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Mixing experiments on fluid released near the closed end of a two-dimensional channel

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Abstract

In a series of laboratory experiments we found that if a line plume is located a finite distance from the closed end of a channel, the fluid between the plume and the end wall becomes partially mixed and a gravity current propagates towards the open end of the channel. In the experiments a steady state is rapidly attained in which the gravity current has approximately one half the depth of the channel and the filled region near the wall has the same density as the fluid in the gravity current. We describe a simple theory to model our experiments and predict the speed and concentration of the gravity current. The situation is very different from the case where the plume is located at the end wall. In the latter case no filled region develops and the gravity current remains significantly thinner and more concentrated. However, in both cases the gravity current travels with the same speed.

1. Introduction

The processes modelled in this paper may occur in a number of processes of environmental interest. For example, when sewage is discharged from a submerged pipe as a two-dimensional diffuse flow into a standing body of water. Similar processes can take place in tunnels and industrial pipes, where gas leaks and fires may occur. The position of the sources of gas or smoke may be near an end wall (Fig. 1a) and, for safety purposes, it is of interest to know the rate of spread of the gas or the smoke and its concentration. The process is also analogous to methane leaks in mines, where the source is less dense than the environment and may leak from the floor. Also at the heads of fjords, plumes of turbid meltwater can often be seen at the surface directly ahead of glacier faces. This meltwater emerges from beneath the ice and rises to the surface. Such plumes in contact with the sea floor may continue to flow horizontally. As

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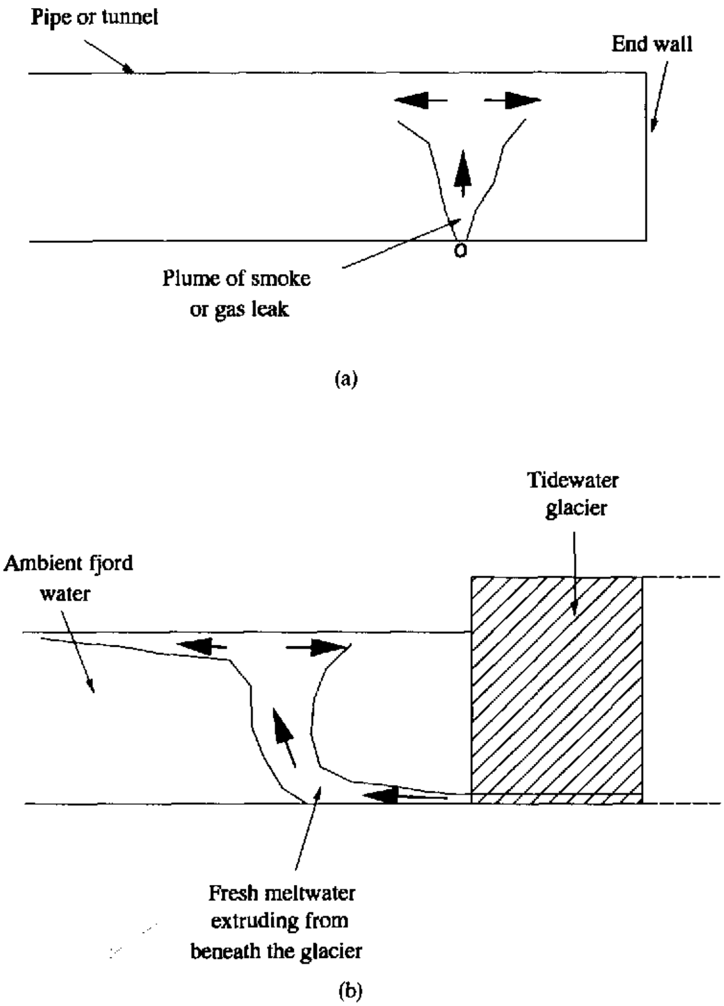

Fig. 1. Environmental examples of a vertical buoyant plume close to a vertical face. (a) Gas leaks or smoke from a fire in pipes or tunnels. (b) Plume of meltwater emerging from beneath a tidewater glacier at the head of a fjord.

the lateral inertia becomes exhausted in a plume of meltwater or the sediment has been deposited so that the flow becomes buoyant, the outflow starts to rise. The plume spreads out as a gravity current at the surface, away from the vertical ice face (as shown in Fig. 1b) and a filled region between the plume and the ice face develops.

The flow outlined above is related to the 'filling-box' mechanism described by Baines and Turner [1], in which buoyant fluid is released from a source at the base of a closed container. A buoyant plume develops above the source of buoyancy and when this plume has reached the top of the tank, it spreads out as a buoyant intrusion. Since the buoyant plume entrains ambient fluid in a closed container, a downward return flow surrounding the buoyant plume develops in order to conserve volume. Therefore, all the fluid outside the plume moves down and ultimately is entrained into the plume. As a result the region outside the plume becomes stably stratified.

In the present problem, the situation is somewhat more complex since the 'filling-box' process only occurs on one side of the plume. When the plume reaches the lower boundary of the tank, the dense fluid initially spreads out equally in both directions as two gravity currents. On the confined side the gravity current reaches the end wall of the tank and then the level of dense fluid on that side begins to rise. The confined side behaves like a 'filling-box', and the region stratifies, with density increasing with time. As a result the pressure at the tank bottom is greater on the confined side than on the open side. The associated pressure gradient diverts a growing proportion of the plume buoancy flux outflow into the gravity current on the open side. Eventually, all the buoyancy flux is diverted into this current and a steady state is reached. The depth of the open-side gravity current increases until it reaches approximately one-half of the total depth [2].

In a fjord environment the source fluid would be less dense than the surrounding environment and emerges at the base of a glacier. However, the process is identical to the laboratory experiments, except that the source was suspended at the surface of the water and the buoyancy of the plume is reversed. Note also that with gases, the flow may be compressible leading to more complex, non-Boussinesq phenomena.

A series of experiments was performed to investigate the factors controlling the physical properties of the filled region and the gravity current. In the first sequence of experiments, the line source was located at different distances from the end wall, with the distance to the opposite end wall of the tank being much longer. Secondly, a series of experiments was performed in which the density difference between the input and the ambient fluid was varied, while the volume flux and the distance of the source from the wall were kept constant. A similar set of experiments were then carried out, but with the source placed at the wall. In the final series of experiments the height of the source was varied, keeping the distance of the source from the end wall, the density and the volume flux of the source constant.

In each experiment a steady state flow configuration was established after about 5–6 minutes. After this time, the gravity current flowing away from the end wall was found to be approximately one half the depth of the layer (note the relatively dense source was placed at the surface of the fresh water in the tank for all the experiments). Since the plume entrains ambient fluid, and this entrained water is fed into the gravity current together with the source fluid, by conservation of volume a return flow is produced in the fresh water above the gravity current. The momentum of the return flow causes the plume to lean over towards the vertical wall at an angle which we found to depend upon the buoyancy of the flow.

A simple physical model is tested with quantitative experimental results. Comments on the limitations and applications of the experiments and the theory are made.

2. Experimental procedure

The apparatus used in the experiments will now be described, including details of the flow visualisation. An account of the experiments performed and the factors controlling the processes taking place are given.

2.1. Apparatus

The experimental set-up is shown in Fig. 2. A perspex tank 7.0 m long, 26.0 cm wide and 47.0 cm deep was used. The tank was filled to the required depth with fresh water. A line source made of perspex tube, with vertical holes on its underside (spaced 1.0 cm apart and 1.5 mm in diameter) supplied saline dense fluid to feed the two-dimensional plume. The tube was 1.0 cm in diameter, the

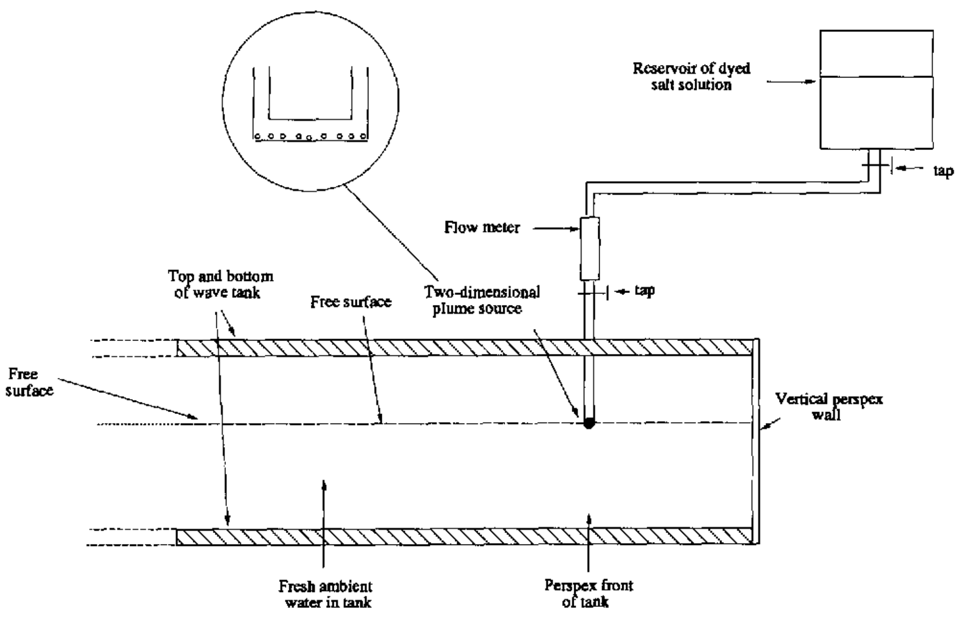

Fig. 2. Set-up of the experiments performed in the laboratory. Schematic diagram showing the line source used to supply the dense fluid in the tank throughout the experiments is inset.

holes extending along the length of the tube, including a hole at each end so that the line plume extended across the width of the whole tank. The tube was wrapped in a thin layer of foam (2.0 mm thick) to distribute the flow evenly along the length. This source arrangement produced a well distributed line plume for the experiments. The dense solution was fed to the source from a reservoir above the experimental tank, and the flow rate was monitored by means of a flow meter. The line source was placed at the surface of the water in the tank, so that the plume descended over the whole depth.

The 7.0 m long tank was sufficiently long so that the flow near the plume reached a steady state before the gravity current in the outflowing region reached the far end wall. When the outflow reached the far wall the experiments were stopped.

2.2. Flow visualisation

In order to obtain uniform illumination, light, shone onto mirrors, was reflected onto a translucent screen fixed to the back of the perspex wall of the tank. This arrangement was necessary so that density measurements throughout the flow could be made using a digital image processing system, DigImage [3]. In order to follow the path of the flow the saline plume was dyed red. During the experiments, green dye was added at different points in the tank in order to visualise the flow and measure current speeds.

Each experiment was recorded using a video camera placed in front of the tank. It was important to place the lighting and the camera as far away from the experimental set-up as possible so that the light beam from the light source was parallel, minimizing parallax in the recorded image. The digital video analysis uses the video recordings of the experiments in which the saline source fluid is dyed red and the ambient fresh water is clear; variations in the red dye intensity correspond to variations in density. An Anton Paar density meter was used to measure densities of samples taken from the experiments using a syringe. These values were used to calibrate the digitised images.

3. Experiments, qualitative and quantitative observations

In this section, we first describe the qualitative features of the experiments. Then, a quantitative discussion of the different sequences of experiments is given, to identify the factors which control the process.

3.1. Qualitative description

Initially, the buoyant plume descended to the bottom of the tank and the flow spread out symmetrically to the left and right as gravity currents (Fig. 3a and b). This phase was similar to the experiments performed by Linden and Simpson [4], but their source was positioned far from the end walls so the new effects resulting from the end wall described here, did not develop over the time scales of their experiments. When the gravity current on the side closest to the

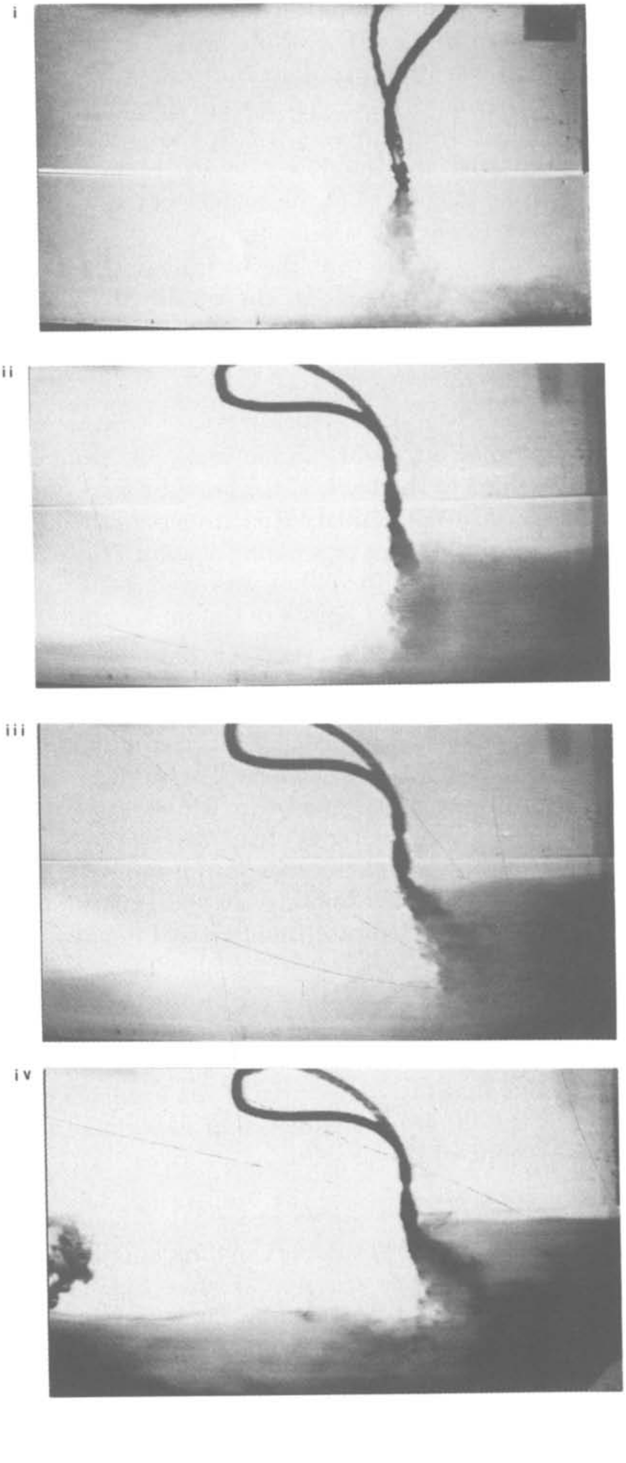

Fig. 3a. Photographs showing the filling of dense fluid between the plume and the vertical wall. (i) shows the initial symmetric flow of the plume and the gravity current, the problem investigated by Linden and Simpson [4]. (ii) and (iii) show the angle of inclination decreasing to the horizontal as the input buoyancy of the plume increases. The salinities of the input plume are as follows: (ii) = 40 and (iii) = 80. (iv) shows the flow to be inertial by the green dye profile in the return flow above the red dyed gravity current. Steady state has been reached in (iv) and the gravity current is approximately half the height of the source.

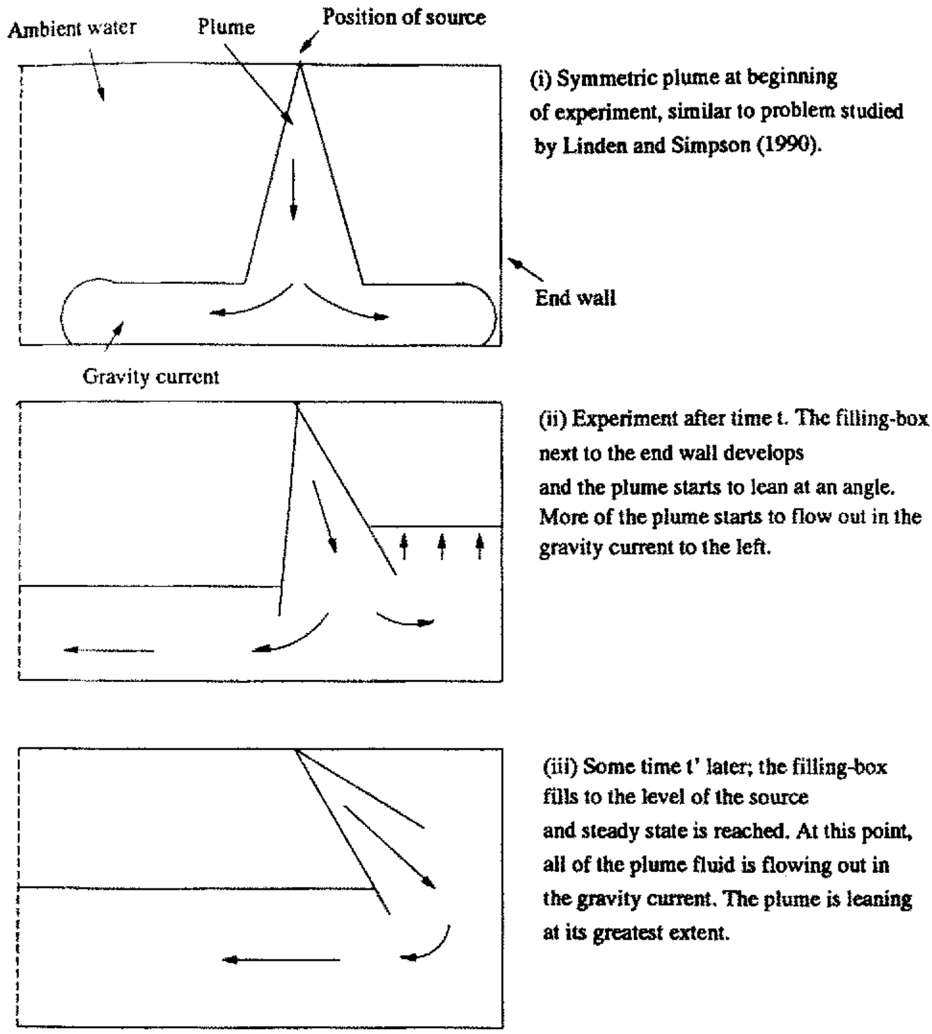

Fig. 3b. Schematics showing the development of the steady state region next to the wall. The gravity current flows away from the wall at approximately half the height of the source, seen at steady state in (iii).

vertical end wall reached the wall, it was arrested and this side started to fill in a similar fashion to a 'filling box' [1] (Fig. 3a and b). As the plume fluid gradually filled the confined region, the plume became progressively more inclined towards the wall. When the ascending front in the confined region had nearly reached the top of the fluid, a steady state was attained. In this steady state, the plume was tilting at its greatest extent (Fig. 3a and b) and the height of the outflowing gravity current converged to a value close to one half the depth of the fluid (Figs. 3a(iv) and 4).

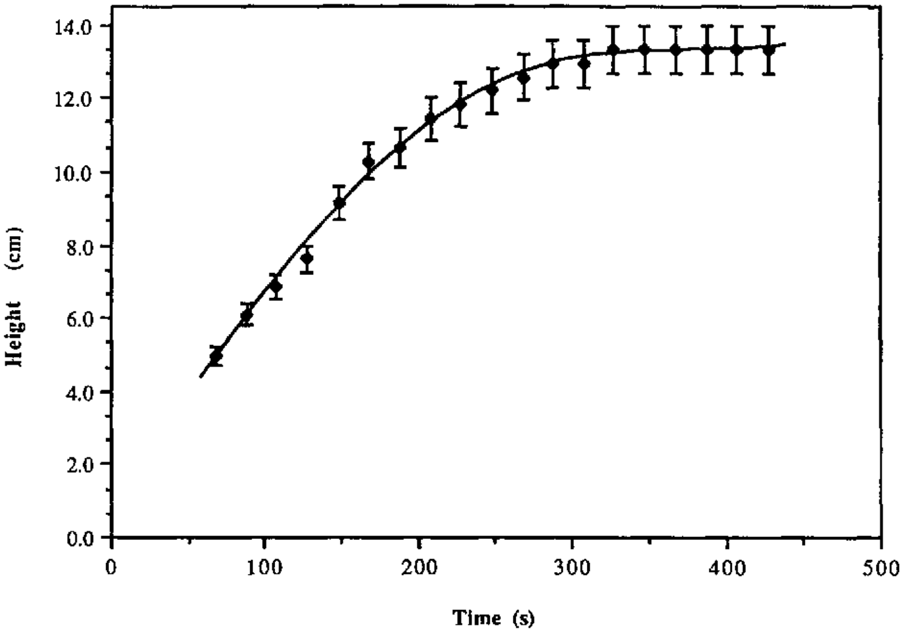

Fig. 4. Graph showing the height of the gravity current as a function of time. Depth of the source in the tank, in this case, was 24.5 cm. The height becomes constant and approximately half that of the source once steady state has been reached. This characteristic is for a source placed away from the wall.

Injection of dye into the filled region suggested it was almost static once steady state had been reached; all the fluid in the base of the plume appeared to flow into the gravity current. This produced a return flow in the ambient fluid which was entrained into the plume.

3.2. Controlling factors

A series of experiments was performed to determine which features controlled the flow. In the first set of experiments we investigated the variation of the flow between the source and the wall as the distance of the source from the wall was increased from experiment to experiment. The height of the source was kept constant, at 22.5 cm, and the buoyancy was constant, 34.0 parts per thousand (ppt) (equivalent to typical salinities in the ocean).

Once steady state was attained so that the buoyancy flux of the gravity current equaled the source buoyancy flux (Fig. 5), it was found that (i) the volume flux and (ii) the speed of the gravity current did not depend upon the distance of the source from the wall (Fig. 6a and b). The source buoyancy flux was found by measuring the source volume flux Q_0 and the effective gravity of the source g'_0. Similarly, the buoyancy flux of the gravity current was found

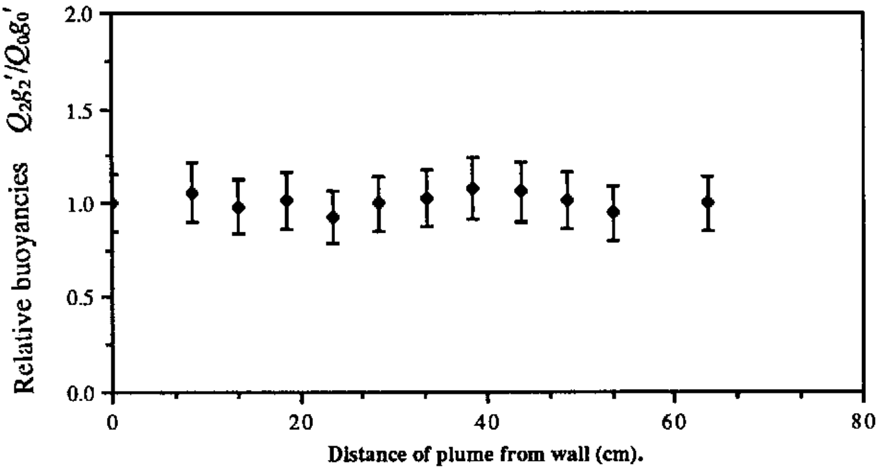

Fig. 5. Relative buoyancy (density) fluxes plotted as a function of plume distance from the wall.

by measuring the volume flux Q_2 and the effective gravity g_2' of the gravity current. Q_2 was deduced from measurements of the speed and depth of the gravity current. The volume flux measured at the base of the plume is very similar to that in the gravity current (Figs. 6a and 7) confirming observations that all the fluid in the plume enters the gravity current. Finally, in the digitised images of the flows of Fig. 8, the densities of the gravity current at the base of the plume and in the region between the plume and the vertical wall, are nearly equal.

The second series of experiments was carried out with the source kept at the same position, 33.3 cm from the vertical wall, at a height of 22.5 cm in the tank and the strength of the source of buoyancy was varied. The angle of the plume to the horizontal, θ, was found to decrease as the buoyancy flux increases.

The third set of experiments were carried out with the source located at the wall, at a height of 22.5 cm, with varying source buoyancy fluxes. In these experiments the height of the outflowing gravity current was constant, about 6.6 cm. As with the experiments of Linden and Simpson [4], no filled region formed. The gravity current produced by the plume positioned at the wall was strikingly different to that in which the source plume was positioned away from the wall. In the first case, the gravity current was concentrated and thin whereas for the case with the source plume away from the wall, the gravity current was more dilute and deeper (Fig. 8). In order that the steady gravity current flows out at half the layer depth, the line source must be located far enough from the wall. This critical distance appears to be approximately equal to the depth of the fluid. If the source is closer to the end wall, then the gravity current is shallower and more saline.

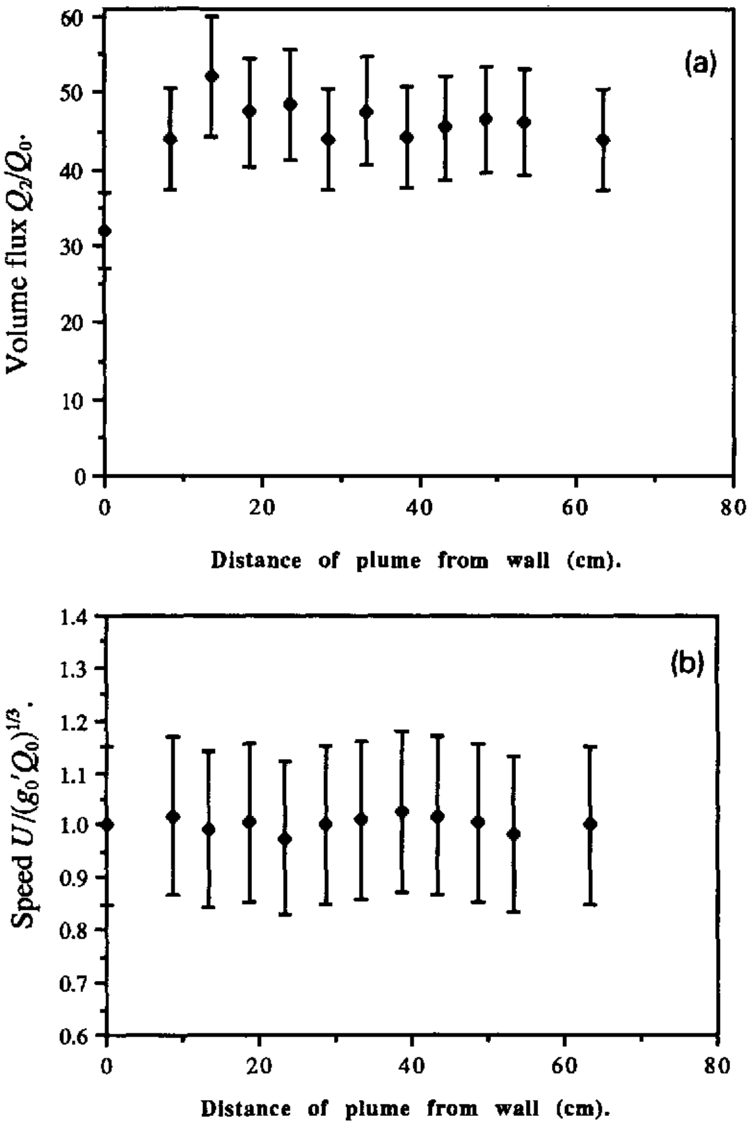

Fig. 6. (a) Graph showing the nondimensional relative volume fluxes of the gravity current and the initial source flow as a function of plume distance from the vertical wall. (b) Graph showing the nondimensional speeds of the gravity current and the source flow as a function of plume distance from the vertical wall.

Finally, a fourth set of experiments were performed in which the source was located 33.3 cm from the vertical wall, the buoyancy flux was held constant and the depth of the fluid in the tank was varied from 10–30 cm. It was observed that

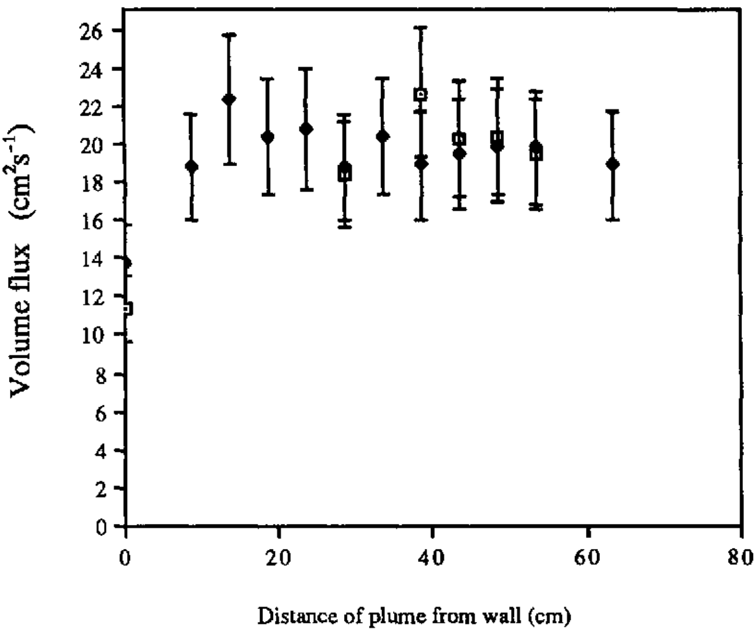

Fig. 7. Comparison of volume fluxes Q_2(◆) and Q_1(□) as a function of plume distance from the wall.

the height of the gravity current was always approximately half the depth of the fluid, shown in Fig. 9. The angle θ of the plume was found to be constant, about 44° to the horizontal.

The source volume flux was kept constant throughout all the experiments presented and was set at $0.43\,\mathrm{cm}^2\,\mathrm{s}^{-1}$. For this flow rate, during the first 100–200 cm, the gravity current moved approximately as a plug flow, with little vertical shear in the velocity profile, as confirmed by dye experiments. This suggests that during the times of interest friction did not have a dominant effect upon the gravity current.

In summary the flow produced in the experiments consisted of the descent region of the forced plume produced by the steady source of buoyancy, the horizontal gravity current flowing away from the plume (the outflow region), and the filled region between the plume and the vertical wall. A summary of the experiments is given in Table 1.

4. Simple theory of the flow regime

We now develop a steady state model of the flow. We compare our results with the case of a source located at the wall; the latter problem being analogous to that studied by Linden and Simpson [4]. For reference, in Fig. 10,

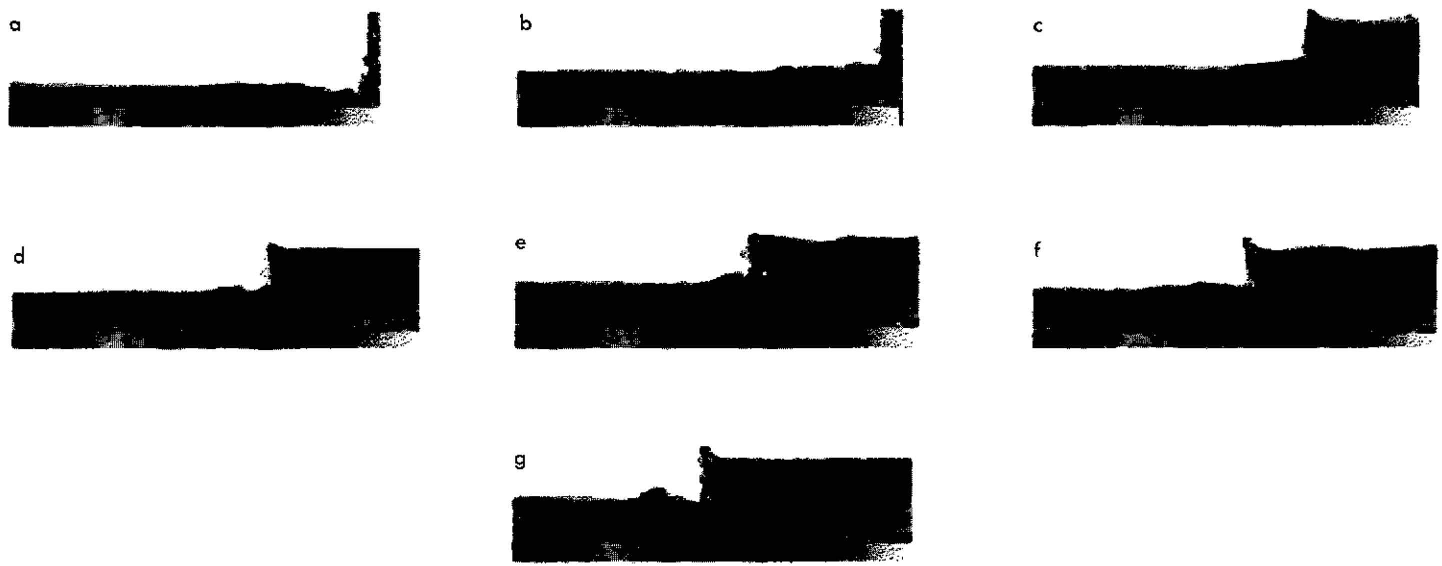

Fig. 8. Digitised images of the plume (a) at the wall, (b) 8.5 cm, (c) 28.5 cm, (d) 38.5 cm, (e) 43.5 cm, (f) 48.5 cm and (g) 53.5 cm from the vertical wall. Shading represents density, with dark corresponding to dense fluid and light to less dense. The height of the source was roughly 22.3 cm for all cases. The densities at the base of the plume and in the mixed region are equal to that of the outflowing gravity current at steady state. (Some parallax was unavoidable at the corners of the images and should be ignored.)

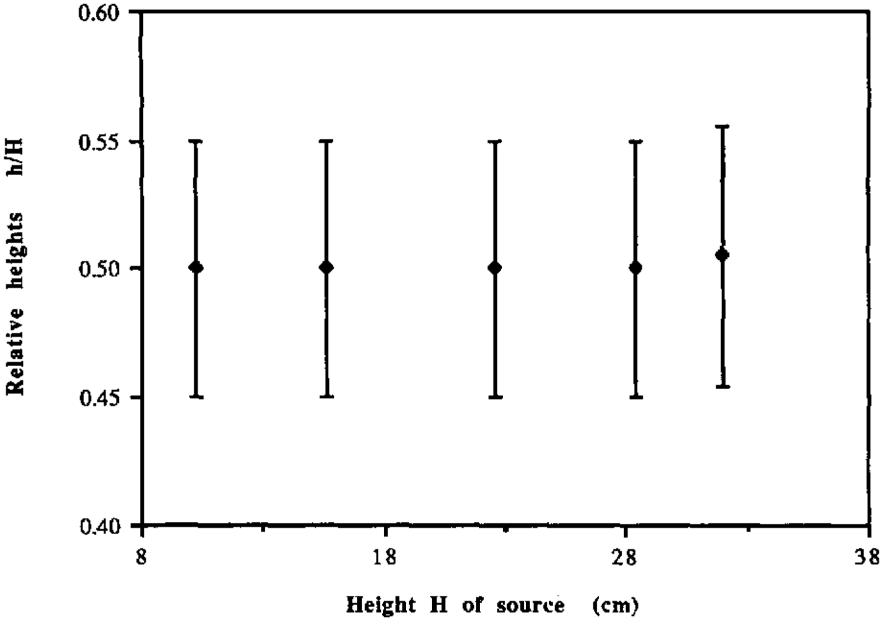

Fig. 9. Graph showing the relative heights of the gravity current/source as a function of source height.

TABLE 1

Summary of the experiments performed, the parameters varied and the parameters kept constant

Experiment sequence	Parameter varied	Parameters kept constant
1	Distance of source from wall	Source volume flux Source height = 22.5 cm Source buoyancy = 34.0 ppt
2	Source buoyancy (salinity)	Source volume flux Source distance from end wall = 33.3 cm Source height = 22.5 cm
3	Source buoyancy (salinity)	Source volume flux Source kept at wall Source height = 22.5 cm
4	Source height	Source volume flux Source distance from end wall = 33.3 cm Source buoyancy = 34.0 ppt

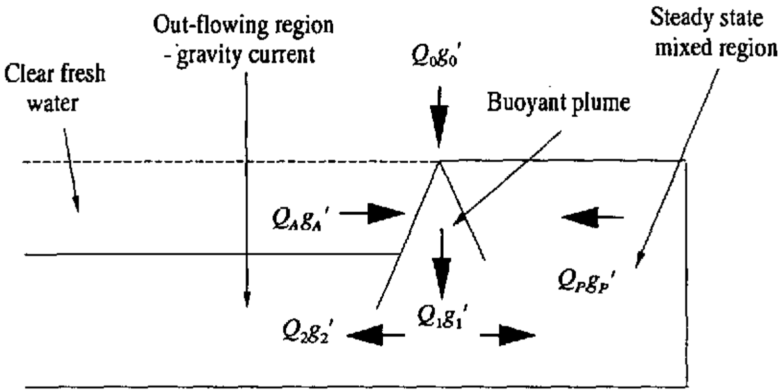

Fig. 10. Diagram showing the different regions and the mass fluxes of the flow regime.

a schematic of the volume and buoyancy fluxes for the flow regime is presented. In the figure, g'_0 is the effective gravity of the input fluid, $g'_0 = g(\Delta\rho/\rho)$, where g is the acceleration due to gravity, $\Delta\rho$ is the difference in density between the plume and the ambient water in the tank and ρ is a reference density of the ambient water. Q_0 and $Q_0 g'_0$ denote the input volume and buoyancy fluxes, respectively. Q_A and $Q_A g'_A$ are the volume and the buoyancy fluxes of the return flow, respectively, where $g'_A = 0$. Q_P and $Q_P g'_P$ are the volume and buoyancy fluxes entrained into the plume from the filled region, Q_1 is the volume flux at the base of the plume and Q_2 is that of the outflowing gravity current. g'_1 is the reduced gravity at the base of the plume, g'_2 is the reduced gravity of the outflowing gravity current, g'_P is that of the filled region and g'_A is the reduced gravity of the return flow. The Boussinesq approximation has been assumed.

4.1. Volume conservation

In most of the experiments, the input volume flux Q_0 was much smaller than the measured fluxes Q_A, Q_2 and Q_1; therefore it has a negligible effect upon the mixing and flow and so we neglect it in the following theory. In steady state, the global conservation of volume may thus be expressed as

$$Q_2 = Q_A. \tag{1}$$

Conservation of volume in the plume may be expressed as

$$Q_1 = Q_A + Q_P. \tag{2}$$

4.2. Buoyancy conservation

In steady state, the global conservation of buoyancy may be expressed as

$$Q_2 g'_2 = B_0, \tag{3}$$

where $B_0 = Q_0 g'_0$ and is the input buoyancy flux. As was shown earlier in Fig. 5, this was indeed the case once steady state had been attained.

In the plume, the conservation of buoyancy may be written as

$$Q_1 g'_1 = Q_0 g'_0 + Q_P g'_P. \tag{4}$$

Analysis of the digitised images of several experiments (Fig. 8) reveals that the density of the gravity current, the fluid at the base of the plume and the fluid in the filled region are very similar. Hence,

$$g'_1 \sim g'_2 \sim g'_P. \tag{5}$$

From the experiments, the filled region was nearly static, which implies that $Q_P \sim 0$. Hence, it follows from eqs. (2), (4) and (5) that

$$g'_1 \sim \frac{B_0}{Q_A} \sim \frac{B_0}{Q_1}, \tag{6}$$

and

$$Q_1 \sim Q_2. \tag{7}$$

We confirmed these simple conservation laws by direct measurement of Q_1 and Q_2 in a number of experiments. As discussed in Section 3, we found Q_1 and Q_2 were within 5% of each other and therefore agree within the limits of the experimental accuracy (Fig. 7).

4.3. The gravity current

Following the work of Simpson [5], we expect the gravity current to have speed

$$U = c\sqrt{(g'_2 h)}, \tag{8}$$

where c is a constant and h is the depth of the outflowing gravity current. Assuming the density of the fluid in the gravity current is of uniform density (as may be seen in Fig. 8). The buoyancy flux in the gravity current is given by

$$B_2 = U h g'_2, \tag{9a}$$

and so from eqs. (3) and (8), it follows that

$$B_0 \sim c(g'_2 h)^{3/2} = U^3/c^2. \tag{9b}$$

Therefore, we expect the speed of the gravity current to scale as $B_0^{1/3}$. This prediction is borne out with our experimental data (Fig. 11) in which we have plotted U as a function of $B_0^{1/3}$. The slope has value 1.0 ± 0.1, and hence $0.85 \leqslant c \leqslant 1.15$. Although the gravity current and return flow have some similarities with the classical lock exchange problem [2], the speed predicted by the lock exchange theory, $U \sim \sqrt{g'h}/\sqrt{2}$, implies $c \sim 0.7$. This value of c is smaller than the values observed in our experiments. Because of the free surface, the

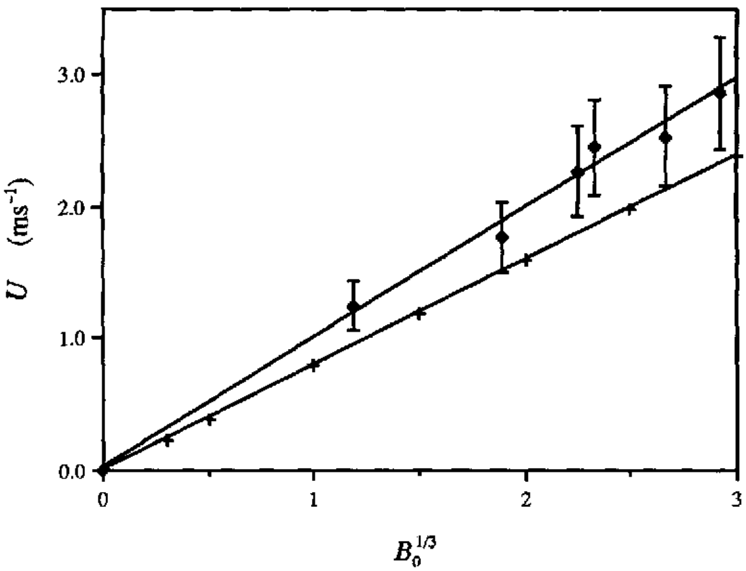

Fig. 11. Graph showing the speed U (◆) as a function of buoyancy, where the slope is approximately 1.0 ± 0.1, hence $0.85 \leqslant c \leqslant 1.15$. The second line, of slope $0.5^{1/3}$, through the + shows the speed of the gravity current in the 'lock exchange' problem [2], to be less than the speed of the gravity current in the experiments presented in this paper.

lower current has characteristics of a gravity current as compared to the confined lock exchange process.

In steady state the rate of change of momentum flux of the gravity current and the ambient return flow is balanced by the pressure force set up by the plume and the filled region between the plume and the wall (Fig. 12). Assuming that the density is uniform in the outflowing gravity current and also in the filled region next to the wall, where P_A is the atmospheric pressure at the free surface of the water in the tank and $z > (H-h)$ at P_1, then the integral of the horizontal momentum equation can be written as (integrating from the surface of the water to the bottom of the tank)

$$\rho \int_0^{H-h} V_R^2 \,\mathrm{d}z + \rho \int_{H-h}^{H} U^2 \,\mathrm{d}z = \int_0^H (P_2 - P_1)\,\mathrm{d}z + F, \tag{10}$$

$$= \int_0^H (\rho + \Delta\rho) g z \,\mathrm{d}z - \int_0^H \rho g z \,\mathrm{d}z - \int_{H-h}^{H} \Delta\rho g [z - (H-h)]\,\mathrm{d}z, \tag{11}$$

$$= \int_0^{H-h} \Delta\rho g z \,\mathrm{d}z + \int_{H-h}^{H} \Delta\rho g (H-h)\,\mathrm{d}z + F, \tag{12}$$

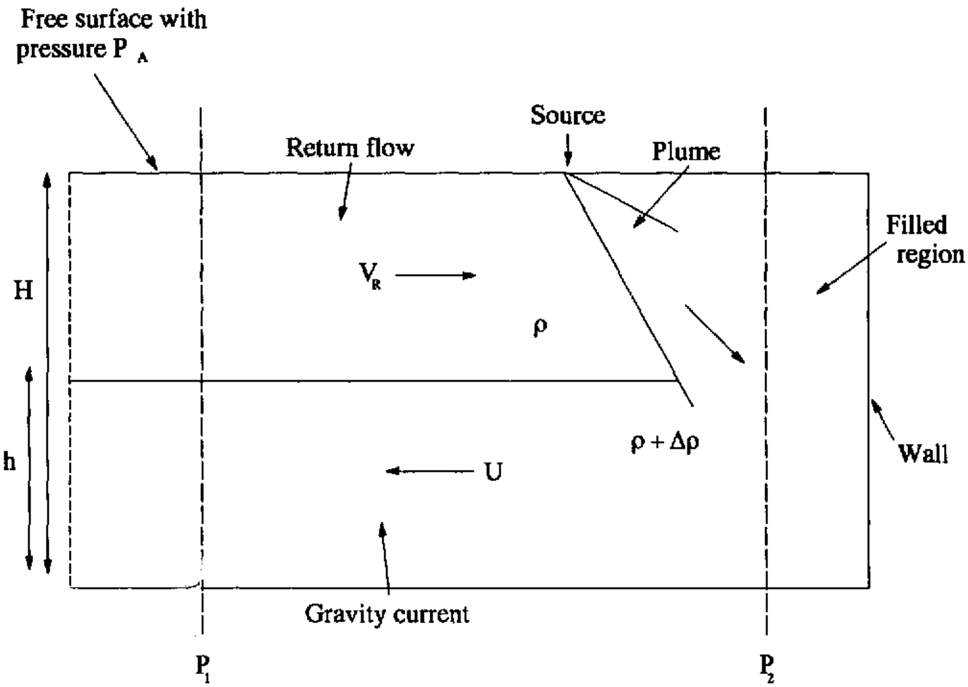

Fig. 12. Diagram showing the momentum flux of the gravity current and the return flow, balanced by the pressure force set up by the plume and the filled region. P_A is the atmospheric pressure; P_1 is the pressure across the gravity current and the return flow; and P_2 is the pressure across the filled region.

$$\rho U^2 h + \rho V_R^2 (H-h) = g\Delta\rho\left(\frac{(H-h)^2}{2} + (H-h)h\right) + F, \tag{13}$$

where

$$V_R = Uh/(H-h) \tag{14}$$

is the velocity of the return flow and F (>0) represents the net horizontal momentum flux associated with any weak flow and effects of stratification in the filled region. In eqs. (11)–(13) $\Delta\rho$ is the difference in density between the gravity current and the fresh water in the outflow region, and ρ is the density of fresh water in the return flow above the dense gravity current.

Combining eqs. (8), (13) and (14) and assuming F is negligible, from the observation that the filled region was quiescent, we can obtain the relationship between c and h/H, as

$$c^2 = \frac{1}{h}\left[\frac{H-h}{h}\right]\left[\frac{h+(H-h)/2}{1+h/(H-h)}\right]. \tag{15}$$

The height of the gravity current (h/H) as measured in the laboratory (Fig. 9) has value 0.5 ± 0.05 and so from the momentum balance eq. (15) we expect c to lie in the range $0.79 \leqslant c \leqslant 0.94$. Within our experimental error, this is consistent with the measured value of c, $0.85 \leqslant c \leqslant 1.15$ (Fig. 11). Furthermore, if F is non-zero, then c is larger than predicted by eq. (15) improving the agreement in the estimates of c. Note, this is very different to the case in which the plume is located at the wall, where the depth of the current has been found to be approximately $\frac{1}{4}$ the height of the source [4].

For a given flow rate we found that the angle of inclination of the plume to the horizontal decreases as the buoyancy flux is increased (Fig. 13). In Fig. 13, we plot the dimensionless relative density since all the experiments had the same angle θ.

The entrainment of fluid from the return flow into the gravity current flow is effected by the mixing induced by the plume and, to a lesser extent, by any hydraulic jumps created as the plume fluid flows into the gravity current. Although the mixing and plume behaviour is complex, we can compare the total entrainment with that of a simple buoyant plume.

In the experiments we found that the dimensionless volume flux ($Q/(B_0^{1/3}H)$) in the gravity current has value (eqs. 1–9)

$$Q_2/B_0^{1/3}H = c^{2/3}(h/H) = (0.9)^{2/3}/2 \sim 0.47. \tag{16}$$

The above does not include any fluid which propagates from the base of the plume and into the filled region beside the end wall of the tank. In contrast, the total dimensionless volume flux at the base of a simple buoyant plume located away from any boundary is given by

$$\frac{Q}{(B_0^{1/3}H)} = (2\alpha)^{2/3} = 0.34, \tag{17}$$

where α is the entrainment constant and the volume flux at the base of a simple plume located adjacent to a wall is

$$\frac{Q}{(B_0^{1/3}H)} = \alpha^{2/3} = 0.22. \tag{18}$$

We deduce that the mixing in the present non-linear plume process is more efficient than in a simple buoyant plume. This is partially accounted for by the tilt of the plume, which can increase the entrainment length by a factor of up to 2 based on the measured angles of tilt, which are in the region of 30°–70° (Fig. 13). The presence of a hydraulic jump at the base of the plume may also effect some additional mixing.

It is also interesting to note that the source must be located sufficiently far from the end wall that the plume can attain the requisite inclination without interacting with the wall; otherwise, the plume behaves partially as a wall plume. In order that the filled region can develop, the plume should be located

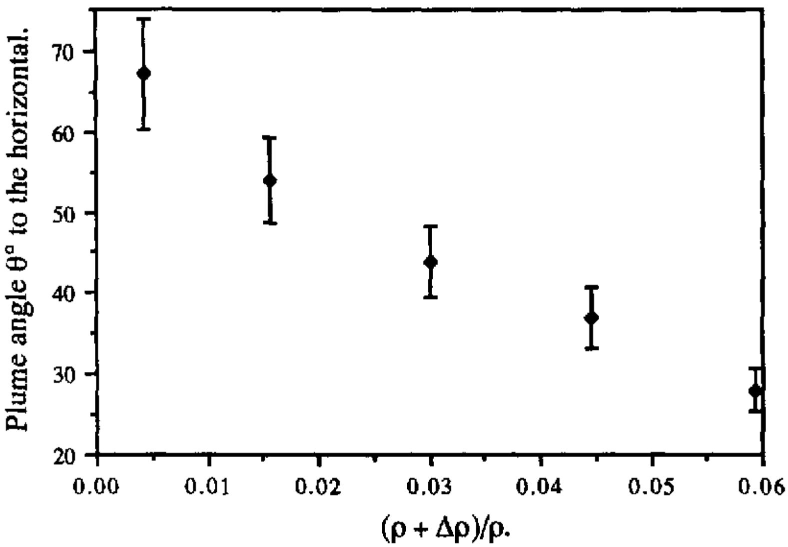

Fig. 13. Graph of plume angle θ to the horizontal, as a function of the nondimensional relative densities.

TABLE 2

Comparison of experimental results with those found by Linden and Simpson [4]

Parameters	
This paper	Ref. [4]
$h \sim 0.5H$	$h \sim 0.23H$
$U \sim B_0^{1/3}$	$U \sim B_0^{1/3}$
$g' \sim 2(B^{2/3})/H$	$g' \sim 4.3(B^{2/3})/H$

a distance $X \geqslant H$ from the wall. The distance of the source from the vertical wall affects the time for the filled region to reach steady state.

4.4. Comparison with end wall sources

In Table 2, we compare the results found in the work presented in this paper with the results found by Linden and Simpson ([4], Table 2) for a plume at an end wall. We have revised their numerical coefficients, in order to conserve buoyancy.

It is remarkable that changing the location of the source of buoyancy can change the properties of the spreading current so dramatically. For the Linden and Simpson [4] experiments on plumes released from the end wall, the dimensionless mass flux in the gravity current was found to be $Q/(B_0^{1/3}H)=0.23$. This

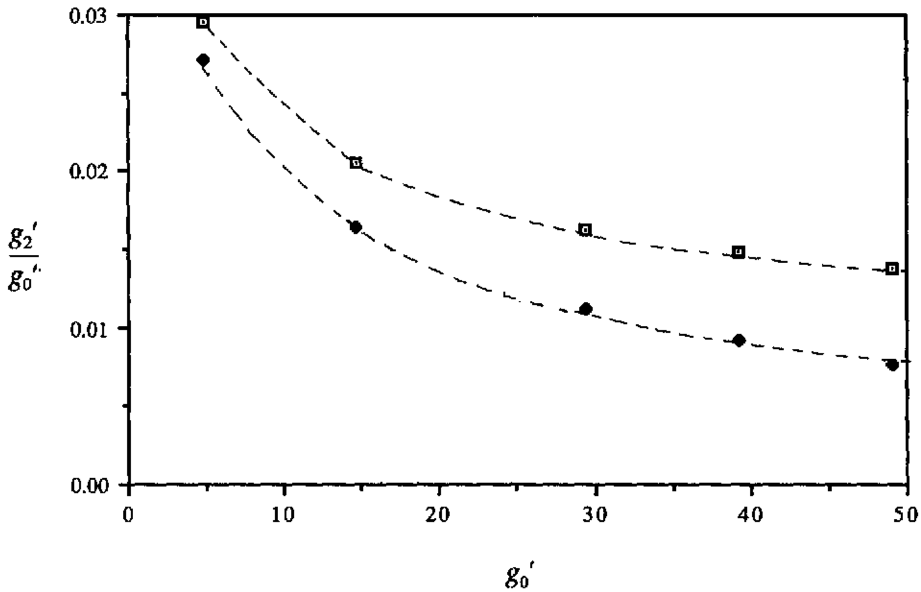

Fig. 14. Comparison of the relative buoyancies of the gravity current/source as a function of the source buoyancy, plotted in terms of g_0': for source at wall (❑) and source away from wall (◆).

is similar to, but a little larger than the simple buoyant wall plume (eq. 18). In these experiments the hydraulic jump at the base of the plume may be responsible for this extra mixing. However, owing to the much greater enhancement of the entrainment, which we have found in the present experiments, we deduce that the hydraulic jump is not the dominant process which increases the entrainment in this case.

5. Conclusions

A series of experiments has been performed to investigate the effect of placing a line source of buoyant fluid at an elevated point in a tank of uniform fresh water. The distance of the source from the vertical wall, the buoyancy flux and the depth of the fluid were varied systematically. In the experiments a filled region developed between the source of buoyant fluid and the wall, and a gravity current spread into the open side of the channel from the base of the plume.

The distance of the source from the end wall and the size of the filled region next to the wall had no effect on the steady flow regime provided that the source was a sufficient distance from the wall. In steady state the flow was controlled by the gravity current running out in the outflowing region at approximately half the height of the source, producing a return flow in the fresh water above. As the filled region reached steady state, nearly all of the plume fluid moved out in the gravity current and the density in the filled region was equal to that of the gravity current. As the buoyancy increases, the plume becomes inclined so that a greater distance was provided for entrainment.

Our experimental results are quite different to those which are obtained when the source is positioned at the wall. In that case, the height h of the gravity current is much smaller and hence it remains much more concentrated (Table 2). When the plume impinges on the base of the tank, a hydraulic jump is set up, which can be seen in the digitised images of Fig. 8. This causes some weak additional mixing.

Since the current is much more dilute when the source of buoyancy is located away from the end wall, the process described in this paper may be useful for diluting the concentration of gas in a situation of danger. However, the rate of spread of the current only depends upon the buoyancy flux and so is not affected by the location of the source. It would be interesting to consider these effects in a three-dimensional system.

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References

1 W.D. Baines and J.S. Turner, Turbulent buoyant convection from a source in a confined region, J. Fluid Mech., 37 (1969) 51–80.
2 T.B. Benjamin, Gravity currents and related phenomena, J. Fluid Mech., 31 (1968) 209–248.
3 S.B. Dalziel, DigImage: System Overview. Cambridge Environmental Research Consultants Ltd., Cambridge, 1993.
4 P.F. Linden and J.E. Simpson Continuous two-dimensional releases from an elevated source, J. Loss Prev. Process. Ind., 3 (1990) 82–87.
5 J.E. Simpson, Gravity currents in the laboratory, atmosphere and ocean, Annu. Rev. Fluid Mech., 14 (1982) 213–234.