

Surface Physics Illustrated in the Operation of a Lava Lamp

The principles we learn during our training to be engineers and geoscientists arise again and again in our daily experience. As an educator, I try to inspire in my students a curiosity about how these principles impact life outside the classroom and job. One of my fondest memories from the years when I and my wife visited Delft from the U.S. is a conversation with a geologist from our Department (then a Faculty). He said that his family hated to go to the beach with him, because he always wanted to get out a shovel, dig a small trench, and see the layering of the sand beneath the surface. There was a man who believed in seeing what he taught in the classroom in life outside of school!

In groundwater flow and petroleum engineering, where fluids flow through tiny pores of geological deposits, surface forces dominate flow. They do so because with flow channels (pores) of diameter 100 μm or less (often much less), there is so much surface compared to the volume of the fluids. These surface phenomena include

- surface tension: the interaction between two fluids (e.g., air and water) brought into contact. Two related issues are snap-off, when surface forces pinch off one phase and create two droplets out of one, and film stability, when a film of one fluid phase prevents the merger of two droplets of another phase.
- wettability: the interactions between a solid and two fluids, and in particular the preference of the solid to be in contact with one fluid over the other
- spreading: the interaction between three fluid phases, and in particular whether one fluid spreads across the interface between the other two fluids.

All of these physical principles, and more, are illustrated in the operation of lava lamps. Figure 1 shows an image of a lava lamp, from the Internet. I have been fascinated by lava lamps since they first emerged in the 1960s, and I have three in my office. They induce a sort of Zen state of relaxation on a stressful day, while not

being so distracting as to prevent working efficiently (at least I hope not!).

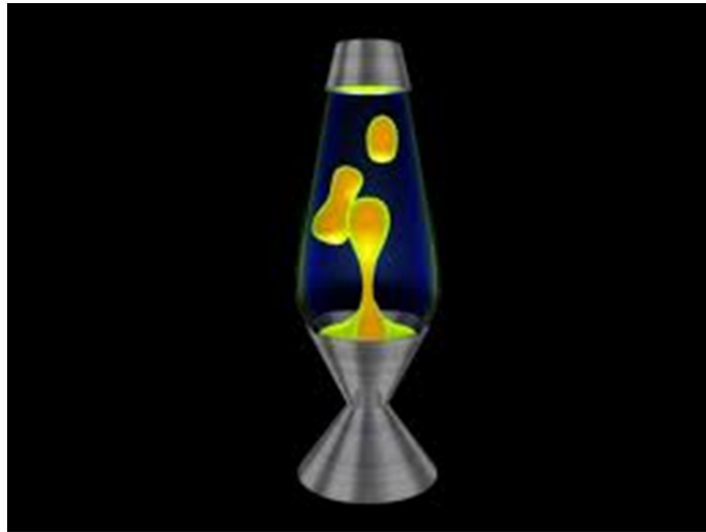


Figure 1. Typical lava lamp in operation.

Briefly, here is how a lava lamp works. Inside a sealed, clear glass bottle are three fluids, one a mixture of candle wax and carbon tetrachloride; the relative amounts of the two are chosen so that at room temperature the mixture is just a bit more dense than water, and when warmed it is less dense than water. I will refer to this phase by the scientific term "goop." At room temperature the goop is a waxy solid. The second fluid is water. The third fluid is a bit of air at the top of the bottle, hidden by the silver cap; the air gap is needed to prevent the bottle from exploding when the two liquids are heated. Both the goop and the water have dyes and perhaps some other additives to give a colored appearance to the phases. The bottle is lit from below by a lamp hidden from view in the silver base.

When the light is turned on, the goop first melts, and then, as it is heated, part of it (the warmest, least-dense part) comes up from the hot bottom of the bottle, rises upwards, breaks off into one or more discrete "blobs" (another scientific term). Over time a blob floats around, cools, becomes more dense than the surrounding water, and falls to merges again with the goop at the bottom. The whole process is lit by the lamp at the bottom.

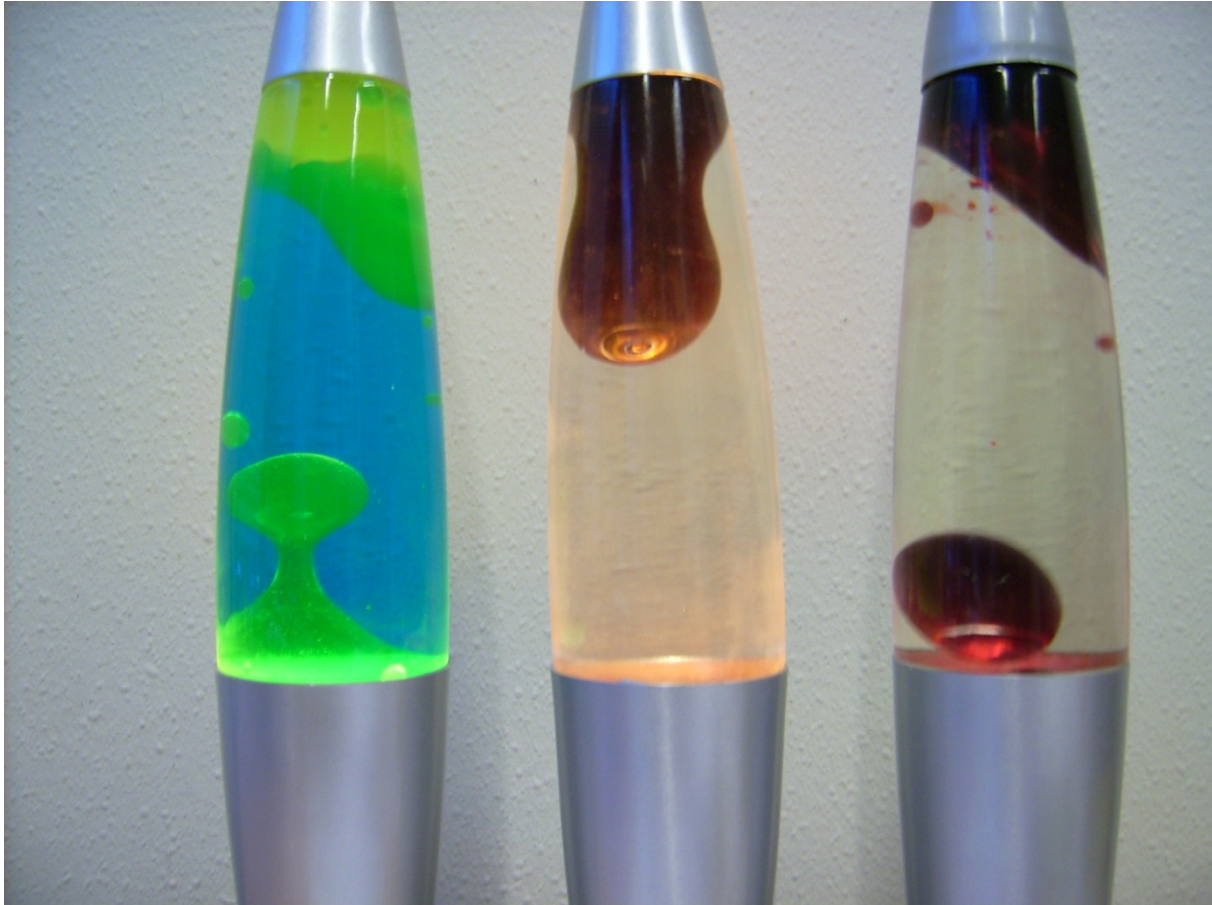


Figure 2. My three lava lamps in operation.

Figure 2 shows my lava lamps in operation. You'll notice a difference with Figure 1, which I will discuss further below. Here are several principles of surface physics I see illustrated in my lava lamps every day, and how they relate to groundwater flow and oil and gas recovery from geological formations.

1. Surface Tension and Snap-Off

Surface tension is the thermodynamic energy penalty for creating an interface between immiscible fluids. It seeks always to minimize the surface area between the two fluids and acts as though the surface itself were elastic. In the lava lamp, as the goop heats, it doesn't rise up as tiny droplets, but as one big mound, fighting against surface tension. Then as the mound rises high enough, it thins down behind its head and breaks off into a separate blob: this is the phenomenon of "snap-off." It is also the reason that a small stream of water from a faucet breaks up into droplets. Figure 3

shows some images of this process either just before or just after snap-off. Of course it is best seen as a movie; you can find lots of examples at www.youtube.com.

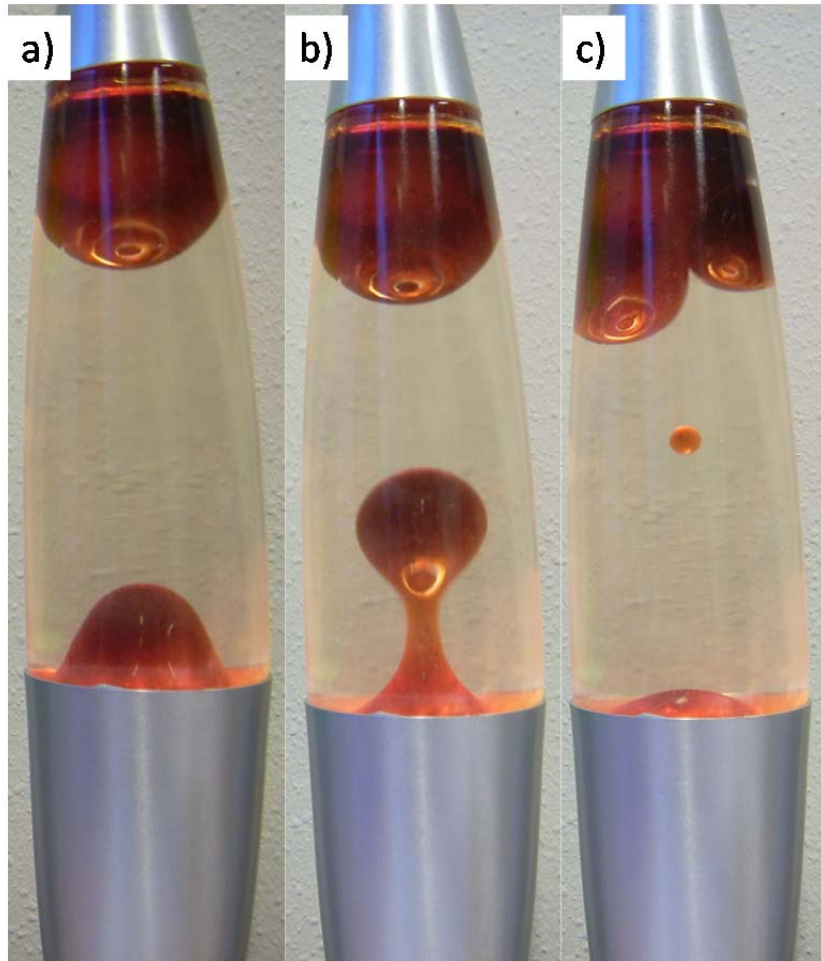


Figure 3. The process of snap-off in a lava lamp. a) Mound of warm goop starts to rise. b) Neck thins down, almost to breaking point. c) After snap-off. The large blob has moved to the top of the lamp; there is a second small blob created from the elongated neck in (b).

In exploiting an oil reservoir, usually one produces oil for a while from the pressure of the oil itself. Quickly that gives out, and, to maintain pressure, one injects water to replace the volumes of oil and gas that are produced (and thereby maintain pressure in the reservoir). In a perfect process, injected water would simply push the oil to production wells, but in real reservoirs most of the oil is left behind as water makes its way from injection to production wells. Eventually one is injecting and producing the same water without

producing much more oil, and the wells may then be plugged and abandoned. The first reason more oil is not produced is the geological complexity of the formation, which causes water to bypass large portions of the oil-bearing formation. Even where water goes, though, it leaves as much as half of the oil behind trapped as tiny droplets within the pores. One major reason the oil is broken into droplets and trapped is snap-off of the oil filaments as they flow through the pores. In geological formations the process is affected by the geometry of the pores: snap-off happens as oil comes out from a narrow "pore throat" (see Figure 4). Nonetheless, the process is much as illustrated in a lava lamp: what was one continuous phase is broken into two by closing-off of a narrow spot, a process driven by surface tension.

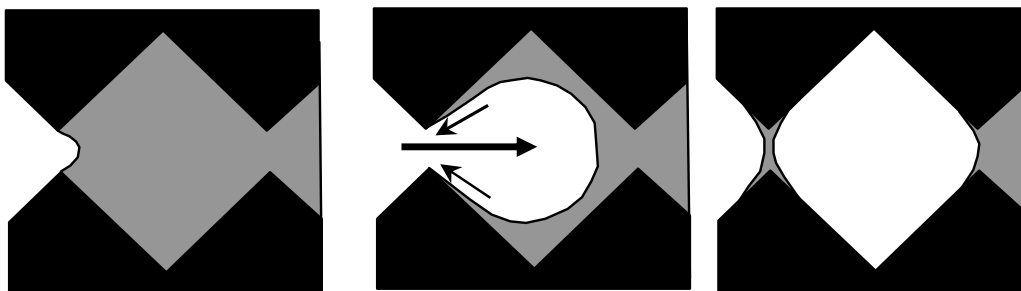


Figure 4. Schematic of the process of snap-off in an oil reservoir. Mineral is black, water gray and oil white.

2. Film Stability

When two blobs of goop meet, they don't necessarily merge. There is a film of water between the two blobs that must break before the blobs can merge. When my lava lamps were new, the water film hardly ever broke (except as described in the next section). Figure 5 shows an example of two blobs that have not yet merged; Figure 4c shows another example. As a blob returns to the bottom of the bottle, it sits on top of the other blob until it slides around to the side and down; when it has slid down far enough, suddenly the two blobs merge. More on that in the next section.

Often oil is produced from wells as emulsions: there are tiny droplets of water within the oil, or tiny droplets of oil within the water, or both. In either case the droplets don't merge and separate

from the other phase because of the stability of the film of the other phase between the droplets. In either case, the films must be broken (with heating and with chemicals), so that the water can be cleaned up and reused, and the oil separated and sold.



Figure 5. Two blobs prevented from merging by a thin film of water.

3. Wetting

The goop does not normally adhere to the glass surface at the bottom of the bottle. Technically, we say that the glass is "wetted" by water, not by goop, or that the glass is "water-wet." Close examination of the bottom of the bottle (Figure 6) shows that there is a coil of metal at the bottom, and this resolves the mystery of the blobs merging in the previous section. Evidently, the goop does wet the metal. As a blob slides around to the side at the bottom of the bottle, it touches the same metal coil already in contact with the resident blob of goop. There is no film of water along the coil, and the two blobs immediately merge. As I mention, when I first purchased my lava lamps this was the only way in which blobs would merge.

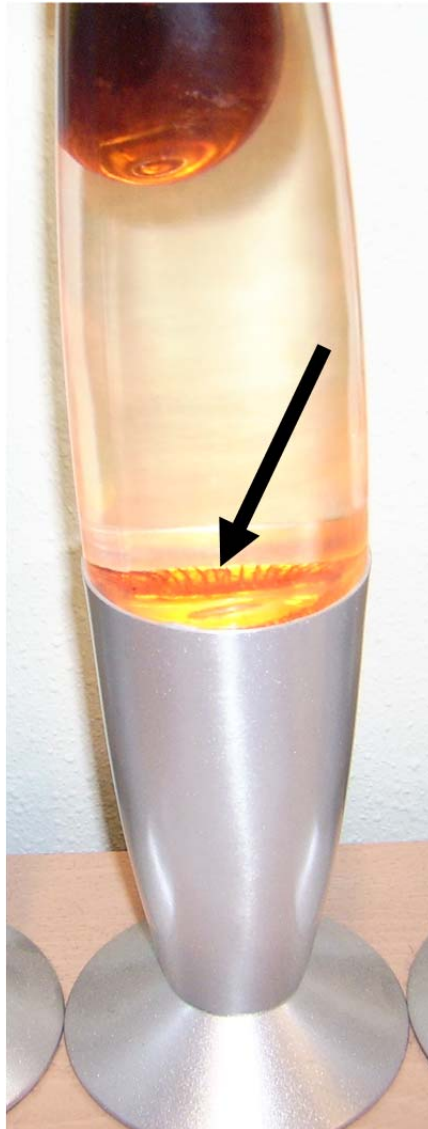


Figure 6. Coil of metal at bottom of lava lamp.

Wettability is the reason that water spreads out on the unwaxed metal surface of an automobile, but water balls-up in tiny droplets on a waxed auto surface. It's why the meniscus of water goes up on a glass but down on a plastic cup. In an oil reservoir, it determines whether it is water or oil that adheres to the mineral surfaces or occupies the middle of the larger pores. The location of the phases (along the walls or in the middle of the pores) dominates the relative abilities of the two phases to flow ("relative permeability"). In aquifers, the mineral is usually water-wet, as we believe it is in oil reservoirs when the oil first begins to accumulate. Which brings us to the next topic . . .

4. Changes in Wetting

As noted, when the oil first arrives at a geological "trap," we think the mineral surfaces are naturally water-wet: water coats all the mineral surfaces as the oil first starts to accumulate. If the oil has surface-active components, it can change the wettability of the minerals, but to do so it has first to break the water film on the mineral surface. As the oil accumulates, its lower density than that of water means that at the top of the formation its pressure is greater than the water pressure, because of hydrostatics in the two columns of fluid of different density. This difference in pressure, or "capillary pressure," means the oil presses against the water film on the mineral surfaces; if the capillary pressure is great enough, the film breaks, the oil comes directly into contact with the mineral, and it can deposit its surface-active agents and alter the wettability of the rock. In this case, the change in the preference of the rock between the two phases starts with the oil pressing on the water surface with a greater pressure than the water pushes back.

One can occasionally see the same dynamic in a change in the wettability in the lava lamps. Before the goop melts, it expands a bit. In some cases the goop, still a solid, presses against the side of the glass with a pressure built up by the expansion of and stresses within the solid (now warmed and plastic) goop. On such occasions the glass changes from being water-wet in this location to goop-wet; the goop adheres to the glass at this location for some time. Figure 7 shows an example. Evidently the goop does not have surface-active components to alter the wetting of the glass permanently; after a time the water comes back and wets the glass at the given location.

5. Interactions Between Three Fluid Phases and Solid: Spreading and Wetting

At the top of the bottle is a small air gap, hidden by the silver plastic cap, which is needed to prevent excessive pressure buildup and explosion as the other fluids heat and expand. I think the original idea was that the goop never reaches the air-water interface at the

top, or at least never breaks the water-air interface at the top. Then the blobs simply float around until they cool and sink (see Figure 1).

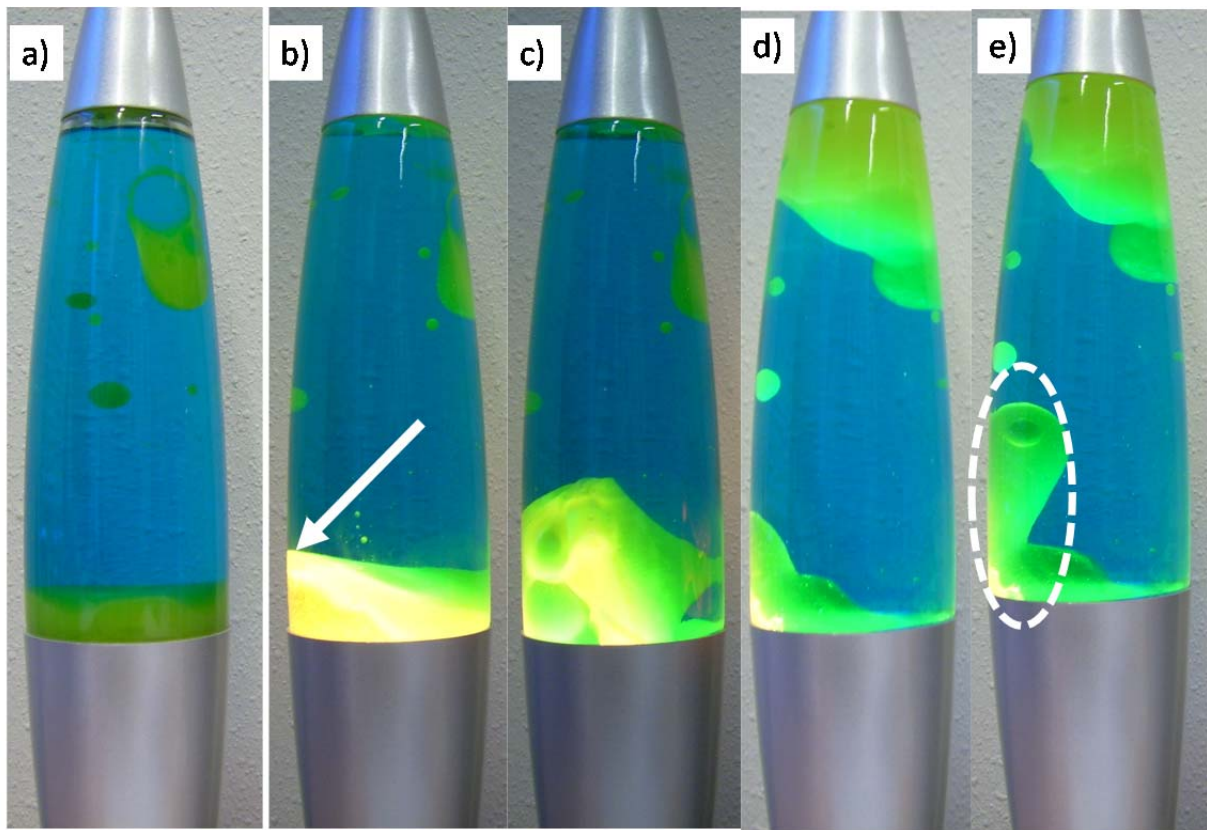


Figure 7. Temporary change of wetting brought about by expansion of goop before it liquefies. a) Initial state. Solid goop is at bottom of bottle. b-c) Goop heats and expands, pressing against the lower left side of bottle. d-e) Now liquid, goop continues to adhere to left side of bottle near the bottom.

In my lava lamps, the goop has broken through the water film at the top and formed a layer between water and air, as you can see in Figure 2. As noted, goop does not wet the glass surface in preference to water, but evidently it does wet it in preference to air. Now, as a result, there is a layer in each lava lamp of goop more or less permanently stuck to the glass near the top of the lamp. Instead of the cycling of blobs up, around and down, there is a process of blobs snapping off, rising, and merging with the layer on top. Then as goop at the top cools, a sagging pool of goop extends downward, snaps off and floats to the bottom.

In an oil or gas reservoir, the interaction of three phases (oil, gas, and water) with each other and with the solid minerals makes it complex to model and predict flow behavior. It matters which phase adheres to the minerals, and also whether any fluid spreads on the interface between the other two fluids. In some cases oil spreads on the water-gas interface. Two everyday examples illustrate the difference between spreading and non-spreading oil. In a tarmac parking lot after a rain, one may notice rainbow colors reflecting off puddles. The rainbow colors are produced by a thin film of oil (that presumably dripped down from automobiles) that spreads on the water to a layer so thin that the thickness of the layer is comparable to the wavelength of visible light; the interference between reflection off the oil-air and water-oil interfaces causes the colors. On the other hand, if you add a bit of cooking oil to a pot of boiling water for cooking pasta or rice, you'll notice the blobs spread out a bit on the water, but not completely: blobs of oil float around on the boiling water surface, sometimes breaking apart and sometimes merging, but not spreading over the entire surface.

In oil reservoirs, some oils spread on a water-gas surface and some do not. Whether this happens determines whether the oil flows as separate droplets or is carried along by flowing water at the interface with gas. The efficiency of oil transport is completely different in the two cases.

Over time, the operation of my lava lamps has changed a bit. Some chemical change in the goop has produced bits of crud (to coin another scientific word) sometimes visible on the interface, and water films are not as stable between blobs as they used to be. Moreover, the goop appears to be non-Newtonian, and possibly viscoelastic. It's all quite complex. As Hamlet said to his friend, "There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy."

There you see it: much of the surface physics we teach in our BSc and MSc courses on flow through porous media is illustrated in

the operation of a lava lamp (and in the dripping of a faucet, the waxing of an automobile, and the cooking of pasta). One goal of our education is that students understand how physical mechanisms affect the processes they design as professionals. We also hope that they see the same physics as they arise in everyday life.

