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ABSTRACT

The dynamics of bottom gravity currents in a laboratory-scale, stratified-flow flume is modelled using a 3D CFD tool. Also, the dense-water intrusion along a channel with a trapezoidal cross-section is characterized hydraulically. The numerical experiments are designed to aid qualitative interpretation of the formation of density-driven, bi-directional stratified flows. The turbulence characteristics of the stratified flow are introduced to investigate the internal-flow hydraulic regimes and the interface mixing between water layers.

1. Materials

An experimental study was conducted at the CNRS Coriolis Rotating Platform at LEGI, Grenoble, to investigate uni- and bi-directional stratified flows generated along a trapezoidal cross-section channel (Adduce et al. 2019) under rotating and non-rotating conditions, with both fixed and erodible bed layer conditions. Experimental measurements focused on obtaining high-resolution velocity and density fields in different vertical planes spanning the width of the channel using 2D Particle Image Velocimetry (PIV) and Laser Induced Fluorescence (LIF), as well as acoustic doppler velocimeters (ADV) and micro-conductivity probes positioned in several cross-channel sections. To investigate the resulting internal-flow dynamics numerically, Computational Fluid Dynamics (CFD) simulations were undertaken with the specific OpenFOAM solver. The model domain of the flume is three-dimensional, and consists of three parts: (i) a basin with the salt-water inflow, (ii) the horizontal trapezoidal channel, and (iii) a fresh water basin with an open boundary (for a detailed description of a laboratory-scale, stratified-flow flume arrangement, see Adduce et al., 2019).

2. Models

Laanearu and Davies (2007) formulated an internal-flow energy function for the hydraulic modelling of bi-directional stratified flows in non-rectangular channels. The cross-sectional channel flow shapes can be presented quantitatively in the internal-flow energy function by a shape factor $(\xi > 1)$ that represents the ratio of bank-full area to cross-sectional area of flow. Hence, the limiting case of this shape factor corresponds to a rectangular cross-section with $\xi = 1$, while trapezoidal channel cross-sections can also be approximated with quadratic-type geometry. Within internal-flow hydraulic theory, the dimensionless internal flow head (H/w_0) of the quadratic channels can be defined as follows:

$$H^* = \xi^2\, K^* \left(\frac{h}{w_0}\right)^{2(\xi-1)} \left(\frac{w_0}{w}\right)^2 \left(\frac{1}{\left(\frac{h_2}{w_0}\right)^{2\xi}} - \frac{q^2}{\left(\left(\frac{h}{w_0}\right)^{\xi} - \left(\frac{h_2}{w_0}\right)^{\xi}\right)^2}\right) + h_2^* + h_s^* \qquad (1)$$

where the dimensionless quantities in Eq. (1) are defined as follows:

$$H^* = \frac{H}{w_0}, \; K^* = \frac{{Q_2}^2}{2\,g'\,{w_0}^5} = \frac{K}{{w_0}^5}, \text{ where } K = \frac{{Q_2}^2}{2\,g'}, \; q^2 = \frac{{Q_1}^2}{{Q_1}^2}, \; h_2^* = \frac{h_2}{w_0}, \; h_s^* = \frac{h_s}{w_0} \quad (2)$$

In Eqs. (1) and (2), w_0 is the channel width constant; $h = h_1 + h_2$ is the total stratified fluid depth, where h_1 and h_2 are the upper and lower fluid layer thicknesses, respectively; h_s is sill height; $g' = g(1 - \Gamma)$ is the reduced gravitational acceleration, where $\Gamma = \rho_1/\rho_2$ represents the density ratio, with ρ_1 and ρ_2 being densities of the less-dense (fresh) upper layer and denser (saline) lower layer, respectively; Q_1 and Q_2 are the upper and lower fluid layer flow rates, respectively; q is the upper-to-lower layer volume flux ratio parameter.

The goal of the present study is to model numerically the development of the bottom gravity current dynamics along the trapezoidal channel for fixed salt-water volumetric inflow rates into the salt water basin (see Figure 1, where the snapshot of the CFD simulation is shown). The almost whole computational domain is meshed using a standard element of varying sizes. The boundary layer mesh is treated differently in the numerical experiments designed to investigate the turbulent-mixing characteristics that are important for the developing gravity current dynamics.

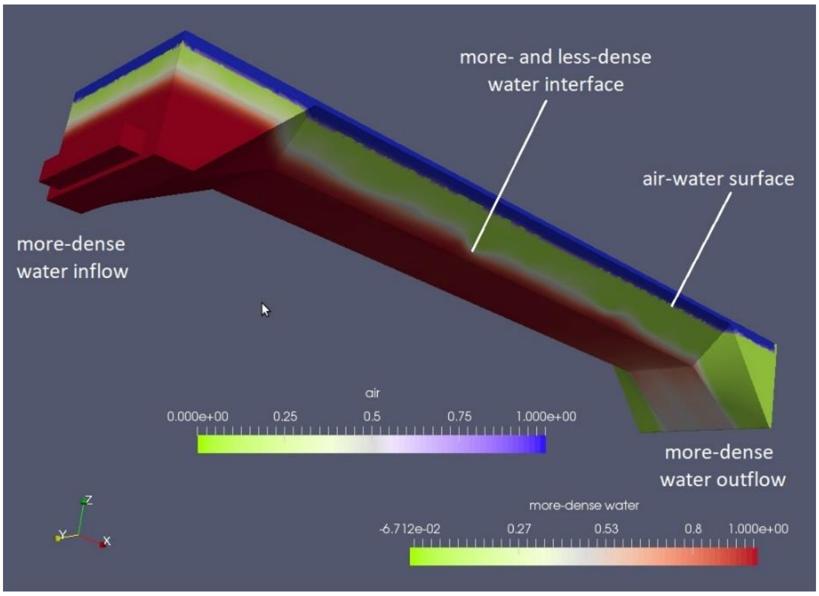

Fig. 1. Three-layer stratified fluid in the Computer Aid Domain (CAD) of an obstructed channel with trapezoidal cross-section. Excess densities of air and more-dense water in the model domain are shown. Colorbar: blue – air, green – less-dense water, red – more-dense water.

3. Methods

According to Laanearu and Davies (2007), the two-layer exchange flow is parameterized with the upper and lower layer densimetric Froude numbers Fr_1 and Fr_2, such that:

$$Fr_1^2 = \xi \frac{u_1^2}{g'} \frac{h_2^{\xi-1}}{h^{\xi} - h_2^{\xi}}, \quad Fr_2^2 = \xi \frac{u_2^2}{g' h_2}, \quad (3)$$

with the composite Froude number G given by

$$G^2 = Fr_1^2 + Fr_2^2 \,. \quad (4)$$

In the case of critical, sub- and super-critical stratified flows $G^2 = 1$, $G^2 < 1$ and $G^2 > 1$, respectively.

The numerically modelled 3D buoyancy-driven flow clearly demonstrates the hydraulically-driven internal flow, which is modified by the interfacial friction and the eddy-diffusivity dependent mixing.

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