The purging of a neutrally buoyant or a dense miscible contaminant from a rectangular cavity

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Key Words: Large Eddy Simulation, Stratification, Open cavity.

ABSTRACT

For environmental applications, the presence of cavity-like geometries in rivers, lakes or urban canyon is of interest of the transport processes (toxic air, pollutants, nutrients, suspended sediments, etc) that occur between the cavity and the main flow current. In this regard the quantitative characterization of the mass exchange between the cavity and the surrounding is highly important. Pollutant, denser water or toxic air may accumulate in these cavities and produce a stagnant pool which may be harmful to the environment.

The objectives of the present paper are to investigate the mass exchange processes between the cavity and the channel from Large Eddy Simulations. At this time, neutrally buoyant or dense miscible contaminant introduced instantaneously inside the cavity is considered and the differences of the ejection mechanism are compared each other. The buoyant effects are expressed as the nondimensional Richardson number with density difference.

In the present work, non-dissipative parallel finite-volume DNS/LES code[1] is employed. The code solves the conservative form of the incompressible Navier-Stokes equations on non-uniform Cartesian meshes. The pressure Poisson algorithm uses a staggered conservative space-time discretization with a semi-implicit iterative method to advance the equations in time such that the algorithm is second order accurate in both space and time. The numerical method discretely conserves energy. The scalar transport is modelled using an advection diffusion equation in which the convective terms are discretized using QUICK scheme. The sub-grid scale viscosity and diffusivity coefficients are calculated dynamically [1]. The viscous Schmidt number Sc was taken equal to 1. The code was parallelized using MPI.

The computational domain considered in the present work is similar to that in the water tunnel experiments of Pereira and Sousa [2,3] for which the upstream flow was turbulent. The length to depth ratio is L/D=2 and the Reynolds number Re_D defined the cavity depth and the mean velocity in the upstream channel is 3,360. The Reynolds number defined with the upstream channel height is Re_H=20,450. Fig 1 shows the overall geometry and computational domain. The length of the computational domain in the spanwise direction is 6D. The flow in the simulations is considered to be periodic in the spanwise direction. The mesh size is close to 14 million cells (320×224×192 in the streamwise, vertical and spanwise directions). The first point off the solid surfaces is located at about 0.15 wall units. The characteristic cell size in the cavity region is close to 6 wall units in all three directions. The resolution in the cavity region is comparable to DNS requirements. No wall functions were used. The instantaneous velocity components at the inflow sections were obtained from a preliminary simulation of the flow in a straight channel of identical section to the one which contains the cavity on its bottom wall. This way we avoided any artificial way of trying to model the inflow turbulence fluctuations.

The mass exchange between the cavity and the main channel is investigated by considering the ejection of a scalar that is introduced instantaneously at a certain time (after the velocity field become statistically steady) inside the cavity. We assume the fluids inside the cavity and outside it are perfectly miscible and the density differences are not very high, such that one can model the flow using the Boussinesq approximation. In this case a buoyant source term (this term in nondimensional from is expressed as multiplication of C and *Ri*) is added to the right hand side of the momentum equations. The nondimensional scalar concentration C is initialized as C=1 inside the cavity and C=0 outside it at the time at which the mass exchange process between the channel and the cavity starts.

The comparison of the velocity profiles and of the normal and shear stress in fig. 2 between our simulation with *Ri*=0.0 and the experimental data of Pereira and Sousa [2,3] allows us to validate the methodology of the present work. There are overall agreements with reference data. From the vertical velocity spectrum, the most energetic frequency is observed to occur at a Strouhal number *St*=fU/D=0.38 which corresponds to the first mode predicted by theory [4] for cavities with L/D=2. Coherent structures educed using the Q criteria in fig 3 do not show the presence of any spanwise vortical structure which is separated at the upstream edge shown in typical cavity flow. Whereas the streaks of vorticity from the upstream channel wall are dominant over the cavity mouth and these are convected in hairpin shaped structures after downstream edge of the cavity.

The instantaneous concentration contours in fig. 4 try to visualize the way the contaminant is removed from the cavity in the *Ri*=0.0 case. At the start of the purging process most of mass transfer is due to the engulfing of high concentration fluid from cavity-channel interface by the vortices convected over the cavity mouth. During partial or complete clipping events patches of low concentration and relatively high vorticity fluid are pushed downward parallel to the trailing edge of the cavity and then recirculated by the jet-like flow inside the downstream half of the cavity. During these times, mass exchange is taking place between the primary recirculation eddy and the channel first and then high concentration scalar is ejected at the upper right corner of the second eddy by the shear layer. Another mechanism is due to the streamwise oriented coherent structures from the near wall region of the upstream channel. [5]

In the buoyant case with *Ri*=0.2, the ejection of the denser contaminant had some similarities with the one observed in the laminar flow simulation [6], however the oscillations of the density interface were found to be irregular. Following the initial engulfment due to the very energetic eddies that populate the separated shear layer and entrain denser fluid directly into the channel, a stable vortex is forming near the cavity trailing edge corner (fig. 4a). For t<100D/U in fig 4, the tilting of the interface (fig 4a and 4b) and the interfacial shear induced by the trailing edge vortex are two of the main mechanism that allow extraction of the denser fluid from the cavity. The third one is the breaking of interfacial waves at the sharp density interface induced by the irregular oscillations in the size and intensity of the trailing edge vortex for t<220D/U. For t>220D/U, practically all the higher density fluid beneath the vortex is removed. The vortex touches permanently the bottom, grows slowly in size and entrains high concentration fluid from its lateral boundary.

The variation of the volume of contaminant left inside the cavity is plotted in fig. 5 in log scale. As expected, the introduction of a heavier miscible contaminant is a considerable increase of the removal time. For the *Ri*=0.0 case it is observed that the contaminant mass decay can be approximated by a straight line over the whole duration of the removal process. The value of the exponential decay expressed in the form of a nondimensional mass exchange coefficient [7] is *k*=0.013. The contaminant decay with *Ri*=0.2 suggests the presence of three phase. Over initial phase (t<35, *k*~0.01), mass exchange is due to the engulfment from the top layer near the interface by eddies. Over the second phase, the decay rate (k~0.006) is much smaller because of buoyant effects. Final phase has the equivalent value with *Ri*=0.0 case, in which the buoyant effects are not very important.

FIGURES

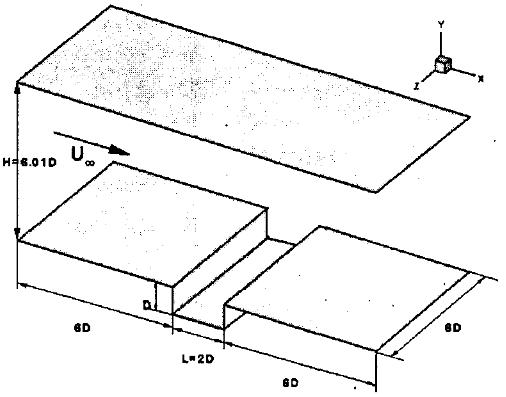

Fig. 1 Computation domain

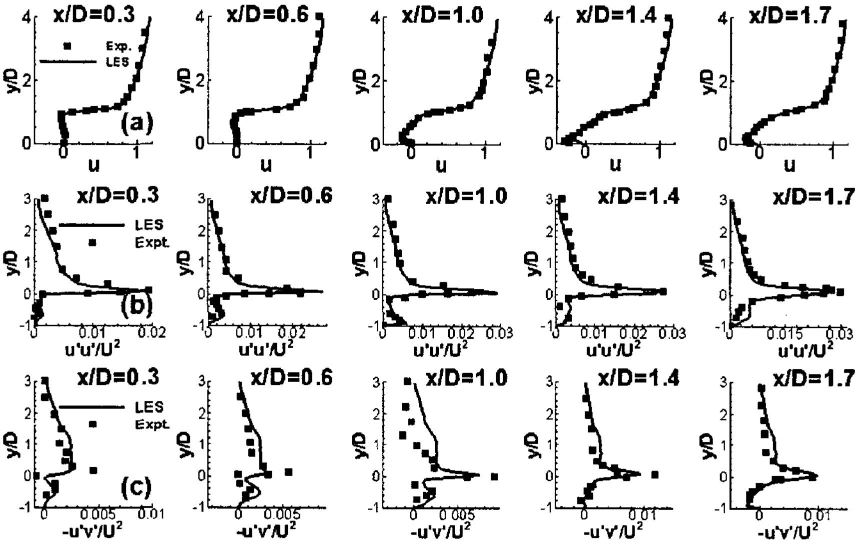

Fig. 2 (a) Mean velocity profiles and (b),(c) Resolved normal and shear stresses for Ri=0.0

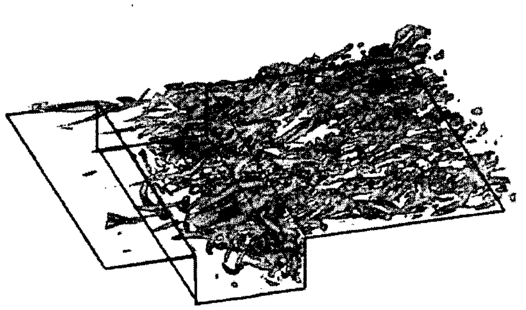

Fig. 3 Coherent structures for Ri=0.0

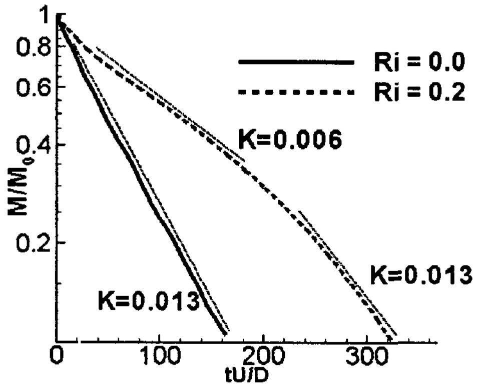

Fig. 5 Variation of contaminant volume

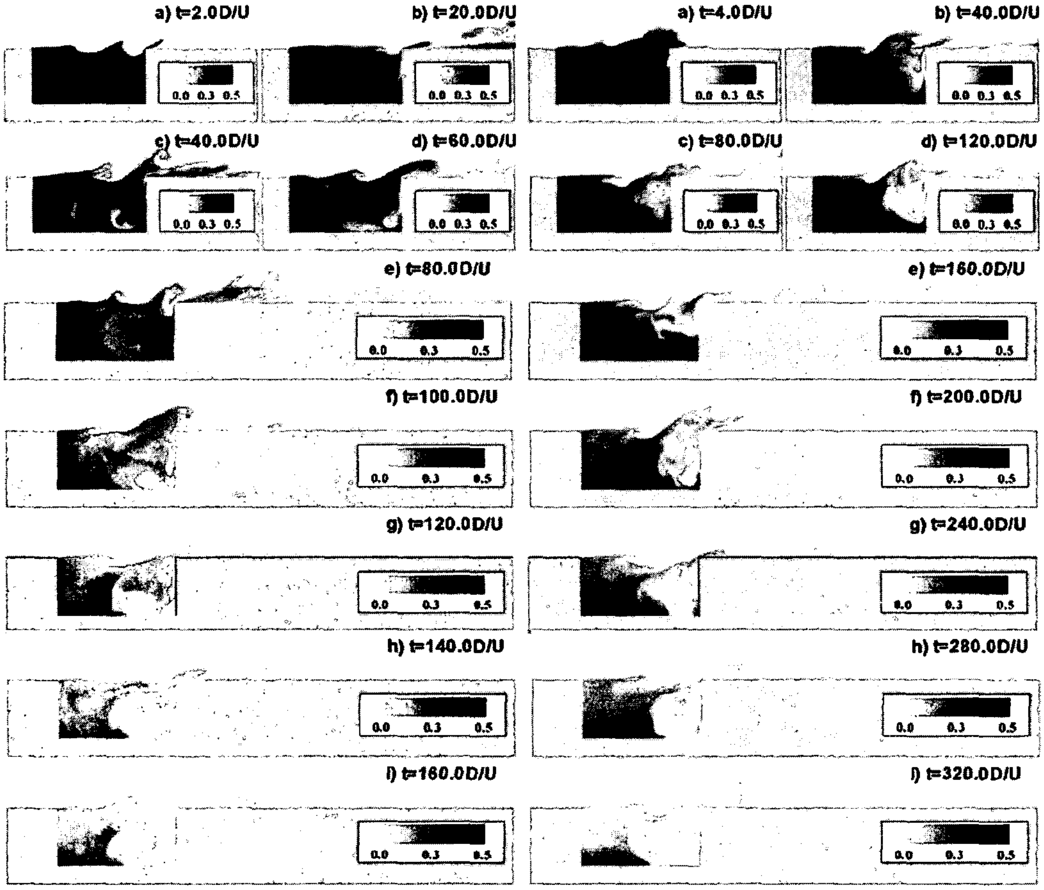

Fig. 4 Instantaneous scalar contours, (left) *Ri*=0.0 case and (right) *Ri*=0.2 case

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