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Numerical simulations of constant-influx gravity currents in confined spaces: Application to thermal storage tanks

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ABSTRACT

This study uses Computational Fluid Dynamics (CFD) to investigate numerically the flow phenomena in the intrusion region of a thermal storage water tank during discharge. The early times of the discharging process have significant effect on the thermal mixing and the associated energy losses. A detailed time-evolution of the flow and temperature fields inside the tank was obtained for a range of relevant Froude (Fr) numbers. Parameters such as the thermocline thickness (δ), the entropy generation rate ($\dot{S}_g$) and the thermal mixing factor (κ) were calculated to quantify the mixing mechanism in the tank. Authors chose several alternative discharging scenarios where the Froude number (Fr) varied between 0.05 and 2.00, a range which corresponds to typical discharging conditions in real applications involving water storage tanks. The gravity currents (GCs) developing as the incoming cold fluid flows along the floor of the tank, their subsequent reflection on the opposite vertical wall and the interaction between the reverse flow and the incoming flow were analyzed and correlated to δ, $\dot{S}_g$ and κ.

1. Introduction

Thermal energy storage tanks permit excess thermal energy to be stored until energy demand exceeds the immediately available solar energy supply. The dynamic process of retrieving the stored energy is called discharging. In order to achieve the best performance (low mixing) during the discharging process, the thickness of the intermediate region separating the hot and cold water layers (thermocline) should be kept as small as possible (Dincer and Rosen [1]). The initial moments of the discharging process play a significant role in thermal mixing in storage tanks (Kaloudis et al. [2]) due to the hydrodynamic and thermal disturbances caused by the interaction of the incoming and outgoing streams of water. In particular, the mixing-rate (quantified in terms of thermocline thickness) is 67% higher in the initial period, in contrast to the later times of the process where diffusion is the dominating mixing mechanism. Yoo et al. [3] pointed out the importance of designing inlet diffusers in such a way that the water flows along the floor of the tank in the form of a density (gravity) current, which leads to a thinner thermocline and thus less mixing. Considering a wide range of inlet Froude number $Fr_{in} = 0.7 - 14.5$ in their experimental study, they demonstrated the importance of the densimetric inlet Froude number Fr_{in} on the thermocline thickness. They concluded that Fr_{in} must be of the order of 1 or less for optimal design. Ji and Homan [4] reported that the maximum entropy production occurs early in the discharging process when the cold fluid moving along the bottom in the form of a gravity current (GC) is reflected on the opposite wall (Fig. 1). For the aforementioned reasons, the aim of the present study is to identify and analyze the main mixing mechanisms that occur during this particular time period, in a tank of initially uniform temperature, through high-resolution, two-dimensional numerical simulations.

The GC flow configuration in the discharging of a storage tank is characterized by complex hydrodynamic phenomena, as may be seen in Fig. 1. The GC flow propagates with almost a steady velocity (u_f) across the tank floor (a phase called *"first pass"* by some authors 5) until it reaches the opposite wall (Fig. 1a). After the impact, it penetrates vertically into the tank up to a maximum height (Fig. 1b) where it gets deflected horizontally and a reverse flow sets in (Fig. 1c). This reverse flow (*"second pass"*) interacts with the GC flow in the first pass, generating a shear layer which is subject to instabilities and potentially increased mixing. Depending on the flow

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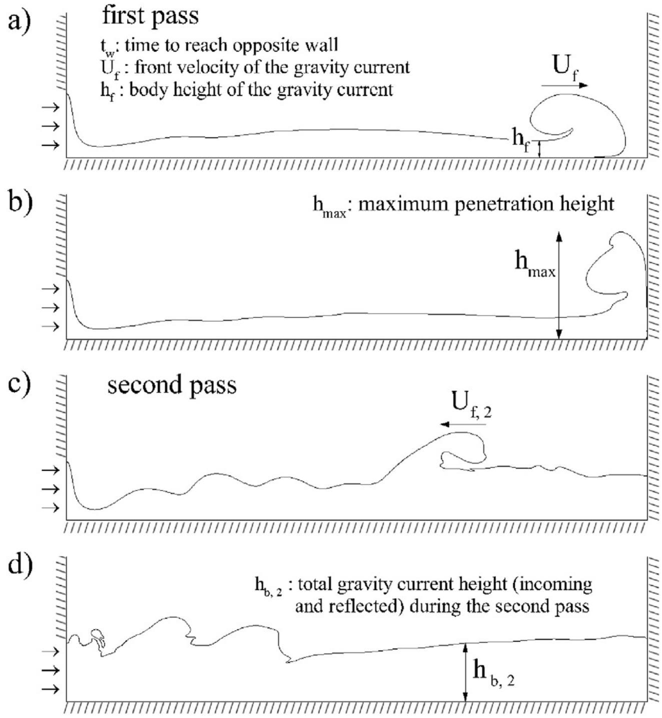

Fig. 1. A schematic depiction of the investigated flow-configuration and the main flow patterns: GC propagation along the bottom (1st pass), wall impact and reflection, reverse flow (2nd pass). The outflow boundary is the entire top surface of the domain, placed at a sufficient vertical distance, here $H^* = 10$.

parameters, the reverse flow may also reach the inlet (Fig. 1d) where it is subjected to a second reflection causing new disturbances in the developing thermocline.

GCs have been studied over the past three decades mainly due to their regular occurrence in the fields of geophysics, oceanography, meteorology etc. In the relevant investigations, the density rather than temperature was used as the transport variable. Typical applications involved problems such as lock-exchange flows (Hartel et al. [6], Ooi et al. [7], Ghasemi et al. [8]), entrainment of two-dimensional gravity currents (Hallworth et al. [9]) and propagation of a gravity current into a two-layer stratified ambient fluid (White and Helfrich [10]). In the majority of cases, the domain of interest is characterized by an unlimited extent in the direction of the GC propagation. Quite a few studies have considered the interaction of a two-layer flow with solid obstacles mounted at the bottom of the channel, with heavier fluid lying below a lighter one. For this problem, and by means of an inviscid hydraulic theory, several regimes of flow (subcritical or supercritical, partially blocked or completely blocked flow) have been identified, depending of the value of the Froude number upstream of the obstacle (Rottman et al. [11], Rottman and Simpson [12], Lane-Serff et al. [13]). The present situation has similar characteristics to the completely blocked flow described in the aforementioned problem, as the presence of the vertical wall opposite the inlet does not allow any possibilities other then the full reversal of the flow direction of the GC, irrespective of the Froude number value. The completely blocked flow over an obstacle normally gives rise to an internal bore, which is an abrupt jump in the level of the interface between the two fluid layers, moving in the direction opposite to that of the GC 12. Essentially, the second-pass of the GC mentioned above is marked by this internal bore movement, which also plays an important role in the ensuing mixing in the tank.

Few studies have considered GC flows in completely confined enclosures such as storage tanks which is the subject of interest here. Among the few relevant studies belong the aforementioned ones by Nakos [5], Ji and Homan [4], as well as Homan and Soo [14]. In his study, Nakos [5] also confirmed the importance of the hydrodynamics of gravity currents in the efficient storage of chilled water. Homan and Soo [14] studied numerically an orthogonal tank and the internal wave phenomena occurring by the impact of the GC to the opposite wall, with his results being limited to $Fr_{in} = 1$. A more recent study by Nabi and Flynn [15] showed that similar situations may also arise in building ventilation problems. The present work aims at further advancing the study of GCs in confined spaces, by considering their interactions with solid boundaries in storage tanks and their implications with regard to mixing, by using Direct Numerical Simulations (DNS).

In the sections to follow, the mathematical formulation is first presented in Section 2, as well as the criteria used to quantify the mixing process. The numerical code and the choice of computational domain and grid is presented in Section 3. Section 4 contains the presentation of results and discussion, followed by the conclusions in Section 5.

2. Mathematical formulation

2.1. Governing equations

Using the Boussinesq's approximation, i.e. a linear variation of density ρ, with temperature T according to $\rho - \rho_o/\rho_o = \beta(T - T_o)$, the non-dimensional equations of motion and energy for mixed convection problems become:

$$\frac{\partial U_i}{\partial x_i^*} = 0 \tag{1}$$

$$\frac{\partial U_i}{\partial t^*} + \frac{\partial U_i U_j}{\partial x_j^*} = -\frac{\partial p^*}{\partial x_i^*} + \frac{1}{Re}\frac{\partial}{\partial x_j^*}\left(\frac{\partial U_i}{\partial x_j^*}\right) + \frac{Gr}{Re^2}\theta^*\delta_{iy} \tag{2}$$

$$\frac{\partial \theta^*}{\partial t^*} + \frac{\partial U_j \theta^*}{\partial x_j^*} = \frac{1}{RePr}\frac{\partial}{\partial x_j^*}\left(\frac{\partial \theta^*}{\partial x_j^*}\right) \tag{3}$$

where U is the dimensionless velocity, "*" denotes the rest of the dimensionless variables and δ_{iy} is the Kronecker's delta.

These equations have been non-dimensionalised using the height of the inlet diffuser H_{in} as the characteristic length scale, the inlet velocity u_{in} as the characteristic velocity and the ratio H_{in}/u_{in} as the characteristic time scale. The initial temperature of the tank T_o and the inlet water temperature T_{in} are used to define the dimensionless temperature as $\theta^* = (T - T_{in})/(T_o - T_{in})$. The Reynolds and Grashof dimensionless numbers are defined as $Re = u_{in}H_{in}/\nu$ and $Gr = g\beta H_{in}^3(T_o - T_{in})/\nu^2$. The ratio Gr/Re^2 also defines the Archimedes number Ar which expresses the relative importance of free to forced convection.

2.2. Methods to assess mixing

One of the most popular methods to quantify the energy losses associated with mixing during the charge/discharge phases, is to analyze the evolution of the thermocline thickness (Haller et al. [16]) presented in Section 2.2.1. A more detailed view of the thermal mixing and its spatial and temporal variation can also be obtained by other indicators such as the entropy production rate (Ji and Homan [4]) and the thermal mixing factor (Homan and Soo [17]) which are presented in the following sections.