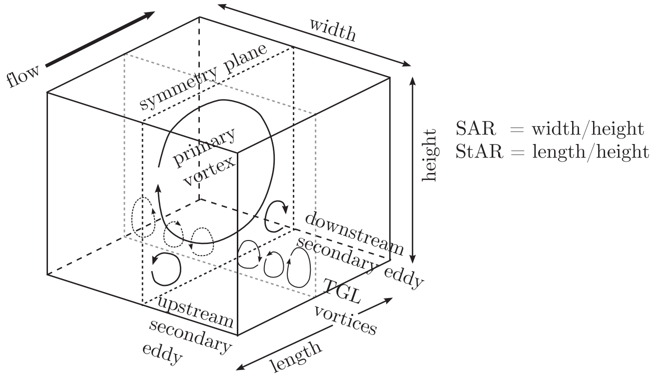

Fig. 1. A schematic view of the principle features of the square cavity outlining the primary, secondary and Taylor–Görtler-like vortices, as well as the symmetry plane at the mid-span. The spanwise aspect ratio (SAR) and streamwise aspect ratio (StAR) are shown here for clarity.

Although it is apparent through a brief review of the literature that the scope of existing studies is both broad and comprehensive, it is just as apparent that many fundamental questions still remain unanswered. In the present study, we investigate the effect of end-walls and compare the velocity fields for the geometries described above at a constant Reynolds number of 60,000 and an expansion ratio (ER) and spanwise aspect ratio (SAR) of 1.4 and 2.87, respectively. In particular, three geometries are tested: square and rectangular cavities (denoted occasionally in this study for convenience as SC and RC) with StARs of one and two, respectively; and the backward-facing step. It has been shown in previous work that only at cavity aspect ratios of five and beyond can behavior similar to the backward-facing step be expected; the current study will characterize this transition for low aspect ratios. The geometries were selected to investigate and quantify the spatial and temporal differences between the vortical structures formed beneath the shear layer. Based on the velocity and corresponding rms information obtained experimentally from the PIV measurements and subsequent CPOD analysis, this work will address the following questions:

(i) Is the rectangular cavity more closely related to the square cavity or the backward-facing step? How is the primary vortex in the separated region affected by an increase in the streamwise aspect ratio?
(ii) How prominent is the effect of side-walls on the flow within the cavities and downstream of the backward-facing step? Can regions of the flow be approximated as two-dimensional for any of these three geometries?

2. Experimental methods

2.1. Facility and test geometries

The experiments were performed in a free-surface water tunnel, as shown in Fig. 2. Water is pumped to a main plenum and through four conditioning units consisting of one honeycomb and three fine screens, before being accelerated into the test section through a six-to-one ratio contraction. Turbulence intensity has been measured at approximately 0.3% of freestream. The two test sections (with a total length of 4 m) end with a reservoir, which facilitates the recirculation of water back to the plenum through the axial pump.