Mixing fluids efficiently in confined spaces: Let the fingers do the working

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Getting two fluids to mix in small or confined spaces is a big problem in many industries where, for instance, the introduction of one fluid can help extract another — like water pumped underground can release oil trapped in porous rock — or where the mixing of liquids is the essential point of the process. A key example of the latter is microfluidics technology, which allows for the controlled manipulation of fluids in miniscule channels often only a few hundred nanometers wide.

Microfluidic devices were first introduced in the 1980s and for many years were best known for their use in ink-jet printers, but have since been introduced in other fields, including the chemical analysis of blood or other sera in lab-on-a-chip technologies. These devices — usually not much larger than a stick of chewing gum — sometimes rely on nano-sized moving components, the geometry of the grooved channels or pulsed injections to induce a mixing of the fluids. But researchers in MIT's Department of Civil and Environmental Engineering suggest that a simpler method might be equally, if not more, effective.

"Getting two fluids to mix in a very tight space is difficult because there's not much room for a disorderly flow," said Professor Ruben Juanes, the ARCO Associate Professor in Energy Studies and principal investigator on the research. "But with two fluids of highly contrasting viscosity, the thinner fluid naturally creates disorder, which proves to be a marvelously efficient means of mixing."

In an analysis published online May 12 in *Physical Review Letters*, the researchers show that the injection of a thin or low-viscosity fluid into a much more viscous fluid (think of water spurting into molasses) will cause the two fluids to mix very quickly via a physical process known as viscous fingering. The thinner liquid, say the researchers, will form fingers as it enters the thicker liquid, and those fingers will form other fingers, and so on until the two liquids have mixed uniformly.

They also found that for maximum mixing to occur quickly, the ideal ratio of the viscosity of any two fluids depends on the speed at which the thinner liquid is injected into the thicker one.

The research team of Juanes, postdoctoral associate Luis Cueto-Felgueroso and graduate students Birendra Jha and Michael Szulczewski, made a series of controlled experiments using mixtures of water and glycerol, a colorless liquid generally about a thousand times more viscous than water. By alternating the viscosity of the liquids and the velocity of the injection flows, Jha was able to create a mathematical model of the process and use that to determine the best viscosity ratio for a particular velocity. He is lead author on the PRL paper.

"It's been known for a very long time that a low viscosity fluid will finger through the high viscosity fluid," said Juanes. "What was not known is how this affects the mixing rate of the two fluids. For instance, in the petroleum industry, people have developed increasingly refined models of how quickly the low viscosity fluid will reach the production well, but know little about how it will mix once it makes contact with the oil."

Similarly, Juanes said, in microfluidics technology, the use of fluids of different viscosities has not been seriously proposed as a mixing mechanism, but the new study indicates it could work very efficiently in the miniscule channels.

"We can now say that on average, the viscosity of the fluid injected should be about 10 times lower than that of the fluid into which it is injected," said Juanes. "If the contrast is greater than 10, then the injection should be done more slowly to achieve the fastest maximum mixing. Otherwise, the low viscosity fluid will create a single channel through the thicker fluid, which is not ideal."

Cueto-Felgueroso said a similar process is at work in the engraved channels of a microfluidic device and in subsurface rock containing oil. "Mixing fluids at small scales or velocities is difficult because you can't rely on turbulence: it would be hard to stir milk into your coffee if you were using a microscopic cup," Cueto-Felgueroso said. "With viscous fingering, you let the fluids do the job of stirring."

Provided by Massachusetts Institute of Technology

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