PERIODIC CYCLE OF STRETCHING AND BREAKING OF THE HEAD OF GRAVITY CURRENTS

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1. INTRODUCTION

Gravity currents, which are geophysical flows driven by density differences within a fluid, are herein investigated under unsteady conditions by means of lock-exchange releases of saline water into a fresh water tank.

Generally, gravity or density currents are caused by temperature differences or the presence of dissolved substances or particles in suspension. Examples of gravity currents include avalanches of airborne snow and plumes of pyroclasts from volcanic eruptions, in the atmosphere, releases of pollutants and turbidity currents, in rivers, lakes and reservoirs, and oil spillage and oceanic fronts in the ocean.

A typical way to investigate in detail the hydrodynamics of unsteady gravity currents is by means of lock-exchange experiments. The currents so produced present three distinct phases: i) a first so-called slumping phase when buoyancy and inertial effects are balanced and front celerity is constant, ii) a second (self-similar) phase when the reflected bore generated at the end wall of the tank overtakes the front, causing the front celerity to decrease and, iii) a third viscous phase when viscosity plays a role and its effects overcome inertial effects.

In terms of anatomy of the density current, two distinct regions are distinguished: the head and the remaining body or tail. On the very first instants of the release, the flow is bulky driven by the whole current mass while the head is not yet well defined. Later, this detaches from the main body and its particular buoyancy drives the advance of the current, with a different celerity from the tail. The head is highly concentrated being the main engine of convection of the released mass, being subjected to entrainment at the interface with the ambient fluid.

The aim of the present work is to experimentally investigate the dynamics of the head, including continuous entrainment and cycles of stretching and breaking observed in the laboratory.

2. EXPERIMENTAL PROCEDURE

Experiments were conducted at the Laboratory of Hydraulics of University of Rome "Roma Tre" in a 3.0 m long, 0.20 m wide and 0.30 m deep transparent Perspex tank (Fig.1).

A vertical sliding gate is placed in the channel at a distance x_0 = 0.15 m from the left wall to form a lock.

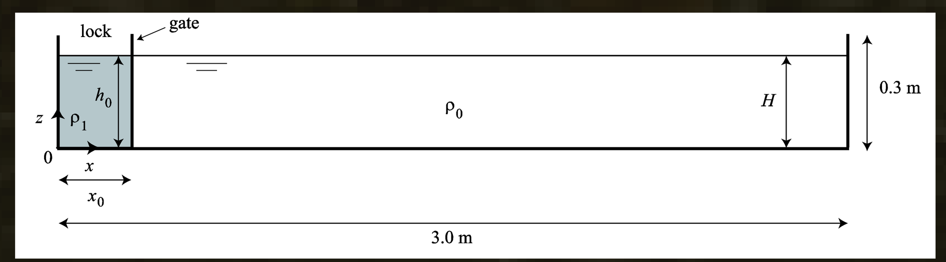

Fig. 1 Longitudinal view of the Perspex tank.

For smooth bed and for a fixed value of water depth in both sides of the tank, H = h_0 = 0.20 m, the following four different initial densities, ρ_1 , of the salt-water mixture were analysed: 1015, 1030, 1045 and 1060 kg/m^3. A controlled quantity of dye is added to the saline water in the lock to provide flow visualization and to serve as density tracer. The development of the current is recorded with a 25 Hz CCD camera under controlled light conditions.

The instantaneous density field of the current was assessed through an image analysis technique applied to the video frames. These, with 768 x 576 pixel points, were subsequently converted into gray scale matrices and then converted into instantaneous density fields of the current through a calibration method described in the next section.

3. DENSITY ESTIMATION

The evaluation of the current density distribution was based on a relation between reflected light intensity and concentration of dye present in the flow; this later is considered linearly correlated with salt concentration within the current body.

A calibration procedure was carried out for each run and for each single pixel to establish the relation between the amount of dye in the water and the values of gray scale in the frames representing light intensities. Assuming a direct relation between the amount of dye and the density of the current, it is thus possible to infer density values at any given pixel and at any given instant from its instantaneous gray scale value.

Fig. 2 shows the development of the current captured in three instants and the corresponding normalized instantaneous density fields ρ^*.

Kelvin-Helmholtz type instabilities are quite visible at the mixing layer of the current and exhibit a quasi stationary behaviour.

Since the head of the current is a region of higher density, the criteria used to characterize and isolate this region was based on the product between local vertically-averaged density and current height: $\overline{\rho_v}(x,t).h(x,t)$.

The upstream limit of the head, and therefore the head length, L_f, were defined taking the position of the local minimum of the function $\overline{\rho_v}(x,t).h(x,t)$ near the front.

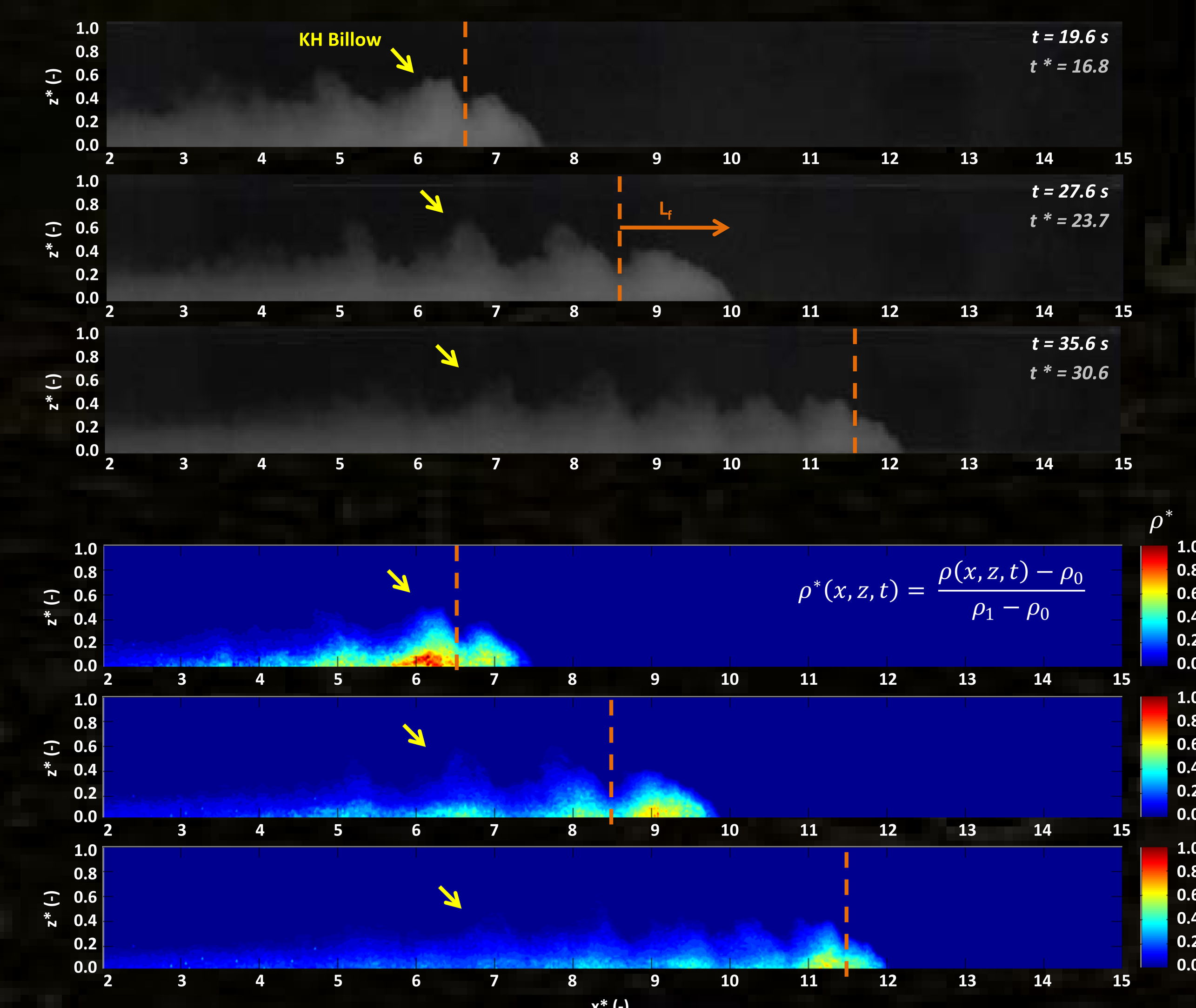

Fig. 2 Photos of the current acquired in run D1 and corresponding density fields.

4. RESULTS

Front velocity

The dimensionless front velocity, i.e, Froude number, is herein defined as: $Fr = u_f/\sqrt{g'_{head}\,h_m}$, where g'_{head} is the local reduced gravity at the head region and h_m is the maximum height of the head. Froude numbers so estimated are shown in Fig. 3.

According to what is reported in literature (Rottman and Simpson, 1983), the transition between first and second phases occurs at $(x_f\text{-}x_0)/x_0$ = 9, being x_f the position of the front, which is corroborated by the results presented in Fig. 3. An evident distinction between first and second phases is observed in all plots: during the constant-velocity phase, $(x_f\text{-}x_0)/x_0$ < 9, Fr exhibits some scatter which is reduced in the self-similar phase, where a narrow collapse around Fr = 1 is observed.

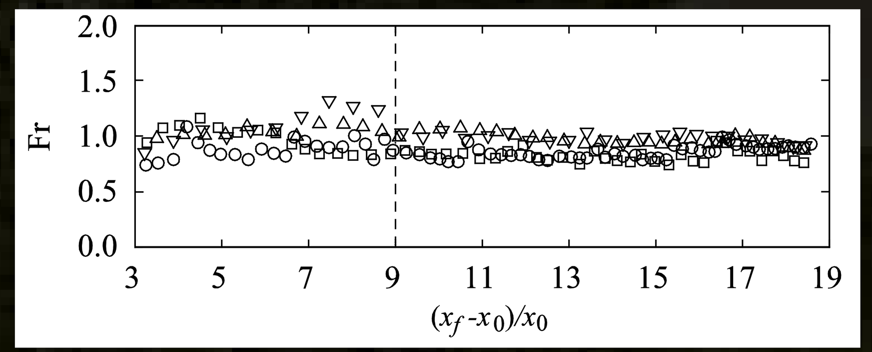

Fig. 3 Evolution of Froude numbers considering local reduced gravity and maximum height of the head.

Head dynamics

Figure 4 shows the temporal evolution of mass M_h per unit width of the gravity current head, plotted as function of dimensionless time, tu_b=x_0, after the gate removal, being $u_b = (g'_0 h_0)^{1/2}$ the buoyancy velocity and g'_0 the initial reduced gravity. The temporal evolution of both length and mass show remarkable patterns characterized by successive events of stretching and breaking of the head. During the stretching phase, the mass of the density current head increases due to entrainment of ambient fluid into that region.

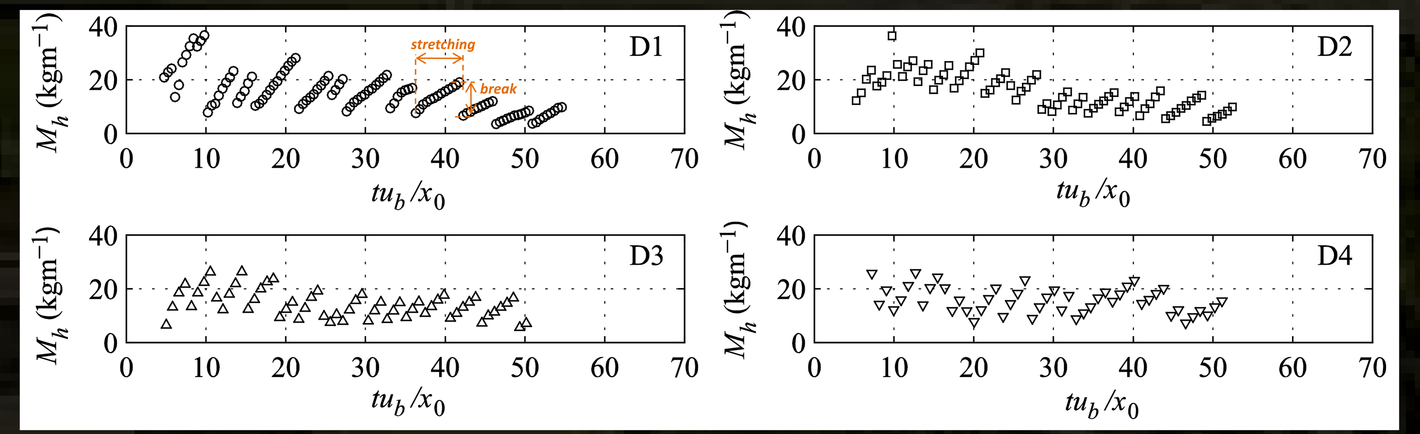

Fig. 4 Mass of the gravity current head.

Entrainment at the head is present throughout its development, inclusively in the early stages, where a faster rate of mass increase is observed. The breaking cycles show that a limit exists in the entrainment capacity of the head, indicating an instability process eventually controlled by a dynamical quantity. After this limit is attained, the head breaks leaving behind quasi-steady large-scale billows, which eventually fade in time by diffusion-type processes. The averaged period, T^*, of the breaking cycles is 3.3 (D1), 2.5 (D2), 2.7 (D3) and 2.6 (D4).

The period of the free surface oscillation, T = 0.8 s, is different from the mean period of breaking cycles, T = 1.5 to 2.9 s, thus those events are independent.

Entrainment

Figure 5 shows the temporal evolution of the mass growth rate within each stretching phase. In general, the mass growth rate decreases as the current advances, suggesting that the entrainment rate at the head is ruled by local reduced gravity: as current develops and ambient fluid is being entrained into the current head, local density decreases and so does the buoyancy force driving the current, leading to less fluid to be entrained at the current head. Rates with a similar decaying trend between runs are observed and their collapse suggest that temporal variation of mass inside the head poorly depends on the initial conditions, i.e., initial density of the mixture in the lock.

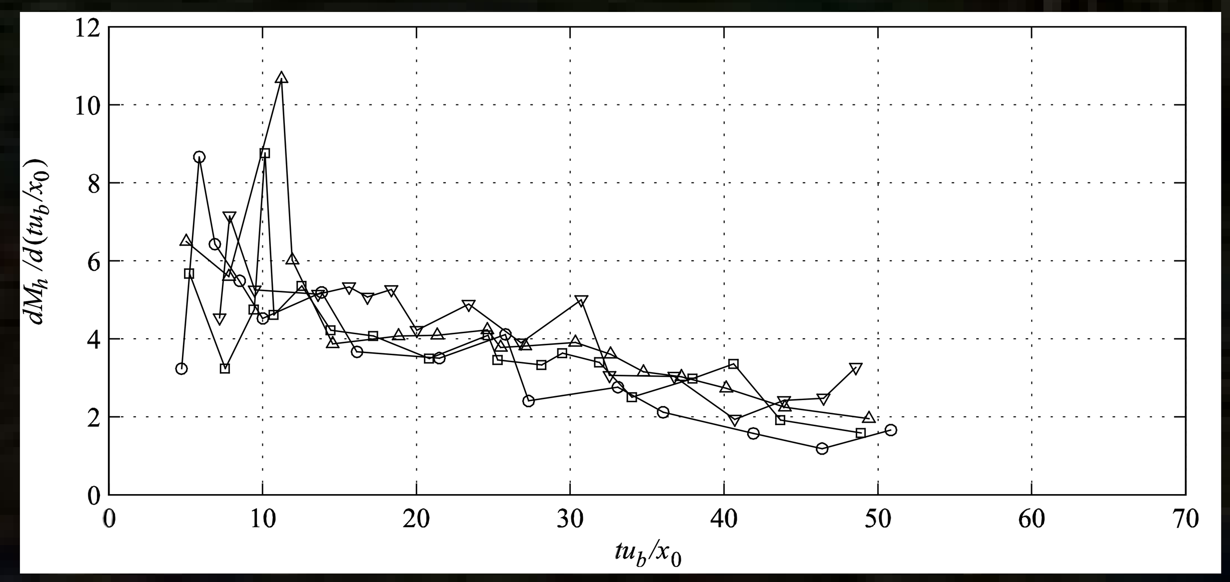

Fig. 5 Mass rate within each stretching phase.

5. CONCLUSIONS

Froude numbers show that front velocity converges to a balance with the local buoyancy. In the early stages of the current development no apparent head detached from the remaining current is observed and this may be responsible for the scatter observed in Froude numbers in the slumping phase, justifying the bulk character of the current propagation. When the reflected bore overtakes the current front, the current is fragmented into a body and well defined head, being the front velocity in equilibrium with its buoyancy celerity.

A cyclic increase of the mass of the current head due to entrainment followed by a division in two distinct patches was observed. A frontal one continues the drive downstream whereas a subsequent one is left behind and incorporated in the tail, thus indicating that the loss of saline mass in the head is not only due to continuous entrainment at the interface layer. Entrainment follows a decaying trend along the current development whereas periodic division of the head seems to be kept. The division of the head is related to mass ejections directing upstream with a clear signature in the current-depth time and spatial evolution maps.

ACKNOWLEDGEMENTS:

Work supported by the Portuguese Science and Technology Foundation through the research project PTDC/ECM/099752/2008 and the research grant SFRH/BD/48705/2008