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VALIDATION OF LES OF LOCK-EXCHANGE DENSITY CURRENTS INTERACTING WITH A VERTICAL EMERGENT CYLINDER

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ABSTRACT

This paper focus on the validation of LES modelling of lock-exchange density currents interacting with a vertical emergent cylinder. Numerical modelling was performed in OpenFOAM using different SGS models and VoF method to simulate the fluid phases. The model is validated using density field measurements in two layouts: side (i.e., transversal cross-channel averaged) and plan (i.e., vertical cross-channel averaged) views. The experiments were conducted in a horizontal and rectangular cross-section channel with 3.0 m long and 0.175 m wide. The gravity current was generated using the classic lock-exchange configuration with both lock and ambient regions filled up at same depth of 0.2 m. The emergent cylinder with a diameter of 2.5 cm is positioned in the ambient fluid region at 0.6 m beyond the gate with its axes vertical and perpendicular to the streamwise direction of the current propagation in the middle of the channel. The lock-release experiments were carried out for four reduced acceleration. Insights on the impact of the SGS models and grid refinement are obtained with comparisons of the concentration isosurfaces, density fields, vertical and transversal profiles. The comparisons show that the current propagation is predicted with reasonable accuracy, including the entrainment, and mixing at a local level (near the cylinder) during the impact stage. On the other hand, the accuracy of the results is affected by changes of the Reynolds number.

Keywords: Numerical modelling; lock-exchange flow; validation; LES model.

1. INTRODUCTION

Density currents are an important class of fluid flows that arise in numerous environmental scenarios in which buoyancy forces, generated by density differences, produce motions with large changes in the flow velocity and areas of intense turbulence. The interaction with bluff bodies increases the drag force acting on the current and provide additional mechanisms for entrainment, mixing, and energy dissipation. Unsteady Reynolds-averaged Navier-Stokes (URANS) equations provided useful information on the concentration field, however, the understanding of the mechanisms that are occurring at various timescales is not satisfactory enough. A solution to this problem is using Large eddy simulation (LES), where direct numerical simulation is used for flow fluctuations greater than the local grid dimension, and a subgrid-scale (SGS) model is used for fluctuations smaller than this dimension. LES models have been used recently to study these mechanisms, however, verification and validation still a challenging task, since both the error induced by the SGS model and the numerical discretization error are dependent on the grid resolution. The main objective of this paper is to validate of LES modelling of lock-exchange density currents interacting with a vertical emergent cylinder.

2. NUMERICAL MODELLING

The numerical modelling was performed using OpenFOAM (Open Field Operation and Manipulation), which applies a finite-volume method to solve the continuity and Navier-Stokes equations. In LES, these governing equations are expressed in filtered fields, where any given flow variable $\phi(\boldsymbol{x},t)$ is decomposed into a resolved or grid-scale part $\tilde{\phi}(\boldsymbol{x},t)$ and a residual or subgrid-scale (SGS) part $\phi'(\boldsymbol{x},t)$, through a spatial low-pass filtering operation defined as

$$\tilde{\phi}(\boldsymbol{x},t) = \int_{\forall} \phi(\boldsymbol{x}',t)\, G(\boldsymbol{x}-\boldsymbol{x}',\Delta) d\boldsymbol{x}' \qquad \text{[Eq. 1]}$$

where *G* represents the filter function. Therefore, $\phi(\boldsymbol{x},t)$ can be decomposed as

$$\tilde{\phi}(\boldsymbol{x},t) = \phi(\boldsymbol{x},t) + \phi'(\boldsymbol{x},t) \qquad \text{[Eq. 2]}$$

Applying the filter operation to the continuity and Navier-Stokes equations for incompressible flow to reduce the number of spatial scales to be solved can be written in the following (Germano et al., 1991)

$$\frac{\partial \tilde{u}_i}{\partial x_i} = 0 \qquad \text{[Eq. 3]}$$

$$\frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial(\tilde{u}_i \tilde{u}_j)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \tilde{p}}{\partial x_i} + \frac{\partial\left(2\upsilon \tilde{S}_{ij}\right)}{\partial x_j} - \frac{\partial \tilde{\tau}_{ij}}{\partial x_j} + g_i \qquad \text{[Eq. 4]}$$

where $\tilde{u}_i$ are the components of the resolved velocity field and x_i are the components of Cartesian coordinate i-direction (I = 1,2,3 refers to the x, y and z directions, respectively), $\tilde{S}_{ij}$ is the resolved strain-rate tensor, t is the time, $\tilde{p}$ is the resolved pressure, g is the gravity acceleration and ρ and υ are the fluid density and kinematic viscosity, respectively. The term $\tilde{\tau}_{ij} = u_i u_j - \tilde{u}_i \tilde{u}_j$ is the SGS stresses tensor, which describes the effect of the SGS on the resolved scales of motion and that must be modelled. In this study, due to the small scales is more isotropic than large ones (Germano et al., 1991), the SGS stresses tensor is closed by assuming local equilibrium between the production and the viscous dissipation of SGS kinetic energy, and by using a turbulent eddy-viscosity hypothesis. The anisotropic part of the SGS tensor   is linked to the eddy viscosity   by the following expression:

$$\tilde{\tau}_{ij} - \frac{1}{3}\delta_{ij}\tilde{\tau}_{kk} = -2\upsilon_t \tilde{S}_{ij} \qquad \text{[Eq. 5]}$$

where δ_{ij} is the Kronecker delta and the resolved strain-rate tensor is defined as

$$\tilde{S}_{ij} = \frac{1}{2}\left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i}\right) \qquad \text{[Eq. 6]}$$

The turbulent eddy-viscosity υ_t is modelled as

$$\upsilon_t = (C_s \Delta)^2 \tilde{S}_{ij} \qquad \text{[Eq. 7]}$$

where $|\tilde{S}_{ij}| = \left(2\tilde{S}_{ij}\tilde{S}_{ij}\right)^{1/2}$ is the norm of the resolved strain-rate tensor, $\Delta = (\Delta_1 \Delta_2 \Delta_3)^{1/3}$ is the SGS filter scale which corresponds to the local grid scale and C_s is the Smagorinsky constant, which depends on the particular flow, and different values have been proposed in the literature. In this work several models are used such as standard Smagorinsky, dynamic one equation eddy-viscosity, wall-adapting local eddy-viscosity (WALE), and dynamic Smagorinsky.

3. DESCRIPTION OF THE EXPERIMENTAL SET-UP

The set-up of the numerical model is performed to represent laboratory experiments of lock-exchange density currents interacting with a vertical emergent cylinder. The experiments were conducted in a horizontal and rectangular cross-section channel at the DEMI laboratory of Faculty of Science and Technology, Universidade Nova de Lisboa, Portugal. The channel is 3.0 m long, 0.175 m wide and 0.4 m deep. The gravity current was generated using the classic lock-exchange configuration. A sliding stainless-steel gate with 1 mm thickness, sealed by PVC board glued in the sidewall, was positioned at x_0 = 0.3 m from the left hand of the channel (i.e., upstream section) forming the so-called lock region. The experiment starts when the gate is suddenly removed, leaving the dense fluid to flow along the bottom of the channel, while the ambient fluid moves above in the opposite direction. The schematic view of the experimental set-up is shown in Fig. 1.

In all experiments, both lock and ambient regions were filled up at same depth, H = 0.2 m. The dense fluid with initial density ρ1 was obtained by a mixture of fresh water, salt, and Rhodamine. The ambient fluid with density ρ0 was obtained by a solution of clear denatured ethanol and fresh water. Both solutions were mixed vigorously for about 20 min to assure that the dense and ambient fluids were homogeneous before the experiment was initiated (Canedese et al., 2018). As density difference between fluids is a result of both temperature and concentration, the density and temperature of both fluids were measured in the beginning of each run. The density was measured using a 100 ml pycnometer. The density fields were obtained using an Allied Vision Bonito CL-400B/C high-speed camera. The camera was connected to the computer by the CL1 (camera link base) and CL2 (camera link medium/full) for the transmission of the data and connected to a 12 V DC power supply. In this paper, the measurements were carried out in two layouts: side (i.e., transversal cross-channel averaged) and plan (i.e., vertical cross-channel averaged) views. The flow was illuminated by a led panel from the rear and from the under in the side and plan layouts, respectively. The schematic view of the experimental layouts is shown in Fig. 1b and c.

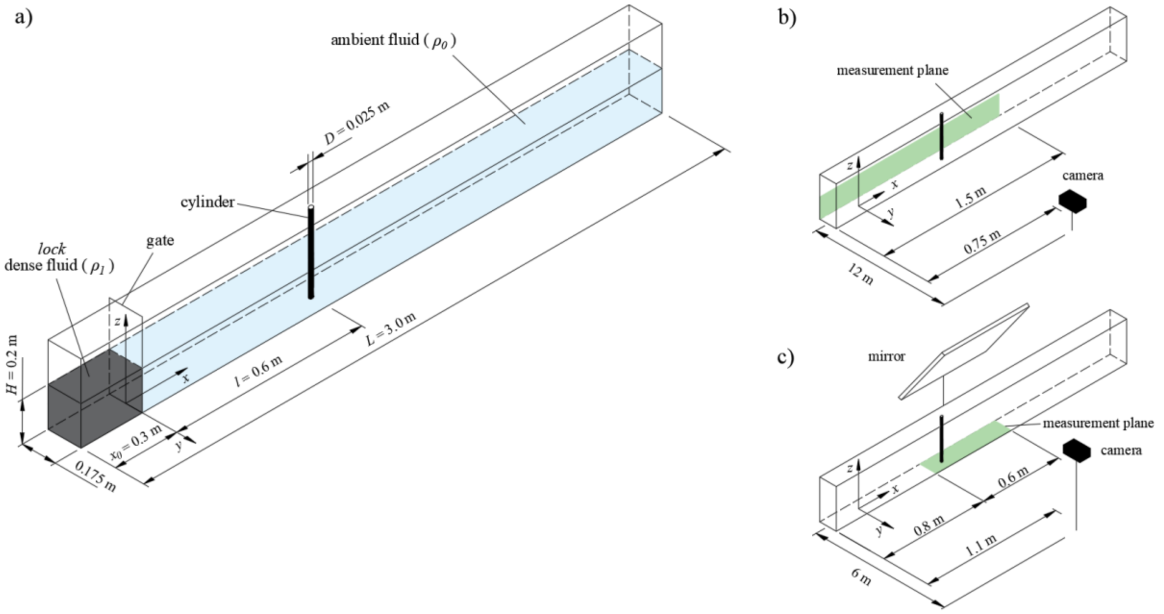

Fig. 1. Schematic view of the experimental set-up (not to scale): a) main dimensions and the Cartesian reference system; b) side view layout; c) plan view layout.

In the side view layout, the camera was positioned at y = 12 m and x = 0.45 m and the measurement plane was 1.5 m wide and 0.2 m high. The camera viewed the flow from the side glass wall of the channel. In the plan view layout, the camera was positioned at y = 6 m and x = 0.8 m and the measurement plane was 0.6 m long and 0.175 m wide. The camera viewed the flow through an angled mirror (Fig. 1) to increase the accuracy of cylinder wake. In this layout 0.1 m upstream and 0.5 m downstream of the cylinder was measured. The emergent cylinder is positioned in the ambient fluid region at l = 0.6 m beyond the gate (Fig. 1a) with its axes vertical and perpendicular to the streamwise direction of the current propagation in the middle of the channel (i.e., y = 0). The cylinder was made of PVC with a diameter d = 2.5 cm and it was glued to the bottom of the channel. The lock-release experiments were carried out for four reduced acceleration $g_0 = g\Delta\rho/\rho_0$ for both side and plan view (Table 1).

Table 1. Main parameters of the experiments for the side view (S) and plan view (P).

Run	g'_0 (m s^{-2})	u_b (m s^{-2})	U_f (m s^{-2})
S1, P1	0.06	0.110	0.052
S2, P2	0.12	0.155	0.073
S3, P3	0.24	0.219	0.100
S4, P4	0.48	0.310	0.139

4. MODEL VALIDATION

4.1. Density currents interacting with a vertical emergent cylinder

The variation of numerical and experimental current front position, x_f, with time for finer mesh is compared in Fig. 2. The size of elements approximately equal to the mean integral length scale, ℓ, calculated by RANS simulation show a relative error over than 20%. Increasing the resolution, with size of elements of about $\ell/4$ the results show a remarkable agreement between the numerical and experimental data throughout the vertical flow column. The results of the two different grids with approximately $\ell/5$ (presented in Fig. 2) and $\ell/10$ size show relative error about 1%, which indicate mesh independence.

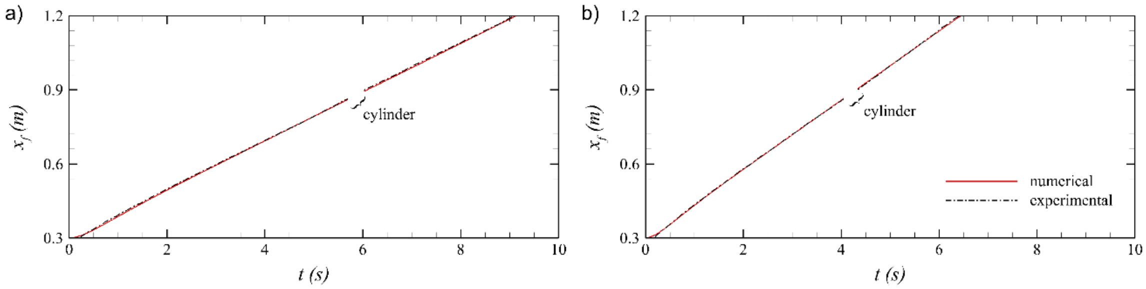

Fig. 2. Front position for run: a) S3; b) S4.

The experimental and numerical contours of the concentration, *C*, for run S3 is presented in Figs. 3. Both experimental and numerical fields present same order of magnitude. However, the numerical model overestimates the current height in the symmetry plane. Therefore, it is proposed the cross-section average of the concentration field, due to the large variation verified in the top view.

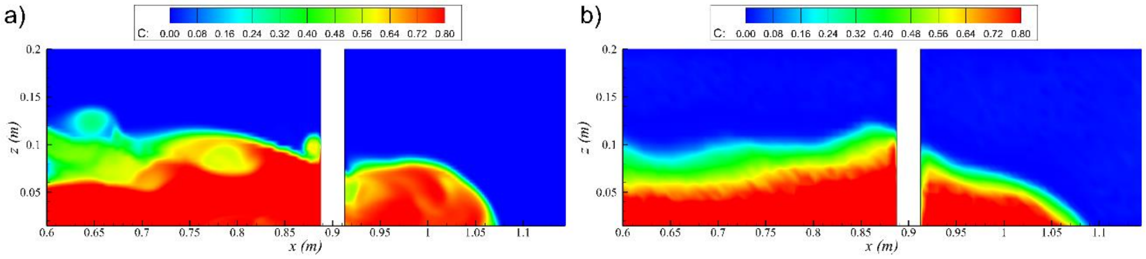

Fig. 3. Concentration contours for run S3: a) numerical; b) experimental.

5. CONCLUSIONS

This paper presents the validation of LES modelling of lock-exchange density currents against new experimental data under various test conditions. From the results, the following conclusions can be drawn: i) the major features of this turbulent flow (e.g., concentration isosurfaces, density fields, vertical and transversal profiles) are predicted with satisfying accuracy; ii) the accuracy is affected by changes of the Reynolds number; iii) the SGS models and grid refinement have a large impact on the entrainment and mixing at a local level (near the cylinder) during the impact stage.

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