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A note on the structure of the head of an intrusive gravity current

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The head of an intrusive flow advancing along the interface between two fluids is studied experimentally when the two layers are of equal depth and the density of the intrusion is the mean of the two densities. The dependence of the flow on the interface thickness and the depth of the intrusion is determined. When the interface is very thin the flow is similar to the nominally inviscid gravity currents observed by Britter & Simpson (1978).

1. Introduction

Many examples of density layering exist in the ocean, and some are believed to be formed by intrusive flows. Buoyancy forces cause the spread of an intermediate density fluid into a stratified medium at an appropriate level (Gregg 1975). Two main classes of such intrusions have been studied in the laboratory. In the first class the ambient medium is stratified through a depth much greater than the depth of the intrusion, and forward propagating disturbances play an important part in the flow, as in the work of Wu (1969), Manins (1976), Amen & Maxworthy (1980). In the second class, which is the one considered here, the intrusive current is deeper than the stratified layer in the ambient medium.

A simple example is the flow along the thin interface between two homogeneous fluids of equal depth but of different density. When a restricted volume of fluid is thoroughly mixed and then released an intrusive current flows along the interface. Thorpe (1973) and Masuda & Nagata (1974) both emphasized the importance of the interface characteristics. In this note we describe experiments in which the ratio of interface thickness to current depth and the ratio of current depth to the overall depth of fluid are systematically varied.

2. Experimental procedure

The tank used was 360 cm long by 20 cm wide and could be filled to a depth of 45 cm. It was filled to half the required depth with salt water and then tap water was carefully added to an equal depth above it. A partition was inserted 50 cm from one end, and the two fluids behind it were completely mixed. Removal of the partition released a current whose head was viewed throughout its journey by shadowgraph.

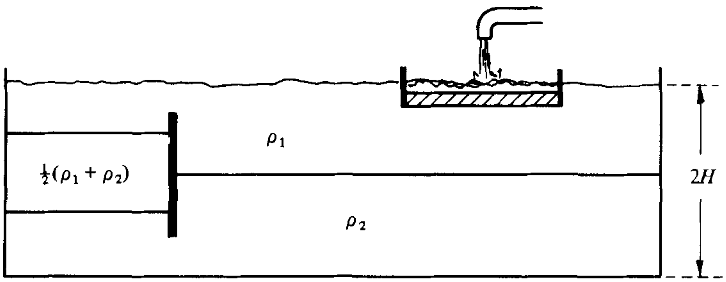

FIGURE 1. Arrangement used to produce thin intrusive gravity currents. The upper fluid is poured onto a raft of floating sponge.

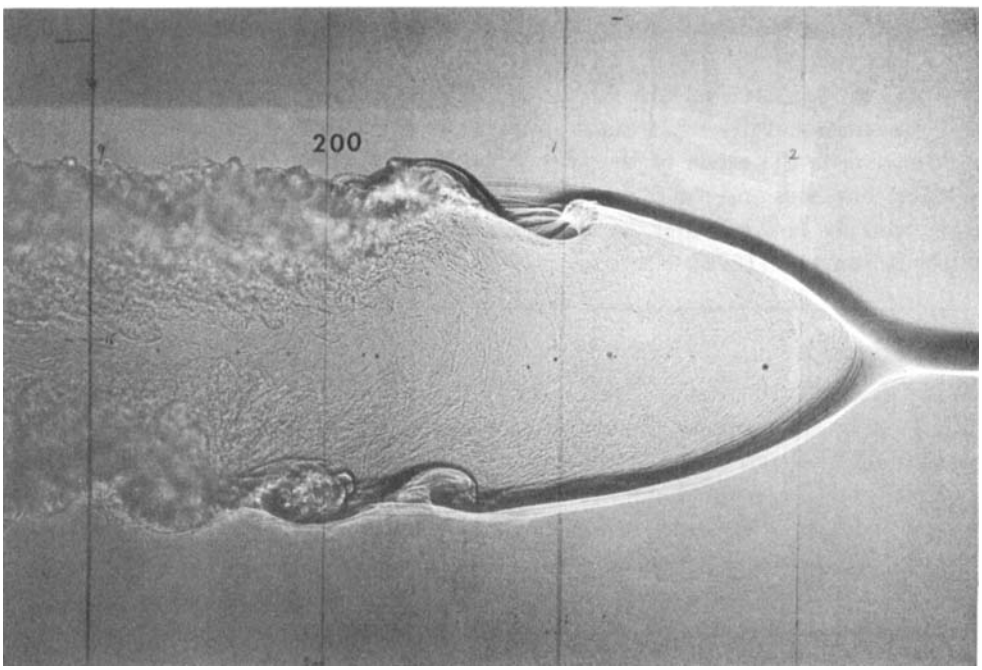

FIGURE 2. Intrusive current with thin interface. $\rho_2/\rho_1 = 1{\cdot}027$, $h_0/h = 0{\cdot}15$, $h/H = 0{\cdot}31$, $R = Uh/\nu = 3300$.

Between six and eight photographs were taken during each run to record the details of the head and the flow close behind it. A digital clock display reading to the nearest tenth of a second was included in each photograph to enable any variations in velocity to be measured.

Thinner intrusive currents were obtained from the collapse of a layer of fluid of appropriate density introduced behind a partition which was less than the total depth of the fluid, as shown in figure 1.

Our intention was to study flows large and fast enough to be independent of Reynolds number and to investigate the effect on such flows of reducing the interface thickness. Keulegan (1958) and Simpson & Britter (1979) both found Reynolds number independence for density currents moving along boundaries when $R = Uh/\nu \gg 1000$, where U is the front velocity, h the current depth and ν the kinematic viscosity. In

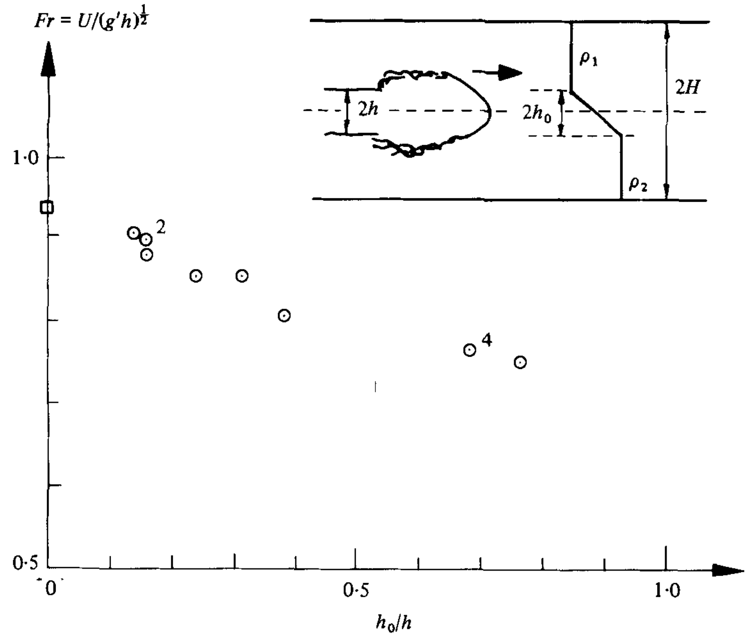

FIGURE 3. Variation of Froude number $U/(g'h)^{\frac{1}{2}}$ with fractional interface thickness, h_0/h when $0{\cdot}3 \leqslant h/H \leqslant 0{\cdot}33$. Point ⊡ is for a nominally inviscid boundary current. The points labelled 2 and 4 correspond to the flows shown in figures 2 and 4 respectively.

our experiments, boundary stresses are absent and so a value of R somewhat less than 1000 was expected to demarcate viscously influenced flows. Preliminary experiments over a wide range of variables suggested that a Reynolds number of 250 was adequate to ensure that the Froude number (see § 3) was independent of R. Nevertheless, the experimental results presented here include only flows with $R \gg 1000$.

The thickness of the interface was varied by allowing it to diffuse for a time t before removing the partition. The characteristic interface depth $2h_0$ was $(4\pi kt)^{\frac{1}{2}}$, where k is the molecular diffusivity of salt in water, taken as $1{\cdot}4 \times 10^{-5}$ cm^2 s^{-1}. The minimum time needed to add the upper fluid was about 30 min, giving a lower limit of about 0·6 cm to the experimental interface thickness, which is similar to that obtained by Linden (1980) using the same technique. Before each experiment the salinity profile was measured with a conductivity probe. As a result of mixing during the addition of the upper layer the interface depths were sometimes found to be greater than the theoretical value.

In some early experiments, the two layers had been laid down by a very simple and convenient method. A central partition was placed in the tank, and the two densities established on either side. When the partition was removed one fluid flowed above the other. There was mixing visible during this process, but, when all had settled, a diffuse interface was visible with the shadowgraph. Interfaces set up by this 'lock-exchange' technique were such that $h_0/H \simeq 0{\cdot}3$, where $2H$ is the overall depth of fluid.

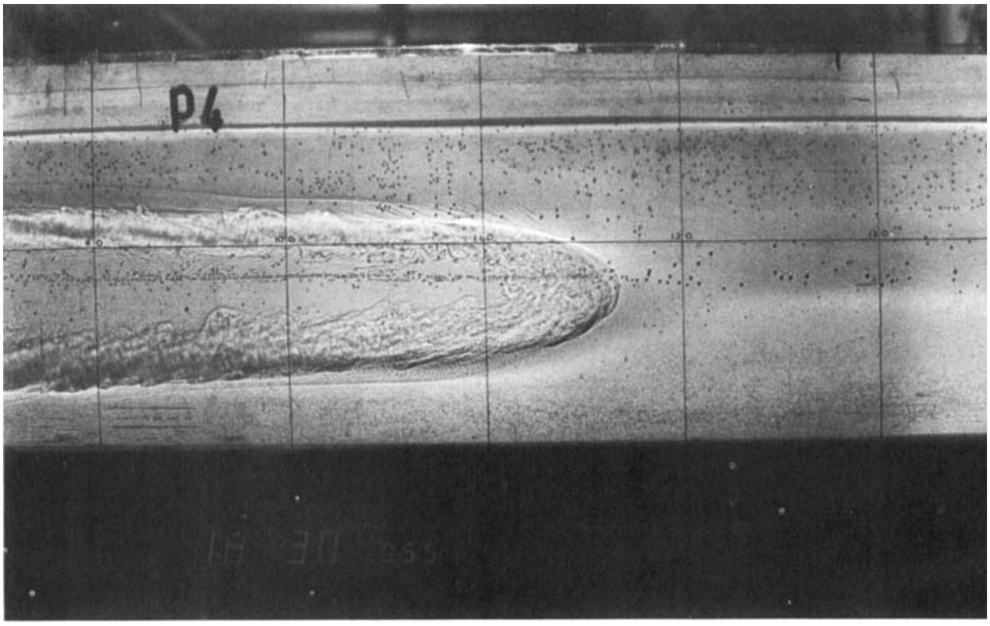

FIGURE 4. An intrusive current running along a thick interface. $\rho_2/\rho_1 = 1{\cdot}12$, $h_0/h = 0{\cdot}7$, $h/H = 0{\cdot}33$, $R = Uh/\nu = 2600$.

3. Results

When the partition was removed and the fluid originally behind it began to move forward along the interface, there was almost a plane of symmetry through the upstream interface. The slight asymmetry seen in figure 2 is required for continuity of pressure (Holyer & Huppert 1980); however, the asymmetry appears much exaggerated in shadowgraphs.

No trends in the velocity U were observed during any experiment and the velocity was, therefore, taken as constant. This agrees with observations of intrusive currents by Faust (1976) and of boundary currents by Yih (1965) and Barr (1967).

From dimensional analysis applied to the flow local to the head, we argue that, after making the Boussinesq approximation with $\rho_1 \simeq \rho_2$, the velocity of the leading edge of the intrusion is given by

$$U/(g'h)^{\frac{1}{2}} = f_1\left(\frac{h}{H}, \frac{h_0}{h}\right),$$

where

$$g' = \tfrac{1}{2}g(\rho_2 - \rho_1)/\rho_1.$$

Rather than consider the complete parameter space, we present here results for

(i) $U/(g'h)^{\frac{1}{2}} = f_2(h_0/h)$ for $0{\cdot}3 \leqslant h/H \leqslant 0{\cdot}33$

to show the influence of interface thickness, and

(ii) $U/(g'h)^{\frac{1}{2}} = f_3(h/H)$ for $h_0/h \leqslant 0{\cdot}2$

to show the influence of the fractional depth of the current h/H.

Variation of the Froude number of the head advance $U/(g'h)^{\frac{1}{2}}$, with interface thickness, is shown in figure 3. Because the Froude number of the advance varies considerably with fractional depth h/H, we have only included here flows restricted

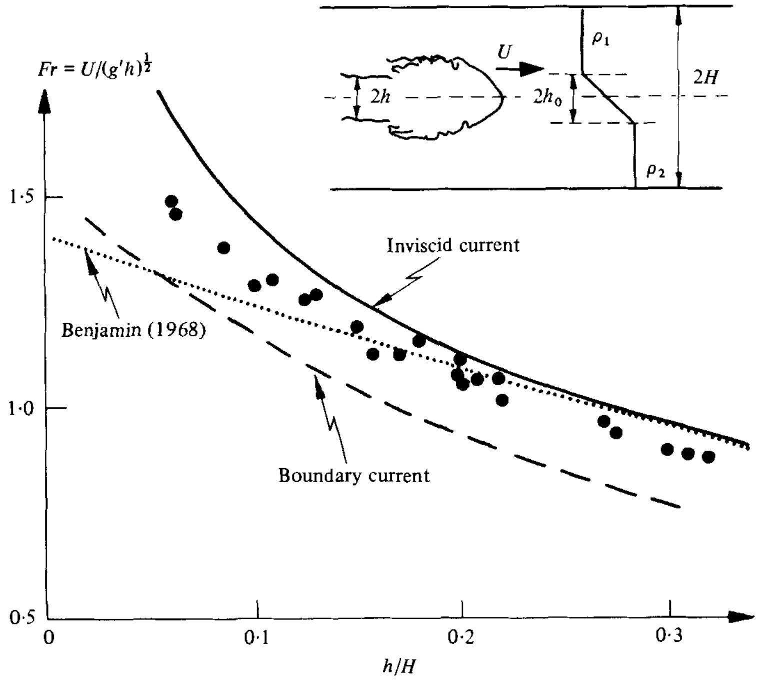

FIGURE 5. Variation of Froude number $U/(g'h)^{\frac{1}{2}}$ with fractional depth h/H. Values of the interface thickness ratio h_0/h are $\leqslant 0{\cdot}2$. The dashed line is from Simpson & Britter (1979) and the dotted line from Benjamin (1968).

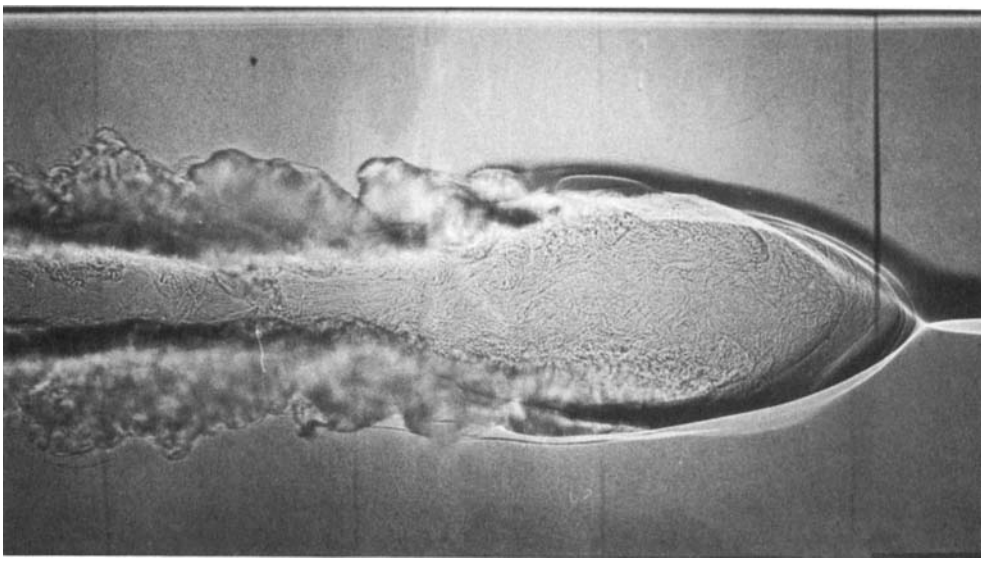

FIGURE 6. Intrusive current with thin interface. $\rho_2/\rho_1 = 1{\cdot}04$, $h_0/h = 0{\cdot}19$, $h/H = 0{\cdot}13$, $R = Uh/\nu = 1200$.

to h/H between 0·30 and 0·33, but we have found a similar pattern of results for flows at other smaller fractional depths. The range chosen is a convenient one to investigate experimentally, as the depth approaches the maximum realizable in lock-exchange flows and the variation of the Froude number is small compared with that for smaller h/H.

The Froude number increases as the interface is made thinner, and approaches that observed for a nominally inviscid boundary current flowing at the same fractional depth (Britter & Simpson 1978). At $h_0/h = 0{\cdot}15$, figure 2, the head resembles a reflected, nominally inviscid boundary current; but with a thicker interface $h_0/h = 0{\cdot}7$, figure 4, breaking billows, though still visible at the head, are much reduced.

The variation of the Froude number $U/(g'h)^{\frac{1}{2}}$ with the fractional depth of the current h/H is shown in figure 5. Because of the variation of the Froude number with interface thickness, only data with $h_0/h \leqslant 0{\cdot}2$ are plotted. All the flows had breaking billows at the head and resembled a nominally inviscid boundary current with a reflected image. An example with $h/H = 0{\cdot}31$ was shown in figure 2 and may be compared with the flow at a smaller fraction depth $h/H = 0{\cdot}13$ in figure 6.

The dashed line in the figure is for a gravity current of depth h moving along a horizontal floor (Simpson & Britter 1979). Results for the intrusive flow lie between this curve and the solid line for nominally inviscid gravity currents (Britter & Simpson 1978) but are consistently about 10 % less than the latter. Thus, throughout the range of h/H, the reduction in Froude number associated with the small but finite interface thickness still applies, as previously shown for a restricted range of h/H in figure 3.

The dotted curve in this figure is the theoretical curve from Benjamin's (1968) paper on gravity currents, and is for an inviscid current without mixing between the fluids.

4. Discussion

It is believed that in all the flows described here the Reynolds number is large enough for the details to be independent of viscosity, and that the different forms of head seen are related to the thickness of the interface. We would expect to see billows at the head of an inviscid flow with a sharp interface, since there will then be a sharp interface bounding the current which has a velocity difference across it so it is unstable to Kelvin–Helmholtz disturbances. However, heads of this nature do not seem to have been described in the past. Our experiments show, at the smallest interfaces, clear Kelvin–Helmholtz billows, whose two-dimensional form is not broken up by any lobe and cleft structure as in boundary currents (Simpson 1972).

We have shown that, when the interface thickness is less than $\frac{1}{5}$ of the depth of the current, the behaviour of the intrusive head approaches that of a reflected inviscid current, described by Britter & Simpson (1978). This supports the conjecture that their results would be directly applicable to flows under a free surface; a difficult experimental arrangement due to the contamination of the free surface.

As the ratio of interface thickness to current depth increases, the Kelvin–Helmholtz billows are reduced in magnitude until, at about $h_0/h = 1$, mixing between the two fluids at the head ceases. Similar experiments by Faust (1976) in which the interface was established by a lock-exchange technique also showed no mixing between the

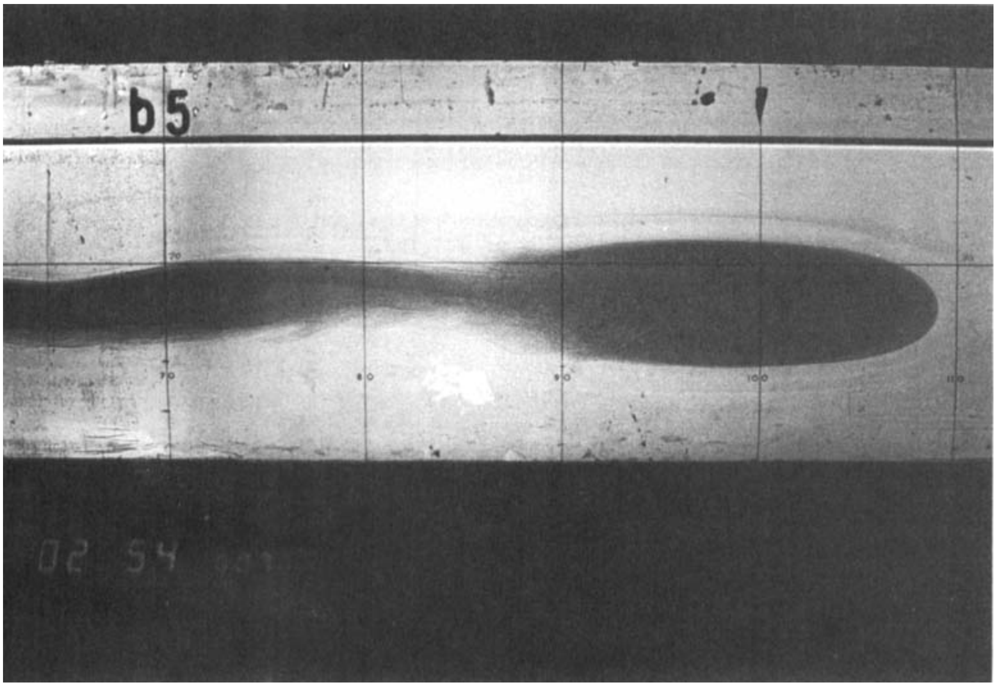

FIGURE 7. Intrusive current running along interface established previously by a lock-exchange technique. $\rho_2/\rho_1 = 1{\cdot}018$, $h_0/h \simeq 1$, $R = Uh/\nu = 1100$.

fluids. When the interface thickness is comparable to the current depth, as in figure 7, the speed of second-mode internal waves may be close to, or greater than, that of the intrusion (Maxworthy 1980) and an interaction between the internal wave and the intrusive flow is observed.

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