Experimental study of smoke propagation in a tilted tunnel

Romain HANOUZET\textsuperscript{1,2}, Olivier VAUQUELIN\textsuperscript{2} and Samuel VAUX\textsuperscript{1}.

\textsuperscript{1}Institut de Radioprotection et de Sûreté Nucléaire (IRSN), Laboratoire ETiC, France
\textsuperscript{2}Aix-Marseille Université (AMU), Laboratoire IUSTI, France

romain.hanouzet@etu.univ-amu.fr

ABSTRACT

In the context of an underground repository, one of the main concerns lies within the management of the smoke produced by a fire. The propagation front of smoke is the first indicator received by the detectors and this front can be represented by a gravity current. In this study, air/helium experiments on the non-Boussinesq gravity currents generated from an instantaneous buoyancy source in horizontal and tilted tunnels have been carried out. A large range of density ratios $\gamma = \rho_c/\rho_0$ (0.29 $\leq \gamma \leq$ 0.88), between the density of the release ($\rho_c$) and the ambient ($\rho_0$) is investigated. First, similarly to the open ambient case, we note that the front of the gravity current propagates in three phases: the slumping, inertial and viscous phase. In each phase, a power-law exists between the front location of the gravity current ($x$) and the time ($t$). In the early inertial deceleration phase, $x \propto t^{2/3}$ is valid for both Boussinesq and non-Boussinesq gravity currents. Moreover, in the late deceleration phase, the viscous effects become more important and a power-law $x \propto t^{1/2}$ has been identified. Then, experiments on tilted tunnels with angles varying from 1% to 17% have been performed to consider the influence of the slope. It is found that the transition between inertial and viscous propagation decreases when the slope increases. One possible explanation is that the mixing layer increases in the higher angle percentages which causes the buoyancy contained within the head of the density currents to decrease more rapidly. A high angle of slope can be seen potentially as a disadvantage for the propagation of the smoke.

KEYWORDS: smoke spreading, tilted tunnel, non-Boussinesq gravity currents
INRODUCTION

In case of an accident in a tunnel with a slope between 10 and 15% of an underground repository, the production of smoke can be instantaneous with a given volume of smoke released or continuously fed by a source. This work focuses only on the instantaneous release of a given volume of smoke. In this configuration, the propagation of the smoke front can be affected by the confinement, the density ratio $\gamma = \rho_c/\rho_0$ between the release and the ambient and by the slope angle of the tunnel. Therefore, there is a special need to quantify these effects on the kinetics of the smoke.

Gravity currents, or density currents, are flows driven by a horizontal density difference. This density difference may be produced by different factors such as, for example, the temperature difference, the presence of suspended sediments or dissolved materials. Several laboratory experiments [1], [3] and [4], and simulations [2], [11], have been performed to describe gravity current kinetics on low differences of density, i.e. for Boussinesq flows. Producing a gravity currents is relatively simple: a vertical gate is placed in a horizontal tunnel and each part is filled with two fluids with different densities. Then, removing the gate generates a natural flow. This experiment is called lock-exchange problem. The propagation of gravity currents has been largely studied using lock-exchange experiments in weak density difference, i.e. in the Boussinesq case (Simpson [10] and Shin & Linden [9]). The location of the front ($x$) of density currents as a function of time ($t$) is mainly studied. It has been observed that the gravity current propagates through three phases [1]: a slumping phase, an inertial-buoyancy phase and a viscous-buoyancy phase. Each phase is characterized by a different propagation rate. During the slumping phase, the front location of the gravity current is proportional to the time. Then, during the inertial phase, the current starts to decelerate and $x \propto t^{2/3}$ which can be explained by a balance between inertia and buoyancy. Finally, in the late deceleration phase, the inertial force tends to be less important than viscous forces and $x \propto t^s$. Different values of $s$ have been found. Hoult [6] proposed $s = 3/8$ by considering a balance between buoyancy and viscous forces from the interface. Huppert [7] revised his analysis and added viscous effects over a rigid horizontal surface and found $s = 1/5$ and Dai [4] have determined $s = 1/2$ by balancing gravity and viscous stress per unit volume.

In the case of fire hazard, smoke flows are mainly non-Boussinesq, i.e. exhibit large density differences. Only few experiments have been made on non-Boussinesq density currents [4], [8]. Recently, Lowe [8] performed lock-exchange experiments on non-Boussinesq heavy gravity currents within a large range of density ratios $\gamma = \rho_c/\rho_0$ (0.61 < $\gamma$ ≤ 0.99). He showed that for large density differences, heavy currents propagate faster than light currents, but in this study, propagation of density current is only studied in the slumping phase. Consequently, there is a need to understand the kinetics of a density current for larger density ratios and for a longer distance in a tunnel. Dai [4] extended the study on gravity currents for the case of propagation down a slope in deep ambient for angles varying in the range 0 to 9° and he found that the power-laws identified previously are robust.

This experimental study focuses on the influence of three parameters: the effect of the confinement, the large density difference between the release and the ambient and the slope of the tunnel, on the kinetics of gravity currents and especially on the three propagation phases described above.

EXPERIMENTAL SETUP

The experimental setup is a reduced-scale rectangular isothermal tunnel model, as in shown Fig. 1. Its internal cross-section is 0.25 m height (H) and 0.5 m width (W), the total length (L) is 10 m and the walls are transparent Perspex. The tunnel is supported by a steel frame which can be inclined, and the angle ($\theta$) can be
adjusted in the range ±17 %. The initial volume of light fluid is fixed with 0.25 m height \((h_0)\), 0.5 m width \((w_0)\) and 0.5 m length \((l_0)\). The light fluid is a helium-air mixture which is injected in the initial volume and the ambient fluid is air. The density of the light fluid is controlled by a helium concentration analyzer with an accuracy of 0.1 % volume concentration. In addition, seeding particles, obtained by a chemical reaction between ammonia and hydrochloride acid, are injected into the initial volume to provide flow visualization. Each experiment has been repeated three times to insure its repeatability. The initial volume remained fixed for all experiments presented hereafter.

**RESULTS**

**Effects of confinement on the kinetics of gravity currents**

A first experiment is made to quantify the effects of confinement on the propagation regimes of the gravity currents for a Boussinesq case with a horizontal tunnel \((\theta = 0 \%)\). The initial density of the released fluid was set at 1.07 \(\text{kg/m}^3\), corresponding to a density ratio \(\gamma = 0.88\). The gravity current produced by our experiments propagates through the three phases described previously, as shown in Fig. 2. The confinement does not change the exponents of the power-laws found in the case of the propagation of a gravity current in an open ambient. In the late deceleration phase, we can note that we recover \(x \propto t^{1/2}\) as suggested by Dai [3] in his experiments for Boussinesq gravity currents in an infinite ambient.

**Effects of large density differences on the kinetics of gravity currents**

Experiments on the kinetics of gravity currents on non-tilted tunnels are presented with a varying initial density in the range \(0.35 \leq \rho_c \leq 1.07 \text{ kg/m}^3\), corresponding to the density ratio range \(0.29 \leq \gamma \leq 4\).
0.88. As shown in Fig. 3, the front of the density current propagates faster when the density ratio is far from 1, i.e. when the density difference, $\Delta \rho$, is high. The mean velocity can be calculated experimentally and $u_c$ varies in the range $0.13 \leq u_c \leq 0.63$ m/s.

Fig. 3: The front location, $x$, versus time, $t$, on a 0 % slope for the gravity current produced from a released volume of initial density: $\bigcirc$ 1.07, $\bullet$ 1.0, $\bigstar$ 0.95, $\bigtriangledown$ 0.9, $\bigcirc$ 0.85, $\checkmark$ 0.8, $\checkmark$ 0.77, $\bullet$ 0.71, $\bigcirc$ 0.65, $\bigtriangleup$ 0.6, $\bigtriangleup$ 0.56, $\bigtriangleup$ 0.53, $\bigstar$ 0.5, $\bigtriangleup$ 0.4, $\bigstar$ 0.35 kg/m$^3$.

The front location and the time were non-dimensionalized, noted respectively $\tilde{x}$ and $\tilde{t}$, as follow: $\tilde{x} = x/l_0$ and $\tilde{t} = t \sqrt{\frac{g(\Delta \rho)}{\rho_c} h_0/l_0}$. These dimensionless front location and time are convenient to describe the propagation in the slumping and inertial phases, as shown in Fig. 4 (a). In the late deceleration phase, the discrepancy of the data can be explained by the errors committed on both the experiment repeatability and the control of initial density. Nevertheless, in the inertial phase, for a large range of density ratio corresponding to non-Boussinesq gravity currents propagating in a horizontal tunnel, we can write, as shown in Fig. 4 (b):

$$\tilde{x} = k\tilde{t}^{2/3}$$

with $$k = 0.82^{+0.05}_{-0.07}$$.

Fig. 4: The front location, $\tilde{x}$, versus time, $\tilde{t}$, on (a) a normal scale and (b) on a log-log scale. The front location, $x$, is non-dimensionalized by $l_0$ and time is non-dimensionalized by $l_0/\sqrt{g(\Delta \rho/\rho_c)h_0}$. In (b), the dashed line represents the inertial propagation: $\tilde{x} \propto \tilde{t}^{2/3}$.

It is important to note that the constant $k$ “absorbs” the confinement and the geometry parameters of the tunnel. For example, if the cross section of the tunnel changes, $k$ will be different, as suggested by Fanneløp [5].
Effects of slope on the kinetics of gravity currents

Results presented hereafter are made with a fixed initial density $\rho_c = 0.5 \text{ kg/m}^3$, i.e. $\gamma = 0.42$, on slopes varying within 1% and 17%. Firstly, experiments carried out with 1, 10 and 17% slope angles are presented in Fig. 5. Here we focus only on the slope influence on the propagation front in the inertial phase. In Fig. 5 is plotted the experimental front location $x^{3/2}$ versus time. When the experimental data can be fitted with a linear interpolation, the density current is in the inertial phase. As we can see in Fig. 5 (a), the flow propagates only in slumping and inertia phase for a 1% slope. In Fig. 5 (b) and (c), for respectively a 10% and 17% slope, the viscous phase appears sooner. On a 10% slope, the transition time between the two phases is 21 s and on a 17% slope, this time is 18 s.

Fig. 5: Relationship between $x^{3/2}$ and time $t$ on (a) a 1% slope, (b) a 10% slope and (c) on a 17% slope. The initial density of the released volume is $\rho_c = 0.5 \text{ kg/m}^3$. The dashed lines represent the linear interpolation existing between $x^{3/2}$ and $t$, corresponding to the inertial phase of the gravity current propagation.

Fig. 6 (a) shows variations of the front location, $x$, versus time, $t$, and Fig. 6 (b) shows the velocity of the gravity current, $u_c$, versus front location, $x$, for 1 and 17% slopes. Surprisingly, for a quite long distance, a gravity current propagates faster at 1% slope than at 17%. Initially, on the acceleration phase, the front velocity is more important for a 17% slope, as shown in figure Fig. 6 (b). We note that the maximum speed for 17% is around 0.9 m/s whereas it is 0.6 m/s for a 1% slope. Then, in the late deceleration phase, the velocity decreases more rapidly for higher angles. Qualitatively, the mixing region between fresh air and gravity current increases as the angle of the tunnel increases. Therefore, the buoyancy contained within the head of the gravity current may decrease more rapidly. Consequently, high slopes in tunnels can be a disadvantage for the kinetics of propagation of a fixed volume of gravity current released in a tunnel.

Fig. 6: (a) The front location, $x$, versus time, $t$, and (b) the speed of the current $u_c$ versus the front location, $x$, on a (x) 1% slope and on a (o) 17% slope.
CONCLUSION

This study presents experimental investigation on the propagation of a gravity current produced by an instantaneous buoyancy source with a large density difference with the ambient in a tilted tunnel. The density current propagates through three flow regimes: slumping, inertial and viscous phases. In the inertial phase, the dimensionless front location ($\tilde{x}$) is proportional to the dimensionless time ($\tilde{t}^{2/3}$) for non-Boussinesq gravity currents in tunnels. In the early deceleration phase, this power-law relationship is robust for the entire range of the density ratio, $0.29 \leq \gamma \leq 0.88$, studied in this work. In the late deceleration phase, viscous effects became more important which resulted in another power-law: $x \propto t^{1/2}$. For gravity currents produced in a tilted tunnel, one noticeable result is that the viscous phase appears sooner when the slope increases. The transition time between the inertial and the viscous spreading decreases as the angle increases. Experimentally, we have observed that the mixing layer increases with the angle and that the buoyancy contained within the head of the gravity decreases more rapidly. Consequently, for high angles of tunnel, the slope can be disadvantageous for the propagation rate of the gravity current. Further works will be presented on the propagation of gravity currents produced by a continuous source.

REFERENCES

[1] Amy, L.A., Hogg, A.J., Peakall, J., & Talling, P.J., Abrupt transitions in gravity currents, *Journal of geophysical research*, 2005, vol. 110, F03001, doi:10.1029/2005JF000197

[2] Bonometti, T., Balachandar, S. & Magnaudet, J., Wall effects in non-Boussinesq density currents, *Journal of Fluid Mechanics*, 2008, vol. 99, pp. 449-475, doi: 10.1017/S002211200800414X

[3] Dai, A., Experiments on gravity currents propagating on different bottom slopes, *Journal of Fluid Mechanics*, 2013, vol. 731, pp. 117-141, doi: 10.1017/jfm.2013.372

[4] Dai, A., Non-Boussinesq gravity currents propagating on different bottom slopes, *Journal of Fluid Mechanics*, 2014, vol.741, pp. 658-682, doi: 10.1017/jfm.2014.5

[5] Fannelöp, T.K., *Fluid Mechanics for Industrial Safety and Environmental Protection*, 1994, Industrial Safety Series, volume 3, Elsevier edition

[6] Hoult, D.P., Oil spreading on the sea, *Annual Review of Fluid Mechanics*, 1985, vol. 4, pp. 341-368

[7] Huppert, H.E., The propagation of two-dimensional and axisymmetric viscous gravity currents over a rigid horizontal surface, *Journal of Fluid Mechanics*, 1982, vol. 121, pp. 43-58, doi: 10.1017/S0022112082001797

[8] Lowe, R.J., Rottman, J.W. & Linden, P.F., The non-Boussinesq lock-exchange problem. Part I. Theory and experiments, *Journal of Fluid Mechanics*, 2005, vol. 537, pp. 101-124, doi: 10.1017/S0022112005005069

[9] Shin, J.O., Dalziel, S.B. & Linden, P.F., Gravity currents produced by lock-exchange, *Journal of Fluid Mechanics* 2004, vol.521, pp. 1-34, doi: 10.1017/S002211200400165X

[10] Simpson, J.E., Gravity currents in the laboratory, atmosphere and ocean, *Annual Review of Fluid Mechanics*, 1982, vol. 14, pp. 213-234, doi: 10.1146/annurev.fl.14.010182.001241

[11] Steenhauer, K., Tokyay, T. & Constantinescu, G., Dynamics and structure of planar gravity currents propagating down an inclined surface, *Physics of Fluids*, 2017, vol. 29, doi: 10.1063/1.4979063