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 utilized flow visualization, 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 visualization 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.

Keywords: Cavity flow, separated shear layer, coherent structure, Large Eddy Simulation, Laser Doppler Velocimetry.

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 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] and [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.

Figure 1 - Schematic of experimental apparatus

2. Experimental Method

The experiments were conducted in a 15.8m long flume in the Robin Hydraulic Laboratory in the Civil Engineering department at the University of Adelaide. The flume had a cross-section of 0.915m wide and 0.60m deep. An overhead tank supplied water through a 300mm 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 **figure 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 0.415m, while the cavity was 0.5m wide and 1m 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 back-scatter mode of light collection was employed, with a half angle, k , of 3.347° and a fringe spacing of $5.419\mu\text{m}$. 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 100kHz 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 micron 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.

Flow visualisation was performed using a simple passive tracer injection technique to visually identify the flow phenomena involved. The passive tracer was made by dissolving salt (NaCl), methylated spirits and some blue dye into the flume water. Pictures of the flow field were captured both on videotape and on high-speed movie film. Measurements of tracer concentration at various locations in the separated flow region were made using electrical conductivity probes. The concentration was determined using a conductance meter and the density was checked with a density meter to achieve a neutrally buoyant solution of 5000 ppm. The tracer was introduced from an injection system, built into the sidewall of the cavity (**figure 1**). The injection was continued until the tracer spread over the entire cavity. Results were taken after reaching to the quasi-steady state condition for all variables in the experiment.

A two-electrode electrical conductivity probe arrangement was used to measure the concentration fluctuations of the tracer fluid, after the design of Alonso [56]. The two 0.2mm thick platinum wires were placed 0.45mm apart and had an exposed length of 1.0mm. An estimated rise time [57] of 1 ms was achieved for a 300 ppm solution indicating a reasonably good response time for the probe. The uncertainty of individual measurements was estimated to be less than 1%. The statistical uncertainties for the measured concentrations were estimated to the 6%. Constructing a concentration distribution function and rejecting data points beyond 3.5 standard deviations made this estimation.

3. Numerical Method

The first numerical model employed here solved the governing equations for the ensemble (time) averaged values of the velocity vector, pressure and turbulence parameters (RANS) using a FORTRAN based code written by the authors. The turbulence parameters were obtained using a two-layer eddy-viscosity model, employing the $k\epsilon$ model of Launder and Spalding [58] in the regions away from the walls and the one-equation model of Norris and Reynolds [59] in the near-wall region. In the standard $k\epsilon$ model the steep gradients of variables prevailing in the near-wall region are not resolved by the numerical calculations, rather they are bypassed by using the logarithmic law of the wall. Some of the assumptions made in the derivation of the law of the wall become invalid in the present flow situation; hence the decision to fully resolve the near-wall viscosity affected region with the simple one-equation model was made. The two-layer model used here has been found to perform well in complex flows involving flow separation and steep pressure gradients [51, 60].

During the experimental stage the thickness of the channel was varied from 5 to 60 cm and it was found that at a thickness of 60 cm the mean flow field was two-dimensional. Because the RANS model was only used to predict the mean flow field, a two-dimensional approximation of the three-dimensional flow field was invoked. Boundary conditions employed at the inlet comprised of a uniform stream-wise velocity of 0.3 m/s, negligible turbulent kinetic energy, k , (1 percent of the free-stream velocity) and a rate of dissipation of turbulent kinetic energy, ϵ , equal to $C_\mu k^{3/2}/0.1H$ where $C_\mu=0.09$. A zero pressure gradient boundary condition was used at the exit plane. Iterative solution of the velocity and pressure equations was performed using the SIMPLE algorithm. The second order central differencing scheme (CDS) was used for the diffusion term in the RANS equations because Central difference type schemes are currently being applied on a regular basis in the solution of the

Euler equations and Navier–Stokes equations. The results using central differencing approximation have demonstrated noticeable improvements in accuracy in smooth regions. But, the first order upwind differencing scheme (UDS) was used for the convection term in the RANS equations. By taking into account the direction of the flow, the upwind differencing scheme overcomes that inability of the central differencing scheme. This scheme is developed for strong convective flows with suppressed diffusion effects.

The second numerical method used the freely available Fire Dynamics Simulator (FDS) provided by the U.S. National Institute of Standards and Technology (NIST), which provided the solution of an elliptic form of the instantaneous Navier-Stokes equations appropriate for low Mach number flow [61]. Taking the divergence of these simplified momentum equations allowed a non-iterative Fast Fourier Transform (FFT) method to be used for solving the resulting linear algebraic system of equations. The LES resolved the motion of turbulent eddies whose size was greater than the grid size, while modelling the dissipative effect of eddies in the sub-grid scale (SGS) using an SGS model first developed by [62].

Spatial differencing was achieved using CDS and an explicit second order predictor-corrector scheme was used for temporal differencing. Time stepping was constrained by the Courant-Freidrichs-Lewy (CFL) condition to ensure the Courant number in any cell was always less than 1. A uniform stream-wise velocity of 0.3 m/s was set at the inlet and at the outlet a constant pressure boundary condition was imposed.

A lattice was placed at the inlet to introduce some turbulence into the developing flow, similar to a wire mesh used to raise inlet turbulence levels in a wind tunnel. The lattice

of 2mm wide blockages evenly spaced 2mm apart was the finest resolution achievable with the grid spacing used. Inlet turbulence in the experiment could be generated by any number of naturally occurring sources of instability; however, forcing the turbulence in the LES by means of these large blockages was the only effective method available even though ideally the blockages should be finer.

To obtain a solution independent of the number and spacing of grid nodes, grid sensitivity tests were performed. For the RANS simulations it was found that the solution became grid independent with 100 grids in the stream-wise direction and 50 grids in the cross-stream direction. For the two-layer model to be properly utilised, grids spacing was reduced in the near-wall region. For the three dimensional LES an isotropic grid spacing of 1mm was used, for a total mesh size of 3,200,000 cells. This was found to provide nearly grid independent results. The grid was made uniform in all directions to improve the efficiency of the solver.

Figure 2 - Comparison of measured velocity profiles with predictions - RANS (left) and LES (right)

4. Results and Discussion

4.1. Measurements and Prediction of Mean Flow Field

Predictions of the stream wise and transverse mean velocities and turbulent intensities from the LES are shown in **figure 2**, with the corresponding measurements from the physical model and the predictions from the RANS model from [51] shown for comparison. The RANS predictions were also reproduced in this study and were found to be in agreement with that of [51]. The RANS predictions were reproduced to obtain more comprehensive data required for comparison with the LES results and also to study the salt

concentration distribution in the cavity, which was not carried out in that paper. Data is presented at five locations downstream of the separation point and inside the cavity. The mean stream wise and transverse velocities from the LES were found by sampling the instantaneous velocities at 0.1 second intervals and averaging over a period of 900 seconds from the time the flow pattern in the cavity had become established.

The stream wise velocity profiles for the physical model, the RANS model (**figure 2a**) and the LES (**figure 2b**) showed linear growth of the shear layer, except near the reattachment region, where the decreased growth rate was attributed to the impact of the shear layer reattaching onto the wall. Due to the impact a reverse flow developed and a recirculating eddy jet was formed near the wall, propagating along the walls of the cavity region. The large negative values in the mean stream wise velocity profiles near the bottom of the cavity indicated the existence of such a wall boundary layer jet.

The maximum mean velocity in the cavity region occurred in the boundary layer jet and was up to 38% of the free stream velocity, U , with the LES predicting a slightly lower value. These were similar to the value of 34% at the same location reported by [63] for airflow in a square cavity, however, the absolute maximum of those measurements was 45% of U close to the rear wall. A maximum velocity of over 20% of U was reported by [64] in the separated flow region of a backward facing step.

The only noticeable difference between the RANS and LES stream wise velocity predictions was in the initial shape of the shear layer close to the separation point at $x/W = 0.4$. The LES profile was almost flat across the channel, with a sharp change at the shear layer boundary. The RANS profile was also fairly flat in the channel, however the change in velocity gradient at the shear layer boundary was not as sharp and the shear layer appeared

slightly thicker. The measured profile shows that the shear layer extended well into the centre of the channel, which could only have been a result of the boundary layer development upstream of the separation point. The two-layer approach of the RANS model appeared to predict this upstream boundary layer development better than the LES but there were still significant discrepancies with the measured profile.

The measurements of v/U indicated the existence of the recirculating eddy. The large negative values near the rear wall of the cavity at $x/W = 1.8$ indicated the deflection of the shear layer into the separated region. At about $x/W = 1.4$, negligible transverse velocity components indicated a relatively stagnant area, at least in terms of mean transverse motion. The positive transverse velocities at $x/W = 1.0$ and 0.4 were indicative of the interaction of the recirculating eddy with the shear layer in that region.

Differences between the measured and simulated profiles were more noticeable for v/U than for u/U , with neither simulation predicting the transverse velocities with the same degree of accuracy as in the stream wise direction. The RANS simulation (**figure 2c**) predicted a significant positive transverse velocity only at $x/W = 0.4$ and a negative velocity only at $x/W = 1.8$, and in both cases the magnitude was smaller than the physical measurements. This shows that the interaction of the recirculating eddy with the shear layer was less pronounced in the RANS simulation. Whereas the experiments indicated a stagnant region at $x/W = 1.4$ only, the RANS model predicted this region to extend from 0.6 to 1.4 , nearly half the length of the recess [51]. The agreement between the LES (**figure 2d**) and the physical model was much better, showing a large vertical flow down the rear wall of the cavity and a significant upwards flow between $x/W = 0.4$ to 1.0 . At x/W the physical model still had a significant degree of reverse flow in the lower section of the cavity while in the

LES the velocity was higher in the transverse direction, indicating that the wall jet turned vertical at a location closer to the front of the cavity in the physical model than in the LES. The smaller v/W in the upper part of the $x/W = 1.8$ station indicated that the coherent structures had not entered the recirculating eddy at that point but must have done so closer to the reattachment point and past the measurement location.

Figure 3 - Velocity power spectra - Experiment

Figure 4 - velocity power spectra – LES

4.2. Velocity power spectra at three locations

Figures 3 & 4 show the velocity power spectra at three locations along the separation line, the u spectra from the experiment is shown on **figure 3** and both u and v spectra from the LES are shown on **figure 4**. The LES results also show the spectra in the upstream ducting for reference in each figure and indicate that a lot of energy was present at low frequencies as a result of the lattice construction placed at the inlet for generating turbulence. Ideally, the turbulence produced by this sort of mesh should be isotropic, having a spectra rising from the low frequencies to a peak, then decaying with an inertial sub-range following the Kolmogorov-5/3 law and then decaying exponentially. The inlet turbulence in the LES was not of this form and may have affected the development of coherent structures in the shear layer. At the very least it imposed a significant amount of low frequency background turbulence on the spectra, which made interpretation of the spectra in the cavity region more difficult.

From $x/W = 0.4$ and 1.8 there was an addition of energy at frequencies below 1 Hz in the frequency range of the coherent structures. A much longer record would be required to get a more accurate picture of the spectra in the low frequencies; however, it is clear that

energy was being concentrated there as a result of the low frequency fluctuations of the recirculating eddy. By $x/W = 1.0$ a short Kolmogorov inertial sub-range was observed, indicative of the turbulence becoming more isotropic as a result of the coherent structures being torn into smaller and smaller eddies. By $x/W = 1.8$ the interval of this inertial sub-range had grown to cover approximately one decade. The measurements of [65] confirm that the inertial sub-range in a cavity flow is expected to be small. After the inertial sub-range is an exponential decay region typical of turbulent spectra [66]. Some change in the slope above 10 Hz in the $x/W = 1.8$ spectrum may be indicative of an additional energy input, possibly due to the close proximity to the rear wall of the cavity.

The large peak at 1Hz and the smaller peaks in the higher end of the spectrum are typical of the processing of a non-sinusoidal signal. These are especially noticeable in the $x/W = 1.0$ and 1.8 data set. Even though the peak at 1 Hz is quite large, we are still confident that it is only a function of the signal processing because it sits in the middle of the inertial sub-range without affecting it. If it were a peak due to a real input of energy then it would destroy the inertial sub-range. The experimental data showed stronger peaks in the low frequencies and indicated that a lot of energy was contained in the low frequencies as a result of the slowly recirculating eddy in the cavity. The inertial sub-range was clearly present and also covered roughly a decade.

Figure 5 - Comparison of turbulence profiles

4.3. The measured stream wise and cross stream Reynolds normal stresses

The measured stream wise and cross stream Reynolds normal stresses are shown in **figures 5a)** and **c)** with the corresponding predictions from the LES in **figures 5b)** and **d)**.

There was a significant difference between the LES and experiment with the LDV measuring larger stresses in both cases, with less discernible peaks and a generally more disordered distribution across the cross section. The profiles of the LES were more organised, with significant peaks appearing along the separation line, which grew and spread somewhat into the channel but more extensively into the separated region. The transverse stresses measured in the physical model were up to twice as large as the stream wise stresses in some cases, which was very unusual. The predictions of $v'v'$ from the LES were between $1/10^{\text{th}}$ to $1/5^{\text{th}}$ $u'u'$, which is more typical of shear layers although up to one half might be expected. Due to their relative magnitudes and unorganised nature, some doubt exists over the accuracy of the stress measurements. The sources of error in the LDV have already been identified in the experimental method section.

In **figure 5b)** a strong peak in $u'u'/U^2$ was found in the shear layer very shortly after the separation point. Some of this was the result of transport from the wall boundary layer upstream, the amount of which would have been roughly the same as that on the top wall, which is also shown. At this location the interaction between the recirculating eddy front and separated shear layer formed coherent structures that contributed to the high turbulence intensities along the dividing line. As they rotated and advected downstream they became larger, increasing the size and width of the peak. The coherent structures impinged on the reattaching surface at the rear of the cavity with parts of the structures being deflected downwards into the cavity and recirculating eddy. This gave rise to a pulsatile motion in the recirculating eddy which manifested as higher turbulent fluctuations in the cavity compared to the free stream channel flow which had minimal turbulence. Some of the rotational nature of the coherent structure was also preserved for at least a part of its life in the cavity, adding

to the turbulence intensity. These phenomena were clearly observed in the flow visualisation experiments, which are described in the next section.

The magnitude of $v'v'/U^2$ (**figure 5d**) near the separation point was quite low but grew steadily larger approaching the reattachment point, where a large part of this turbulence was convected into the cavity by the deflected coherent structures. This resulted in much higher values at $x/W = 1.8$ than elsewhere in the cavity region. Without any significant mean transverse velocity gradients present in the flow for producing $v'v'$, the only source of this stress was redistribution of the stream wise normal stress $u'u'$.

The following relation approximated the profiles of turbulence kinetic energy from the physical measurements, $k = 0.5\{\overline{u'^2} + \overline{v'^2} + 0.5(\overline{u'^2} + \overline{v'^2})\}$. **Figure 5e**) compares RANS prediction of k and shows that the RANS model also predicted much lower turbulence levels in the shear layer than those measured in the experiment. The RANS model predicted that turbulent kinetic energy was concentrated along the dividing line between the channel and the cavity, with very little being generated or transported into the cavity itself. It is widely acknowledged that no turbulence model exists for the RANS equations that can even reproduce a plane mixing layer accurately. This is due to the fact that these types of flows are dominated by the formation and advection of large coherent structures while production terms in conventional turbulence models are only based on the local mean velocity gradient and will always fall short of the actual production levels. Diffusive transport played a more dominant role in transport into the cavity in the RANS simulations, which is a relatively slow transport mechanism. Therefore it was not surprising to find low turbulence levels in the recirculating eddy since there were only small mean velocity gradients in the cavity itself, insufficient to add very much to the production. Rather the origin of production was actually

in the shear layer and the model had to rely to a large extent on diffusion for transport of the turbulent kinetic energy into the cavity.

Large negative peaks in the Reynolds shear stress $u'v'$ (**figure 5f**) were observed along the separation line. This indicates that positive u' is mostly associated with negative v' and vice versa, which is understood by the fact that the coherent structures rotate clockwise. Towards the rear wall the shear stress inside the cavity became positive, indicating that the sense of rotation of the vortices had reversed, due to impact with the rear wall. Along the bottom wall however, the clockwise sense of rotation returned manifesting in negative shear stress.

Figure 6 - Long time-scale fluctuation of v velocity

4.4. Long time-scale fluctuation of velocity

Although the time-averaged nature of the RANS equations removes the small-scale fluctuations of the velocity and replaces them with Reynolds stresses (or turbulent kinetic energy in this model), a time dependant term was included to predict transient events much larger than the grid size and of much longer time-scale than the time step. **Figure 6** shows a graph of the transverse velocity predictions at a point located at $x/W = 0.4$ and $y/W = -0.5$, which was inside the cavity and close to where the wall jet interacted with the separated shear layer. Although there was no vortex shedding present in the shear layer of the RANS simulations, there was definite unsteadiness in the recirculating eddy. **Figure 6** clearly shows a long time-scale fluctuation in the recirculating eddy with a frequency of the order of 100 to 200 seconds in the RANS results. A constant line in the figure indicates the mean transverse velocity and shows there was a significant fluctuation. The instantaneous transverse velocity from the LES is also shown in **figure 6**, along with a moving average with a period of 20

seconds and the arithmetic mean, indicating that similar unsteadiness was observed in the LES.

Figure 7 - Decay of tracer in cavity – Experiment.

Figure 8 - Decay of tracer in cavity – RANS model.

Figure 9 - Decay of tracer in cavity – LES model.

4.5. Decay of tracer in cavity – Experiment, RANS and LES model

Salt concentration measurements were taken, indicating the concentration of dye tracer, for a run where dye was released from the bottom wall of the cavity. The instantaneous values of tracer concentration were obtained at 10-second intervals and normalised by the maximum concentration value in the entire cavity region for a particular run. Temporal variations in the measured iso-concentration contours are shown in **figure 7**. Each contour map illustrates the change in instantaneous concentration with time, at a particular transverse section of the flow field. During the initial stage it appeared that the regions of high concentration were at $x/W = 0.4$ (between $y/W = -0.4$ and -0.8) (**figure 7a**) and at $x/W = 1.4$ (between $y/W = -0.4$ and -0.8) (**figure 7d**). This suggests that these were two relatively stagnant areas with low diffusivity. The corresponding iso-contours predicted by the RANS model are presented in **figures 8a & 8d** and show similar behaviour.

The most important feature of these contour plots is the decay in concentration with time. In Fig. 7a, it is apparent that at $y/W = -0.8$ the decay of concentration was not constant. At first the concentration decreased with time up to about 10-seconds and then increased at about the 20-second mark, after which it decreased again. At about the 60-second mark the concentration remained unchanged from its value at 40-seconds, which was $C/C_{\max} = 0.40$. Therefore, the concentration at that point was not decaying constantly at a certain rate, rather it decreased and suddenly increased after some time, and then the rate of change appeared to

be quasi periodic. This particular feature of concentration decay was due to the re-entrainment of dye into the cavity by the periodic impingement of coherent structures in the separated shear layer on the rear wall of the cavity.

On the other hand the iso-concentration contours predicted by the RANS model show a constant decay at all the locations, with the maximum concentration region located at $y/W = 0.6$. This is associated with the failure of the predictions to reproduce the coherent eddy structures. The reason for the failure lies in the assumptions made in the modelling of turbulence phenomenon using the Reynolds averaged approach.

The concentration contours predicted by the LES (**figure 9**) exhibited similar decay characteristics to the experiment. Towards the bottom of the cavity at $y/W = -0.8$ the concentration of dye initially decreased but then showed some increase between 20 to 40 seconds later, followed by another decrease. Just as in the experiment the coherent structures periodically entrained fluid from the cavity with some structures being convected into the channel flow and some being entrained back into the cavity after impinging on the rear wall.

Figure 10 - STA concentration measurements from the physical model and RANS simulations

Figure 11 - STA concentration measurements from the physical model and LES

4.6.STA concentration measurements, RANS and LES simulations

Figure 10 shows the decay of the short time average (STA) concentration from the physical model at different locations in the separated region. The short time averaging removed the very rapid fluctuations while retaining the interesting features associated with the coherent structures in the separated shear layer and within the recirculating eddy in the

cavity. Averaging over a period of one second (100 measured values) was considered appropriate in the present case considering the average passage time of a large eddy in the shear layer was in the order of three seconds. The STA concentration was normalised by the maximum average value of the entire region. The corresponding predicted values from the RANS simulation are also plotted.

The plots in **figure 10** show the decay of STA concentration at four different downstream locations along the separation line at $y/W=0$ (**Figure 10.(a-d)**) and along the line at $y/W=-0.4$ (**Figure 10.(e-h)**). The peaks in the decay curve certainly demonstrate the periodic passage of coherent eddy structures. **Figure 10(d)** shows a decreased number of peaks as one would expect at a downstream location but plots (b) and (c) did not manifest a similar trend. Moreover the peaks did not show any decaying trend, due to the continuous supply of tracer from the cavity region, which was then entrained by the large structures in the shear layer. Contrastingly, the RANS results showed gradual decrease of concentration without any peak in the decay curve. This is due to the ensemble-averaged nature of the equations, as explained above. The absence of peaks indicates that the transfer of concentrated fluid to the mainstream was much slower, resulting in higher predicted concentration values within the cavity.

These STA measurements are further evidence that part of the large eddy structures in the shear layer were deflected back into the cavity region after impinging on the reattaching surface, which resulted the recirculating eddy intermittently carrying either a lump of tracer or a lump of fresh fluid from the mainstream. The concentration decay curves in **figure 10 (e, f, g & h)**, with varying peak levels at different locations, are indicative of this process. However, it should be pointed out that the tracer blobs torn from the large structures

at reattachment were being diffused as they travelled along the recirculating eddy due to the small scale fluctuating motion. The concentration levels were also affected by diffusive transfer of tracer from the relatively stagnant regions in the recirculating eddy (at $x/W = 0.4$, $y/W = -0.4$ and -0.8 ; and $x/W = 1.4$, $y/W = -0.4$), although this occurred at a much slower rate. The process of transfer of tracer blobs or fresh fluid being absent in the RANS predictions resulted in the predicted concentration values remaining high at these locations.

In general, the rapid fluctuations in concentration seen on the dividing line were due to the passage of coherent structures in the shear layer. In the cavity the fluctuations were due to the remnants of coherent structures as they travelled around the cavity in the recirculating eddy, but much slower than the coherent structures in the shear layer resulting in lower frequency fluctuations.

Figure 11 shows the same experimental data compared with the LES predictions of dye concentration in the cavity. In the LES the concentration was sampled at 0.2 second intervals but was an instantaneous value and not short-time-averaged as in the experiment. It should be noted that the level of similarity in the comparison was dependent on the time period over which the sampling was conducted. The 20-second periods shown here were somewhat arbitrarily chosen out of a larger data set as those that best matched the measurements at each location. The data set covered 1000 seconds of statistically stationary flow.

Figure 11 a) shows that sharp peaks of very high concentration were found on the separation line at $x/W=0.4$, which marked the birth of the coherent structures. The frequency in the LES results was higher, with a period oscillation of approximately two seconds

compared with a little over three seconds in the experimental data. The amplitude of the oscillations in the concentration measurements was quite similar in both data sets at all locations. Long periods with minimal significant fluctuations were observed at this location where the shear layer was quite stable, with only relatively small disturbances and no large structures formed, however, they are not shown in this figure.

The level of correlation was similar on the separation line at the next downstream locations in **figures 11b, c and d**, with similar magnitudes in concentration but at a higher frequency. Both the LES and experimental data showed periods of up to 6 seconds with low activity and periods with higher frequency peaks of approximately the same amplitude. The magnitude of the fluctuations reduced as the measurement location moved downstream. This was due to the diffusion and dispersion of the dye by the coherent structures as they grew in size.

The variation in concentration in the cavity was much less than in the shear layer. In the cavity the dye was more homogeneously distributed, with some disturbances due to blobs of fresh channel water being sucked into the cavity. The major point of difference was at $x/W = 1.4$ where the LES consistently predicted lower concentrations of dye than the experiment. This was a relatively stagnant section of the cavity where diffusion would have played a larger role in transport than elsewhere in the cavity. It is possible that the LES model was under predicting the contribution of diffusion to the transport of the dye fluid around the cavity and hence the diffusion of dye into this stagnant region. Additionally, a larger proportion of the actual turbulent mixing in this region may have occurred at scales below the sub-grid scale. In that case the model would have been relying more on the LES sub-grid scale turbulence model, which is known to have deficiencies.

Figure 12 - Frames from video (left) and LES (right), tracer release at point-of-separation (1&2) and bottom cavity wall (3&4).

4.7. Flow pattern of the separated flow field

The general flow pattern of the separated flow field is shown in **figure 12** and the existence of coherent structures in the shear layer is evident. Video stills of the physical model are shown on the left and the LES results are shown on the right. The dimension of each of the square divisions in the photos on the left is 100mm, and the line marked with increasing numbers is the dividing line between the main channel flow and the cavity region. The upper section of each picture shows a portion of the width of the main channel, the flow being from left to right, while the lower section shows virtually the entire separated region, with the point of separation being located at the zero mark. In the top 2 frames the tracer was released at the point of separation, but just inside the cavity region to avoid any interference with the natural evolution of coherent structures at the point of separation [51]. The bottom 4 frames show the case where the concentration measurements reported in the previous section, with tracer released from the bottom of the cavity.

The coherent structures formed in a manner typical of Kelvin-Helmholz vortices. The fast moving channel flow was dragged into the still cavity through a shearing process, where it was slowed down and began rotating, forming a vortex pattern. This process is common in many shear layers from jets and wakes to mixing layers. Coherent structures of approximately the same size and spacing formed in the LES. The visualisations shown here were from a slice plane through the centre of the model at $z = 0.3\text{m}$. The spacing between structures was similar, even though the frequency of the concentration peaks and troughs on the separation line shown in **figure 9** was slightly higher for the LES than the experiments.

While the formation process of the coherent structures at the large scale was quite regular and repeatable, it should be noted that the driving force of the process was inherently random turbulence and therefore it would be unreasonable to expect an exact matching of the LES with the physical model.

4.8. Formation of coherent structure at point-of-separation and bottom cavity wall

The frames where the dye was released from the bottom of the cavity clearly show the exchange of fluid between the channel and the cavity. The formation of coherent structures is very clear in frame 4 of **figure 12** where they are perfectly shaped in the classical pattern of shear layer vortices, while the eddies in frame 3 were less coherent. This was typical of the flow with periods of very distinct coherent structure followed by periods with minimal eddy formation. The experimental images in frames 3 and 4 show striking examples of how a large lump of clear fluid from the channel has been engulfed by the shear layer and has begun to circulate around the cavity. The same phenomenon was seen in the LES.

Figure 13 is a closer view of the shear layer shown in frame 4 of **figure 12**. The topmost frame of the video footage shows a bumpy interface between the dye and the clear channel fluid and is evidence of mixing on a scale smaller than that of the coherent structures. Some of this irregular bumpy pattern was also seen in the LES result in the middle frame indicating that the LES was resolving reasonably fine turbulence levels. However, the bottom frame shows that this scale was close to the grid size, below which the turbulence was no longer directly simulated but was modelled with an SGS turbulence model. Subgrid-scale (SGS) modeling is used to represent the effects of unresolved small-scale fluid motions (small eddies, swirls, vortices) in the equations governing the large-scale

motions that are resolved in computer models. So while the LES may have been reproducing a fine-scale mixing phenomenon, it may not have been doing so with a great deal of accuracy. The importance of accurate representation of these scales on the rest of the simulation cannot be determined from these results.

Figure 13 - Mixing at the interface between dye in the cavity and channel fluid

4.9. Passage of Coherent structures in shear layer

Apart from the coherent structures in the separated shear layer, several other important features of the separated recirculating flow were observed. The most striking result of the visualisation study was the realisation of the pulsatile motion in the recirculating eddy, which lead to the quasi-periodic lateral movement of the shear layer. The process was observed to be associated with the passage of the coherent structures intermittently impinging on the reattaching surface at the downstream end of the cavity. A part of the structure was deflected back into the recirculating region giving rise to a pulsatile motion in the recirculating eddy.

Figure 14 shows the primary eddy in the cavity region, with the eddy front approaching the shear layer near the point of separation, indicating the direct interaction between the recirculating flow in the cavity and the shear layer. The frame sequence covers 12 seconds of the simulation and begins with a large structure having impinged on the reattaching surface. The coherent structure was then torn apart with a portion being convected downstream with the channel flow and a portion having entered the cavity. This lump of fluid then travelled down the rear wall, hitting the bottom in frame 3 and was then carried along the bottom of the cavity with the wall jet in a direction opposite to the channel flow. At around $x/W = 0.8$ the jet left the wall and headed towards the point of separation in frames 5,

6 and 7 whereupon it impacted with a newly forming coherent structure, pushing it out into the main flow in frames 8 and 9. The location of a secondary recirculation is also indicated in the lower left hand corner of the cavity, which became apparent in frames 8 to 12 when some of the dye became entrained in it. Secondary recirculation such as this is frequently noted in literature when the aspect ratio of the cavity becomes larger [8] and [10], their location and structure dependent on Reynolds number.

Figure 14 - Passage of Coherent structures in shear layer and development of recirculating eddy in the cavity

From the time of its impact on the rear wall of the cavity until the blob of fluid returned to the reattachment point there were four coherent structures formed in the shear layer, with the blob interacting with the fourth one. Also of note is that the third structure after the initial one almost completely missed the rear wall of the cavity in frame 7. The pulsatile motion of the recirculating eddy was somewhat out of phase with the shedding frequency in the shear layer. This occurred because the circulation velocity of the coherent structure remnants in the cavity was lower than the velocity of coherent structures in the shear layer and also because some structures deflected into the cavity and some missed the rear wall. Sometimes the recirculating eddy enhanced the formation of coherent structures, sometimes it had no effect and sometimes it actually suppressed their formation, leading to periods of stability in the shear layer.

Figure 15 - Frames from Cine film of the experiment with corresponding frames from LES

4.10. *Frames from Cine film of the experiment Vs. frames from LES*

Another more detailed look at the passage of one coherent structure is shown in **figure 15** and demonstrates the low frequency fluctuation (lower than the passage of the

coherent structures) using a series of selected frames from the high-speed cine photography. The original frame rate of the cine camera was 32 frames per second, but only every tenth frame is shown. The 20 stills presented here cover 6.25 seconds. Corresponding frames from the LES are also shown, with 20 frames covering 5.7 seconds due to the different sampling rate used.

Focusing firstly on the experimental series, three separate structures can be identified in frame 1 at three downstream locations; the third structure (leftmost) still in the process of forming. By frame 3 this process was complete when it had evolved into a larger coherent form while the second structure in front of it became elongated due to local straining. As the third structure advected downstream and rotated across the shear layer, it captured the elongated second structure, and the growth of the new eddy due to the pairing interaction was completed by frame 7. Afterwards this new structure advected downstream, maintaining its coherent nature until the reattachment region (by frame 18) and did not interact further with any structures. This paired structure remained below the dividing line between the channel and the cavity region for almost its entire lifespan. At the point of impingement in frame 20 most of the structure impinged on the back of the cavity deflecting downwards, while only a small portion was swept away with the main flow in the channel.

Returning to frame 1 of the experimental series, the first structure (rightmost) was above the dividing line, i.e. deflected into the main channel flow. This deflection was most likely caused by an upward thrust event of the recirculating eddy while the structure was forming. The rest of the frames show how this eddy remained mostly on the channel side of the dividing line until it reached the reattachment point, where it impacted slightly on the back of the cavity (frame 10) but was mostly swept away with the channel flow.

The time sequence from the LES shows four structures in total. The first three structures remained mainly above the dividing line convecting downstream with the channel flow. However, there was some impact with the rear wall of the cavity and a part of each structure was deflected downwards. The fourth structure began forming in frame 13 and seemed to remain more inside the cavity than the preceding three eddies. By remaining below the dividing line in the slower moving fluid this coherent structure seemed to advect more slowly than the others. This structure kept a long trail of dye behind it in contrast with the third ring, which was seen to break off in frame 8. An upwards thrust event then appeared to push the tail of this structure upwards into the main flow, accelerating it and allowing it to overtake the main part of the structure by frames 19 and 20. This was not quite the same as the pairing interaction seen in the experimental photos but it was caused by the same phenomenon.

Both [64] and [67] previously reported the lateral movement of the separated shear layer described above, however, they did not clearly establish the reason for this movement. It was indicated by [64] that the instantaneous imbalance between the shear layer entrainment from the recirculating region and the re-injection of fluid near the reattachment point was the likely cause of such long time scale motion. For instance an unusual event may have caused a short-term breakdown of the span wise vortices in the shear layer. The entrainment rate would then be temporarily decreased while the re-injection rate would remain constant, causing an increase in the volume of recirculating fluid, thus moving the shear layer away from the wall and increasing the reattachment length. It was suggested by [67] as well as [68] that the oscillation of the shear layer was caused by feedback from the disturbances from the impingement point towards the separation point. Such disturbances would appear as low-frequency modulation of the shear layer downstream of the separation, which would be

amplified by the free shear layer. They postulated that this could be the mechanism responsible for such low frequency motion (lower than the eddy passing frequency).

The visual observations presented here suggest a different explanation for the lateral motion of the shear layer. As the large eddy structures in the shear layer impinged on the reattaching surface, part of the structures was deflected back into the separated region, giving rise to a quasi-periodic pulsatile motion in the recirculating eddy. Normally the shear layer would be deflected into the separated region due to its asymmetric nature. This deflection results in more fluid entering the shear layer, which must be accommodated by forcing fluid out upstream near the separation point. The recirculating jet inside the cavity is now stronger and at the same time pulsatile, and interacts with the shear layer, pushing it outwards into the main channel flow. Consequently the trajectory of the newly forming coherent structures in the shear layer are deflected more into the channel and either totally miss the downstream end of the cavity or at least only partially clip it with no or only a small portion of fluid being re-entrained into the cavity region. This weakens the recirculating eddy and the shear layer is again able to deflect back into the cavity. The process appears to be a steadily pulsating one and it takes some time for the recirculating eddy jet to regain sufficient momentum to push the shear layer out again. The pulsatile motion, through interactions with the coherent structures of the shear layer, produced the lateral movement of the shear layer.

4.11. *Iso-surface of dye/water interface Vs Shear layer vortices*

The LES modelling of [30] predicted stream wise braid vortices between the Kelvin-Helmholtz vortices in the shear layer for a rectangular cavity at high Mach number (**figure 16**, bottom frame), while [39] showed the existence of similar braid vortices for a square cavity at low Mach number. These structures are known to enhance mass transfer across

many shear layers, especially in jet flows [69]. The visualisation of these structures is best achieved in LES modelling using the Q criterion [70] or the λ_2 criterion [71].

Visualisation of the structures by this method was not performed in the current work. Instead an iso-surface of constant dye concentration is shown in the top frame of **figure 16** to indicate the presence of stream-wise streaks between the Kelvin-Helmholtz vortices, which is possible evidence of stream-wise vorticity being present in this flow. Braid vortices in a mixing layer form as counter rotating pairs [29] drawing fluid between them from one side of the mixing layer and ejecting it to the other side. This should manifest itself as ripples in the dye sheet where dye was drawn between the braids from the high concentration side, creating local stream-wise ridges in the sheet with corresponding troughs present between adjacent braid pairs.

5. Conclusions

Flow visualisation experiments as well as LES modelling have revealed the formation of coherent structures in the separated shear layer between a cavity and a channel flow. Mean and fluctuating velocity measurements with corresponding power spectra of velocity fluctuation, in addition to measurements of instantaneous concentration variation of a seed/dye tracer also indicated the existence of these structures. A pulsatile motion in the recirculating eddy was established as a result of impingement of coherent structures on the downstream end of the cavity, seen in the flow visualisation and concentration measurements. This pulsatile motion in turn caused a low frequency transverse motion of the shear layer, which further impacted on the dynamics of the coherent structures in the shear layer, forming a closed feedback loop. A numerical model using RANS equations satisfactorily reproduced some of the mean velocity characteristics but failed to accurately predict the rate of

concentration decay rate in the cavity. This failure was due to the inability of the model to reproduce the coherent structures formation and evolution in the shear layer.

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Nomenclature

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

7. References

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Figure 16