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Experimental and numerical investigation of coherent structure dynamics on mass transfer in a separated cavity flow

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ABSTRACT

This study presents the experimental and numerical investigation of coherent structure dynamics on mass transfer in a separated cavity flow. The flow field dynamics of a cavity type stagnation zone with a length to width ratio of 2 were studied. The cavity was driven by a channel flow with a Reynolds number of 1.8E5. The study utilised flow visualisation, laser Doppler velocimetry (LDV) and electrical conductivity probe measurements. Measurements of mean velocity and turbulence intensity profiles across the separated flow field showed the development of the shear layer and the recirculating flow pattern in the cavity. The numerical simulations were also performed for comparison with the experimental results considering the solution of the RANS, LES model and two-layer turbulence model. LES produced the formation and dynamics of coherent structures within the separated shear layer. Flow visualisation revealed a pulsatile motion in the separated flow region associated with the formation and passage of coherent structures and was supported by measurements of tracer concentration. The study showed how coherent structures in the separated shear layer enhanced the mass transport process from the stagnation zone and how the recirculating flow in the cavity influenced the development of those structures.

1. Introduction

The dispersion of contaminants in natural streams is a major environmental concern. In a study of dispersion in turbulent shear flow [1], it was concluded that the mechanism of turbulent mixing and transport could be described by the so-called one dimensional dispersion equation in terms of cross-sectional mean concentration. This model has been widely used when dealing with mixing and transport of contaminants in natural streams. In many cases, however, the results have failed to produce a generally acceptable description of the mixing process and the resulting contaminant concentration distribution [2,3]. A numerical model was developed for analysing the two-dimensional mixing in rivers with unsteady pollutant source [4]. Differential advection effects were approximated by gradient-type dispersion terms, but longitudinal mixing effects were neglected under the assumption that the transverse mixing effects were the overwhelming contributor to the dispersion process. However, these assumptions are not rigidly valid for the dispersion from stagnation zones.

There have been a number of studies on the so-called stagnation zone concept and a number of stagnation zone models [5–7] of varying reliability have been proposed for the prediction of contaminant mixing and transport in natural streams. It has been noted that the analysis of the stagnation zone models could not be applied directly to natural streams since the detailed geometry of the stagnation zone and its contribution to the mainstream flow could not be quantified. Stream function equations were solved to determine the mean flow patterns in cavity flows at low Reynolds number [8], reproducing some of the experimental towing tank experiments of [9]. Three different operating regimes of low Reynolds number cavity flows have been identified in the transitional Reynolds number region [10], and the effects of attenuation of a transverse pressure wave on the intermittency of the shear layer oscillation were noted. Recent studies highlighted the combined forced and natural convection heat transfer in a deep lid-driven cavity flow [11], the characteristics of chaotic fluid mixing in non-quasi-static time-periodic cavity flows [12], mass and heat transfer by natural convection in a vertical cavity [13] and unsteady thermal flow around a thin fin on a sidewall of a differentially heated cavity [14].

Studies on coherent structures in shear layers [15–21] raised fundamental questions on the applicability the traditionally

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Nomenclature

k	turbulent kinetic energy	y	Cartesian coordinate in transverse direction
ε	turbulent kinetic energy dissipation rate	C	salt concentration
u	stream-wise mean velocity	C_{max}	maximum salt concentration
u'	stream-wise instantaneous velocity	C_{μ}	Constant in the transport equation for ε
v	transverse mean velocity	L	length of cavity region
v'	transverse instantaneous velocity	U	free stream mean velocity
x	Cartesian coordinate in stream wise direction	W	width of cavity

accepted concepts of gradient transport and eddy diffusivity for mixing and mass transfer analyses. Shear-opposed mixed-convection flow and heat transfer in a narrow, vertical cavity has been presented in the combined experimental and theoretical study in [22]. Interest in quasi-steady or repeatable coherent structures in free shear flows [23], which co-exist with small-scale turbulent phenomena, has shown the problem to be very complex. These eddies are now believed to play the major role in the mixing and mass transfer processes in free-shear flows [24]. Recent studies present the turbulent buoyancy-driven flow in a rectangular cavity [25], confined cavity [26] and Passive heat transfer in a turbulent channel flow simulation using large eddy simulation based on the lattice Boltzmann method framework [27]. Role of large coherent structures in turbulent compressible mixing is demonstrated by Yu [28]. Span-wise concentration non-uniformity was reported by [29] who concentration measurements at various locations in a gaseous mixing layer. They associated this non-uniformity with the secondary stream-wise vortex structures, which, according to them contributed to the mixing of a passive scalar. Interest in high Mach number flows over cavities has prompted LES modelling [30] and a number of experimental studies [31–37]. These studies mainly focused on the acoustic feedback and control properties of cavity flows.

Although there have been a large number of investigations on coherent structures in plane mixing layers [24,28,38], very few investigations have been performed on coherent structures in reattaching shear layer flows. It is now accepted that mass transfer between the stagnation zone and the free stream is mainly governed by advective transport of mass due to the lateral turbulent fluctuating motion of coherent structures formed in the separated shear layer. However, there still remains an incomplete understanding of the detailed dynamics of the turbulent structures in such separated flows. The LES modelling of both [30,39] showed the existence of stream wise braid vortices between the transverse Kelvin–Helmholtz vortices in the shear layer, which may enhance the mass transfer process across the shear layer. The review presented above lead to the present study of a rectangular, cavity-type stagnation zone with the objective of investigating the physical processes involved, particularly the interaction of the large coherent structures in the separated free shear layer with the recirculating flow inside the cavity.

The experimental study involved flow visualisation using dye injection to show the generation and development of eddies in the shear layer and the interaction of eddies with the resulting circulating flow inside the cavity. Measurements of dye concentration at select locations in the shear layer were taken to measure the frequency of passage of eddy structures. Measurements of mean stream-wise and transverse velocity and turbulence intensity across the entire separated flow field were also taken using a single channel LDA. The experimental study was supplemented by numerical predictions using two different methods. The first method solved the RANS equations [40–46] for mean flow in two dimensions using a two-layer eddy viscosity based turbulence model in conjunction with the SIMPLE algorithm [47–50]. The second method used LES, which solved the instantaneous Navier–Stokes equations, to predict the formation and dynamics of the three-dimensional coherent structures within the separated shear layer. The mean velocity measurements from the physical model and the predictions using the RANS numerical model have been presented previously in [51], but are repeated here to provide a benchmark for the LES model and to aid explanation of the concentration measurements and predictions. Some of the flow visualisations have also been presented but are included for the same reasons.

2. Experimental method

The experiments were conducted in a 15.8 m long flume in the Robin Hydraulic Laboratory in the Civil Engineering department at the University of Adelaide. The flume had a cross-section of 0.915 m wide and 0.60 m deep. An overhead tank supplied water through a 300 mm diameter outlet pipe and a constant level was maintained in the overhead tank by pumping water into it from a sump, with the overflow being returned to the sump. The detailed specifications of the flume are shown in Fig. 1. Also shown in the figure is the plan view, showing the cavity type separated flow region that was created in the flume. The width of the free stream section was 0.415 m, while the cavity was 0.5 m wide and 1 m long, with the x and y origins located at the point of separation at the upstream end of the cavity. Free stream mean velocity was maintained at 0.3 m/s, resulting in a Reynolds number of 180,000 calculated on the basis of the width of the separated flow region.

Velocity measurements were made using a single channel laser Doppler velocimeter (LDV) [52]. A dual beam method with backscatter mode of light collection was employed, with a half angle, k, of 3.347° and a fringe spacing of 5.419 μm. With a frequency shift of 0.5 MHz for the velocity range of ±1.0 m/s, the low and high-limit filters were set to 100 kHz and 1 MHz respectively. Typical data rates in the channel and high-speed side of the shear layer were 100 measurements per second. In the separated flow region this rate was substantially reduced leading to velocity biasing, which results from less sampling in the low speed part of the flow, a problem that increases with increasing turbulence [53]. A time-weighting correction method was used in an attempt to alleviate velocity biasing [54]. Fringe biasing was addressed using a frequency shifting technique [55] and the signal-to-noise ratio (SNR) was kept to the lowest level possible by removing as much background light as possible and painting parts of the model black to prevent spurious reflections. Seeding particles were 20–40 μm phenolic micro balloons produced by Union Carbide. Sizes smaller than these improved the measurements for velocity fluctuations higher than 0.1 Hz but were found to add to the SNR, while particles larger than this yield a stronger signal by scattering more light but were less likely to faithfully follow the flow.