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Surface Solidification in Open Channel Flow

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Abstract

The solidification of channel flows that are cooling from their surface is studied in experiments in which polyethylene glycol wax flows under cold water down an inclined, open channel of rectangular cross-section. We find two regimes, depending on the flow velocity and on the temperatures of the wax and the water relative to the freezing temperature of the wax. For sufficiently high flow speeds and temperatures, a solid surface crust develops in the centre of the channel some distance from the source. The crust remains separated from the walls by crust-free shear regions as it is carried down the channel. Under these conditions solidification also occurs very close to the source within the sidewall boundary layers, where the solid phase is continually sheared and broken into small pieces. At lower flow speeds and temperatures the solid creates a stationary roof and flow continues through an insulated channel beneath.

Introduction

Molten basaltic lava from large eruptions on volcanoes such as Hawaii is often channelled into rapidly flowing rivers of melt. Channels are commonly 10-100 m wide and of the order of 10 kilometres in length, with the flow being 2-10 m deep during its active period [2]. Much longer channels, up to 750 km, were important in transporting lavas from large prehistoric flood basalt eruptions [19,21] and spreading them over broad areas of the Earth. Lava tubes, channels that become fully encased in solidified lava, are also common. Tubes arise when the lava surface solidifies and forms a connected roof over the flow. The roof greatly reduces the rate of heat loss (cf. [14]) and hence enables the lava to flow much greater distances then would be possible if the roof were continuously disrupted [3, 15,16]. The dynamics of solidifying channel flows thus influence the surfacing of much of the Earth's crust. These dynamics may be central to the interpretation of the geological evidence and estimates of the rates and volumes of prehistoric eruptions (e.g. [19,22]). We therefore search for an understanding of the relationships between eruption conditions, the form of lava flows and the distances they spread. Similar questions arise in attempting to infer the geological histories of Venus, Mars and the Moon from remote images of their surfaces [1,13,17,18].

The physical processes that govern the formation of channels and the continued flow through them are complex, and involve the interaction of fluid and solid mechanics [9]. Even small amounts of solidification on the surface will influence the rate of cooling of the flow (e.g. [4,5]). Some progress has been made using laboratory experiments with polyethylene glycol wax, a clear, water-soluble fluid having a freezing temperature conveniently close to room temperature [6,7,8,11,12]. In these experiments, molten wax was released from a small vent beneath cold water to form a viscous gravity current, and high-Rayleigh number convection in the water carried heat away from the flow surface. These slow wax flows on a sloping plane extended down-slope, either in an open channel bounded by lateral levees of solidified wax or in internal channels insulated by a rigid roof. The style of flow depended primarily on the bottom slope and the dimensionless parameter

$$\psi = U_0\, t_s / H_0 \ , \qquad (1)$$

where t_s is a time scale for cooling of the flow surface temperature (by convection in the overlying water) down to the solidification temperature, and U_0 and H_0 are velocity and depth scales for viscous gravitational spreading of an isothermal fluid. The parameter ψ (or its inverse) is simply a measure of the rate of solidification relative to the (known) rate of flow expected without solidification [9,11]. These studies indicated regimes for the overall behaviour of a spreading flow and found conditions under which open channels or interior tubes were formed on slopes.

The alternative approach taken here was to consider a prescribed rigid channel and observe the flow through it. In this way we were able to study flow in very long channels, with the aim of determining the conditions under which the channel flow either remained open or became encased in solid to form the equivalent of a lava tube. Other observations of the flow gave new information on the way in which channelled lava flows may cool. Volume fluxes and flow speeds achieved were much greater than in previous experiments with PEG extrusions and gave moderate Reynolds numbers comparable to those of large basalt channel flows.

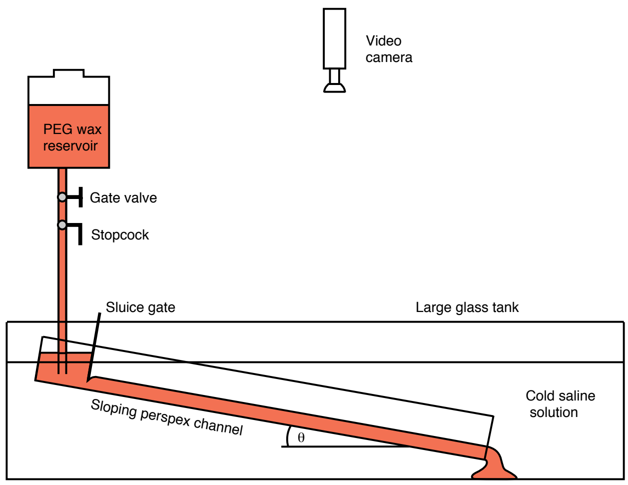

Figure 1. Diagram of the experimental apparatus.

Apparatus and Measurements

Our experiments involved sustained releases of polyethylene glycol wax (PEG, grade 600) at a constant flow rate and temperature under cold saline solutions in a sloping, perspex channel (figure 1). The channel was placed inside a glass tank that was larger in all dimensions: 0.4 m deep, 0.2 m wide and either 2 m or 4 m long. The channel was inclined at the desired angle and its lower end was open. The lower end of the channel was raised off the floor of the tank (by 50 mm or 70 mm) to provide a waste repository for the liquid and solid wax that flowed down the channel. The tank was filled with pre-chilled saline solution (with a salt concentration chosen to give the desired wax-water density difference $\Delta\rho$ and reduced gravity $g\Delta\rho/\rho_0$) which also flooded the channel. A number of channels of differing geometry were used to vary channel length L and channel width W: 1.5 m x 80 mm, 3.0 m x 80 mm and 2.4 m x 44 mm. In most runs we used a slope $\theta = 3.5^\circ$. However, a few runs had $\theta = 1.6^\circ$ or $\theta = 0^\circ$ (horizontal).

The wax supply was gravity fed via a tube from an overhead reservoir through a stopcock and a multi-turn gate valve. The tube supplied a lock behind a sluice gate placed 120 mm from the end of the channel. The sluice kept the lock dry before it was filled with wax prior to starting a run, and later separated the water from the wax in the lock. The sluice could be slid upwards to release the wax flow and so provided a means of generating an outflow that spanned the channel width. The volume flux q was controlled by the valves and measured by timing head loss in the reservoir. On starting a run the sluice gate was pulled up from the bottom of the channel high enough to allow the wax to flow out but not far enough to allow water to flow in. The height of this opening was typically a little more than half the depth of the wax flow downstream of the gate. After a period of constant flow the flow rate could be quickly increased or decreased, or the sluice closed and the channel cleared for another run.

The water temperature T_a in the tank (and channel) and wax (effusion) temperature T_e in the reservoir were measured immediately before starting the flow and again at intervals during and after the experiment. The wax reservoir was close to room temperature, which during this project was set to 25.5 ± 1.5°C. This was chosen to be well above the solidification temperature T_s, in order that the difference $T_e - T_s$ was known to within 10%. We measured $T_s = 18.5^\circ \pm 0.5^\circ$ and $19.5^\circ \pm 0.5^\circ$, depending on the manufacturer's batch. Measurements were taken of the actual flow depth H outside the sluice gate. A video camera mounted above the channel on a travelling gantry provided a continuous record of each experiment, from which we measured details of the distribution of solid crust.

Additional experiments involved the continuous release of dyed wax from small tubes placed immediately inside the sluice gate and at a height such that the dye lines lay close to the surface of the wax immediately downstream of the gate. These provided an indication of vertical and cross-stream transport within the flow.

Tubes or Mobile Crust?

For each run we calculated both the surface velocity U_0 at the centre of the channel and the flow depth H_0, for a flow with no cooling. These were evaluated from a theoretical solution for isothermal laminar flow in a sloping channel with a rectangular cross-section [20] using the measured volume flux q, channel width W and initial wax viscosity ν_0. All the flows were laminar, with Reynolds numbers $Re = U_0H_0/\nu_0 = 0.2 - 70$. The cross-stream aspect ratio was defined by $r = H_0/W$. The measured flow depths tended to differ from H_0, generally being larger for flows undergoing extensive solidification. To evaluate ψ from equation (1) the solidification time scale t_s was calculated (in the manner described by Fink & Griffiths [6] and Griffiths & Fink [10]) from the temperature ratio $(T_s - T_a)/(T_e - T_a)$ and a parameterisation of the turbulent convective heat flux.

Photographs illustrating the range of solid crust distributions are shown in figure 2. For a given channel width, large volume fluxes and high water temperatures

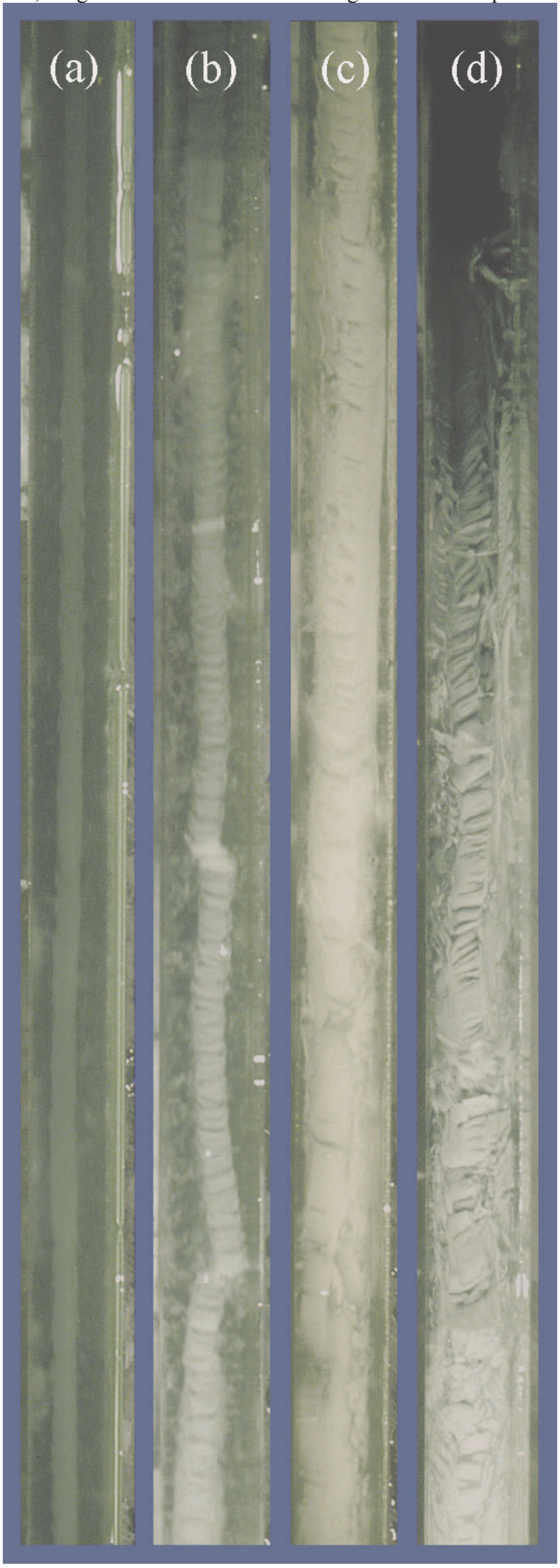

Figure 2. Photographs showing the extent of solid in the 44 mm wide channel under conditions ranging from: (a) $\psi\, r = 3.1$, $r = 0.82$; (b) $\psi\, r = 2.2$, $r = 0.57$; (c) $\psi\, r = 0.92$, $r = 0.34$; (d) $\psi\, r = 0.43$, $r = 0.33$. Solid wax is white, liquid PEG is transparent and the base of the tank is painted black. Flow is from top to bottom. The photographs correspond to

distances from the sluice gate of about: (a) 1.0 m to 1.8 m; (b) 0.5 m to 1.3 m; (c) 1.0 m to 1.8 m; (d) 0 m to 0.8 m.

prevented crust formation on the wax surface until far downstream of the vent (figures 2a,b). The crust grew only slowly in thickness (as determined qualitatively from its increasing opaqueness) with distance and reached a constant width. Under these conditions solid phase was also visible as small flakes within the side wall boundary layers, even very close to the vent. While these particles were advected down channel they were also carried down the wall from the surface and then across the base of the channel towards the centre. This vertical and cross-stream transport from the side wall layers was further demonstrated by the experiments where dyed wax was continuously released into the side wall boundary layers.

For smaller volume fluxes and/or lower water temperatures the central strip of crust appeared closer to the vent, its thickness grew more quickly with distance, and its final width was greater. However, the side wall shear regions again remained free of connected crust and the central strip of crust was not impeded by friction between the solid and the walls. Channel length L had no influence on the flow.

At still smaller fluxes and/or water temperatures the solid crust began to reach the sidewalls and the crust-free shear regions vanished. Under these conditions we observed the development of a completely stagnant roof (which first formed some distance downstream and then grew upstream toward the vent, figure 2d). A transitional regime was also observed in which the solid rafts spanned the full width of the channel but were able to slide along the channel walls until they became stuck (generally more than 1.5 m from the vent). Under these transitional conditions the flow tended to override and subsume the stagnated crustal segments, thereby slowing the flow upstream until another segment of crust stagnated (figure 2c). In this way the flow slowly backed up toward the vent. We consider this transitional behaviour, which was reproducible, as peculiar to the straight, uniform channel. It is likely to give rise to a completely stagnant solidified roof in the presence of irregular walls, constrictions or bends in the channel.

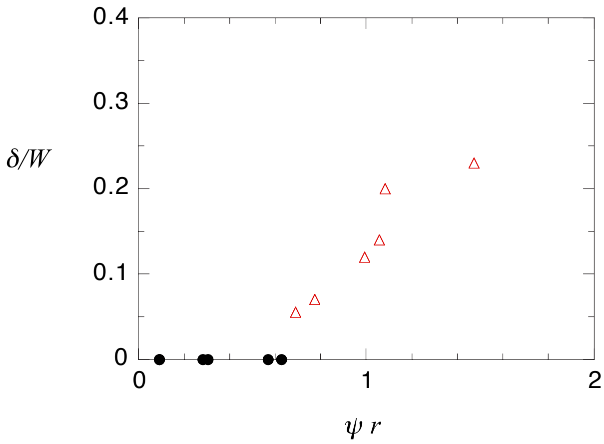

Figure 3. Shear region width δ/W as a function of ψr, for small aspect ratios ($r < 0.25$). The experiments had a bottom slope $\theta = 3.5^\circ$, and consisted of either flow with a central solid crust bounded by shear layers (Δ) or tube flow with $\delta = 0$ (●).

The width of the crust-free shear zones decreased with decreasing values of flow speed or water temperature. In dimensionless terms, the shear regions occupied a fraction δ/W of the channel width, where δ/W decreased both with decreasing ψ and (because ψ is based on flow depth scale H_0) decreasing aspect ratio r (figure 3). For the bottom slope $\theta = 3.5^\circ$ and small aspect ratios ($r < 0.25$), we found the empirical relation

$$\delta/W \approx C\,(\psi\, r - b), \qquad \psi\, r \geq b, \tag{2}$$

where C is a constant and $b \approx 0.6$. For $\psi r < b$ the flow develops a rigid and fixed roof (and $\delta = 0$).

The observations of shear region width lend weight to a classification of flows, on the basis of whether or not the crust was moving, into either the "mobile surface" or "tube" regimes discussed above. The distribution of these regimes is shown in figure 4 in terms of ψr and r. Results for the smaller slope $\theta = 1.6^\circ$ and shorter channel length $L = 1.6$ m are included and are consistent with the transition for $\theta = 3.5^\circ$, $L = 3.0$ m. That is, the critical value of ψr is not sensitiv e to the magnitude of θ. This is because the dependence on U_0 and H_0, the only flow characteristics directly affected by θ, is already taken into account in the definitions of ψ and r.

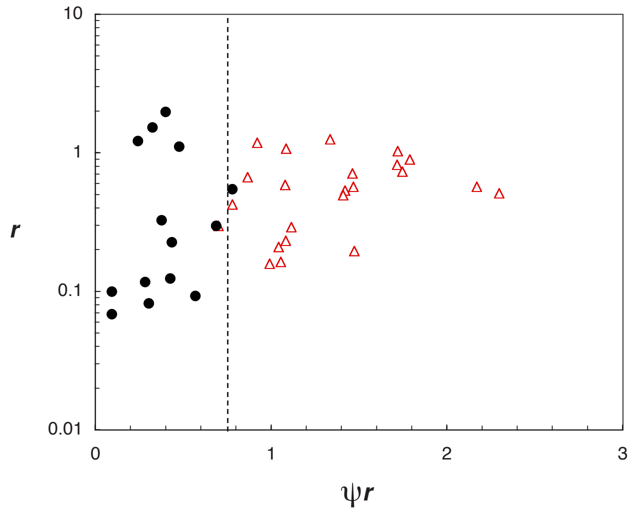

Figure 4. Classification of flows under all experimental conditions into either tube flow with a fixed solidified roof (●) or flows with a mobile solid crust confined to a central strip (Δ). Runs with bottom slopes of both $\theta = 1.6^\circ$ and $\theta = 3.5^\circ$ are included. The boundary between the two flow regimes is given approximately by $\psi r = 0.75$ (shown as a vertical dashed line).

Conclusions

For laminar flow with surface cooling and solidification in uniform sloping channels, there exist critical conditions delimiting flows that develop a fully roofed internal channel equivalent to a lava tube from those that maintain an open channel through which solid is freely advected down slope. The conditions can be written in terms of the two dimensionless parameters: ψ, which includes both thermal and flow conditions, and aspect ratio $r = H_0/W$. The dependence on aspect ratio is an unforeseen result and is due to the influence of r on the distribution of lateral shear within the channel. For small aspect ratio the sidewall shear is confined to regions of order the flow depth and there is relatively little horizontal shearing in the remainder of the channel, whereas for r of order one and greater the whole width of the channel undergoes strong horizontal shearing. The two lateral shear zones separating central crust from the sidewalls are critical features of the channel flow because the shear stress in these zones continually breaks up any solid skin, which would otherwise develop and connect the central crust to the sidewalls.

The observed vertical and cross-stream transport of solid from the side wall layers, which we believe is a manifestation of organised thermal convection within the wax flow driven by both lateral and vertical temperature gradients, may play an important role in keeping these zones clear of connected solid crust. When the shear zones cannot maintain this break up and clearing of solid from the surface against the pace of solidification, or the convective heat transport within the flow cannot match the surface heat loss, the central raft of solid spreads to the walls and becomes fixed. The flow is then confined to an interior channel in which it experiences different mechanical and thermal boundary conditions. Lateral shear zones are obvious features of channelled lava flows (figure 5). Hence the thermal balance and the mechanics of solid disruption and removal from the surface in the shear zones warrants further investigation.

In the central region of the channel the experiments reveal the growth of compression folds in the region of early crust development, where the solidifying skin can be deformed by the imposed viscous stresses. Farther downstream the solid crust is rigid and covers a significant fraction of the width of the channel, altering the velocity distribution there. The crust therefore travels more slowly than the central surface velocity upstream of the crust, causing the deceleration and folding of the surface. The folding is sensitive to other effects that lead to convergence or divergence of the stream-wise velocity, and we find that it can readily be changed to pulling apart of the solid crust by a decrease in the volume flux or an expansion in channel width. A range of additional complexities are of possible importance in real lava channels and experiments similar to those reported here can be used to address the effects of variations of volume flux from the vent, channel bends, narrowing or widening of the channel, and bottom or side wall irregularities.

Figure 5. An aerial photograph of a basaltic channel flow on Mauna Loa, Hawaii, in 1984 (from [17]). The channel is about 24 m wide, 5 m deep and flowing at 0.95 m/s, and is flanked by marginal shear zones in blocky a'a'. Also shown are some persons (circled) standing on stable marginal levee.

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