Gallery of Fluid Motion

Soap opera in the maze: Geometry matters in Marangoni flows

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The ancient Greek myth of Theseus and the Minotaur is perhaps the most famous example of the fascination that maze solving has historically triggered in humankind. Maze-solving strategies also have important practical applications, including path finding in robotics [1], urban transportation [2], and cognitive neuroscience [3]. Since the digital computation of the shortest path across a maze is efficient for simple cases only [4,5], numerous more unconventional, analog methods have been suggested in the past few decades. For instance, amoeboid organisms are able to solve mazes when a suitable gradient of nutrients is present [6], and chemical waves have been reported to find optimal pathways in complex labyrinths [7]. Other examples among these analog maze-solving techniques rely on fluid-mechanical effects, such as exploiting a pressure gradient between the inlet and outlet of a complex microfluidic network in order to drive a dyed fluid between the two [8].

We demonstrate here that the Marangoni effect produced by a surfactant is a fast and highly efficient mechanism of maze solving. We present the experimental observation of a small amount of dilute soap, which successfully solves a maze filled with milk with minimal penetration into side branches. While maze solving using thermal [9], pH-induced [10,11], and surfactant-generated [12] Marangoni flows have previously been reported, in those cases the motion is established in the maze by introducing an alteration at the outlet, with the tracer particles being drawn from the inlet by the resulting flow, such that a tracer anywhere in the maze is also transported towards the exit. However, in the present work the decrease in surface tension originates at the inlet, and the tracer follows the correct path to the outlet without any pre-existing gradient of surface tension ahead of its path.

The experiment consists of a square plate of acrylic (127×127 mm) with a series of open channels approximately 3 mm deep and forming a small maze. First, the maze is filled with milk [13], and a drop of red dye is added at the inlet reservoir, acting as a passive tracer. Subsequently, a brush previously

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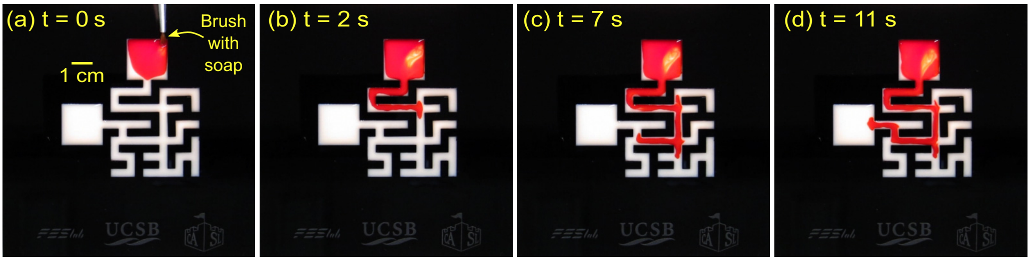

FIG. 1. Snapshots of a 0.2% solution of soap solving a small maze filled with milk, from time $t = 0$ s until $t = 11$ s, when the red dye reaches the exit. The width of the channels is 4 mm. DOI: https://doi.org/10.1103/APS.DFD.2017.GFM.V0098

immersed in a soap solution (0.2% volume, Seventh Generation brand) is briefly introduced in the milk at the inlet, for a time not exceeding 1 s [Figs. 1(a) and 2(a)]. Immediately after the brush is introduced, a Marangoni flow away from it is triggered, due to the locally lower surface tension of the milk-air interface in the area with soap, which overlaps with the dye.

The dyed milk, entrained by the soap, barely penetrates into side channels with dead ends, opting for the right path toward the outlet at every bifurcation until it solves the maze [Figs. 1(b)–1(d) and 2(b)–2(f)]. This fact may appear surprising since, as mentioned above, the front of red dye does not advance following a gradient of surface tension originated from the outlet. However, it could potentially be explained by the presence of *endogenous surfactants*, trace amounts of other surface-active substances that are naturally unavoidable in the fluid. These small quantities of surfactant are usually insufficient to produce a noticeable decrease of surface tension in the initial fluid, but can

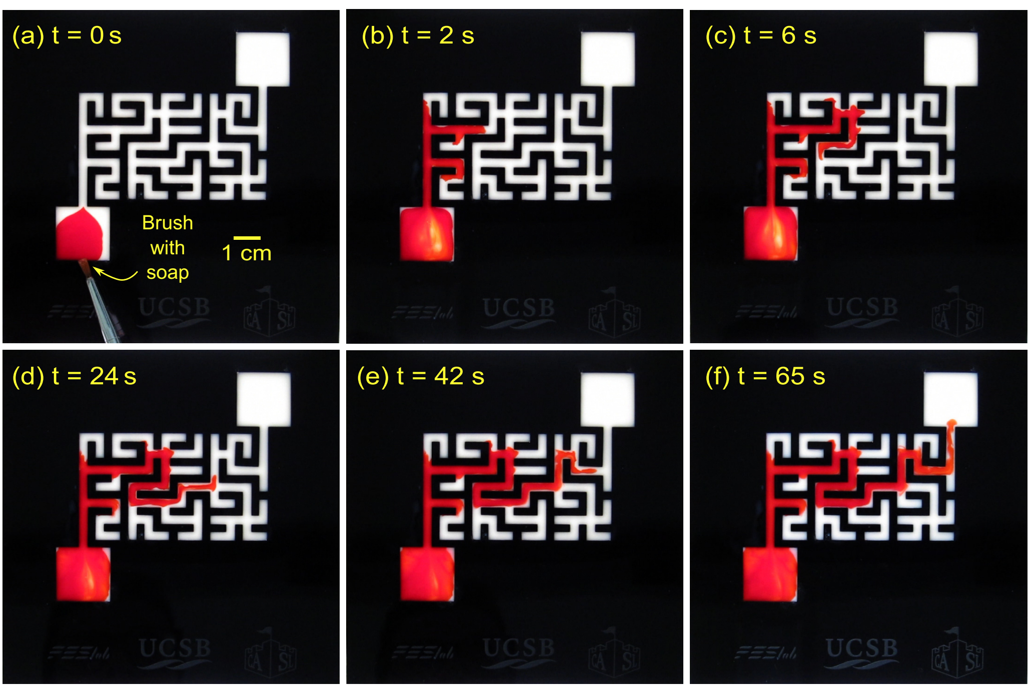

FIG. 2. Snapshots of a 0.2% solution of soap solving a larger and more complex maze, also filled with milk. The red dye used as tracer reaches the exit at time $t = 60$ s. The width of the channels is 3 mm. DOI: https://doi.org/10.1103/APS.DFD.2017.GFM.V0098

have a marked effect on the dynamics, described as follows. As the front of dye spreads across the maze, it compresses the interface ahead, thus increasing the concentration of endogenous surfactant and creating a Marangoni force opposing the motion, eventually stopping the flow. This effect has been reported to occur in the spreading of surfactants in a thin film of liquid [14], and could explain the maze-solving effect here. Indeed, when reaching a bifurcation the dye would naturally choose the path of least resistance, which is the one with the largest surface area ahead, since it would minimize the downstream concentration of endogenous surfactants. According to this hypothesis, the relatively large surface area of the outlet reservoir of the maze offers the lowest resistance at every bifurcation, thus enabling the soap to solve the maze correctly.

This result is a striking example of the dramatic consequences of surface-active impurities in fluid flows. Their role in slowing down the rising motion of bubbles in a liquid [15] has been known for decades [16]. Very recently, it has been shown experimentally that trace amounts of surfactants can also critically hinder the drag reduction ability of superhydrophobic surfaces [17]. Taking these effects into account can therefore be essential in the study and prediction of flows involving fluid interfaces.

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