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Title
Clogging: The self-sabotage of suspensions

Permalink
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Journal
Physics Today, 76(2)

ISSN
0031-9228

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Publication Date
2023-02-01

DOI
10.1063/pt.3.5174

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CLOGGING: The self-sabotage of suspensions

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Brian Dincau, Emilie Dressaire, and Alban Sauret

Whether it's pipes, highways, or arteries that are clogged, stopping the flow is always inconvenient and sometimes dangerous.

Whenever a suspension, composed of discrete particles dispersed in a liquid, flows through a confined geometry, clogging can occur. Channels or constrictions, such as the pores of a filter, can be microscopic, or as in pipes transporting water and in log jams that form under a bridge, they can be macroscopic. As a result, the phenomenon occurs in many environments and scales, as illustrated by the examples in figure 1.

Clogging is problematic in many engineering systems. The blockage of inkjet printer nozzles by colloidal particles impairs their performance. Similarly, the frequent formation of clogs in nozzles used to dispense fiber-filled polymer inks in extrusion-based additive manufacturing processes limits the concentration of fibers that can be used in three-dimensional printing.[1] Another problem—encountered in bioengineering—is the presence of protein aggregates in solutions of monoclonal antibodies. The aggregates threaten the reliability of autoinjection devices that allow patients to self-administer medicine.

On larger scales, clogging is detrimental to water sustainability. Many arid regions rely on underground water as their primary source of fresh water. Those aquifers are either naturally recharged by precipitation or artificially recharged by the redirection of surface water. Both cases depend on water flowing through porous rock and sediment, as in a filter. Over time, cycles of drainage and recharge can cause fine suspended particles to block the aquifer. The progressive clogging increases the energy cost of extraction and recharge and reduces the operational life of the aquifer.

Aquifers are not the only water resource that can be crippled by clogging. Roughly 70% of the water in the US is used for irrigation. And microirrigation, which uses a series of small targeted emitters to water crops, is at least 50% more efficient than sprinkler and furrow irrigation, both of which lose a lot of water to evaporation. Given its superior efficiency, one might expect drip irrigation to be a popular choice. But less than 10% of irrigated land in the US uses drip irrigation, in part because of its susceptibility to clogging, often by suspended sediment, fertilizers, and biofilms of microorganisms, such as algae and bacteria.[2]

Civil engineering is another field in which clogging presents many challenges. As cities have grown, their infrastructure must continually handle more waste. In particular, sewers that channel wastewater and storm runoff allow cities to maintain sanitary living conditions and protect against flooding during periods of high precipitation. The sewers are typically accompanied by inlet and outlet grates that prevent people, animals, and other large objects from entering the sewers. Over time, those grates can become blocked by moss, dirt, leaves, and all kinds of urban trash, such as plastic bags and cardboard.[3] When sewers clog, they cannot handle their designed throughput, which can potentially result in significant flooding. Maintenance of sewer inlets and outlets is thus essential.

Clogging also poses a significant challenge in disease prevention and medicine. A blood clot is an aggregate of platelets and red blood cells, which can block the constriction of a blood vessel and restrict flow.[4] Those clots can become dislodged and clog elsewhere, potentially resulting in a stroke or heart attack, which can be painful, debilitating, and even lethal. Medical devices, such as catheters or bile-duct stents, can likewise be prone to clogging from the buildup of bacterial aggregates, often requiring surgery to remedy. Although they resemble the clogging of nonliving systems, bioclogs are highly complex and largely beyond the scope of this article.

Instead, we focus on clogging by particles in liquid suspensions. But particles in air, where the interstitial phase is negligible, can also clog. Perhaps the most classic case is that of granular flow, such as grains draining through a silo. Grains such as wheat are rough and irregularly shaped. And with no liquid to lubricate them, they interact frictionally with each other, which may easily lead to jamming at the silo's outlet. The effect worsens with high humidity as the grains become more cohesive. When silos clog, the stuck grains must often be manually cleared, either with a long pole, which can be dangerous, or with an air cannon, which is much more expensive.

The clogging of grains shares many similarities with the clogging of active particles, such as cars, people, or livestock passing through a constriction. When sheep enter or leave their corral, they often overload the passage and prevent other sheep from moving. Such overloads are important to consider when planning for evacuation from large buildings and event spaces.

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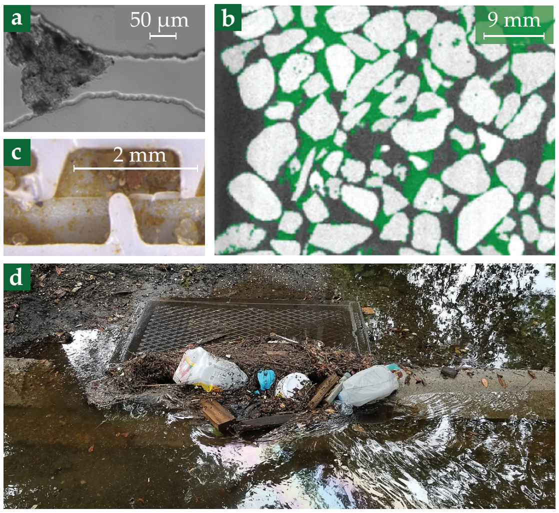

FIGURE 1. CLOGGED SYSTEMS at different scales. **(a)** A protein aggregate is stuck in a microfluidic constriction smaller than the aggregate size. (Adapted from ref. 7.) **(b)** X-ray computed tomography of the internal structure of a porous medium, in which suspended solid particles have flowed for several hours. Trapped particles are shown in green. (Adapted from Y. Tang et al., *Granular Matter* **22**, 37, 2020.) **(c)** An irrigation emitter has become clogged by fine sediment sticking to surfaces along the flow path. (Adapted from ref. 2.) **(d)** A sewer drain outlet is clogged by plastic bags, trash, and other debris. (Courtesy of Bart Everson, CC BY 2.0.)

People tend to rush toward an exit during an emergency, for instance. Emergency exits can become a bottleneck if too many people try to pass through at once.[5] In the best case, the exit limits how quickly people can evacuate. In the worst case, people may try to force each other through or even trample one another. (See the Quick Study by Arianna Bottinelli and Jesse Silverberg, Physics Today, September 2019, page 70.)

The physics that governs how flowing particulate suspensions clog a system has become an increasingly active research topic—partly because of the problem's complexity. It spans many length scales (from bacteria to boulders) and time scales (from less than a second to years), and it often requires sophisticated equipment to study. Yet predicting when clogging is likely to occur can lead to new design principles and improve reliability. One of the first steps in tackling the topic is to categorize its dynamics.

A tale of three mechanisms

Generally, clogging mechanisms include sieving, when particles are too large to pass a constriction; bridging, when particles jam each other at a constriction and form a stable arch; and aggregation, the successive deposition of small cohesive particles at a constriction.[6] One or two of those mechanisms may be more common in certain systems, but generally all of them happen during the clogging process, as can be seen in figure 2, which adds to the complexity of establishing a general picture.

To understand clogging, keep in mind some common parameters. The particles' size, shape, and deformability, and the geometry of the system in which the suspension flows influence the clogging dynamics. When a particle is quasi-spherical, its size is often described by a diameter D, though more complex shapes, such as fibers or particle aggregates, can also jam a constriction. Equally important is a constriction's minimum dimension W, which could represent the diameter of a filter pore, a reduction in a pipe's cross section, or the width of an emergency exit. The volume fraction Φ of particles in a suspension also influences the probability of clogging. (Think about volume fraction as how close, on average, the particles are to each other.) Finally, the physical and chemical properties of the particles—for instance, their roughness, adhesion, and cohesion—also play a crucial role, especially in determining which mechanism dominates.

The combination of those mechanisms establishes a unified framework for the physics of clogging. Nevertheless, each one can be isolated for a more fundamental understanding.

Too big to fit

The simplest case of clogging happens when one dimension of a particle is too large for the particle to pass a constriction. For a rigid spherical particle of diameter D passing through a constriction of width W, clogging occurs for $W/D \leq 1$. That mechanism is one of the most common, as it is routinely used to separate small particles from larger ones with a screen. Because most industrial suspensions are polydisperse—made of different particle sizes—the presence of only a few large particles in the suspensions can greatly hinder the performance of a system with constrictions.

Although sieving seems to be a simple mechanism for spherical particles, it becomes less straightforward when more complex shapes are involved. Anisotropic particles, such as fibers or leaves, may enter a system in a given orientation but later clog the channel after shifting position. That's why gutters must be periodically cleaned. For anisotropic particles, an approach to predict the clogging of a constriction of width W is to characterize the particles' shape using so-called Feret diameters, which entail measuring an object along a specified direction. An anisotropic particle has a maximal Feret diameter L_F along its largest dimension and a minimal Feret diameter l_F along its smallest dimension, as illustrated in figure 3a.

Such a rigid particle will always clog by sieving at a constriction if $l_F > W$, and it will never clog if $W > L_F$. For an intermediate size constriction, $l_F < W < L_F$, however, the particle's orientation determines what happens when the particle reaches the constriction. If the particle passes the constriction with its minor axis aligned with the flow, it won't clog, but if it's aligned perpendicularly to the flow, sieving will occur.

Another complexity arises when the particles are deformable. If larger than the constriction, such a particle can still enter it and may even squeeze through when a large enough pressure is applied,[7] as illustrated in figure 3b. That situation is particularly relevant to biological applications that include deformable vesicles, cells, and protein aggregates.

Clogging by sieving can be described as a random process that depends on the number of particles larger than the constriction or pore sizes. For systems with many pores, sieving can usually be modeled as a Poisson distribution, in which the clogging of each pore represents an independent event. The probability of that event depends on the size distribution of suspended particles.[8] Overall, the most common way to prevent sieving is to stop large particles from entering the system—usually through upstream filtration. Even then, sieving still happens at the filter, where small pores prevent the passage of large particles.

Too crowded to pass

For dilute suspensions—typically of a volume fraction smaller than a few percent—particles tend to pass through constrictions

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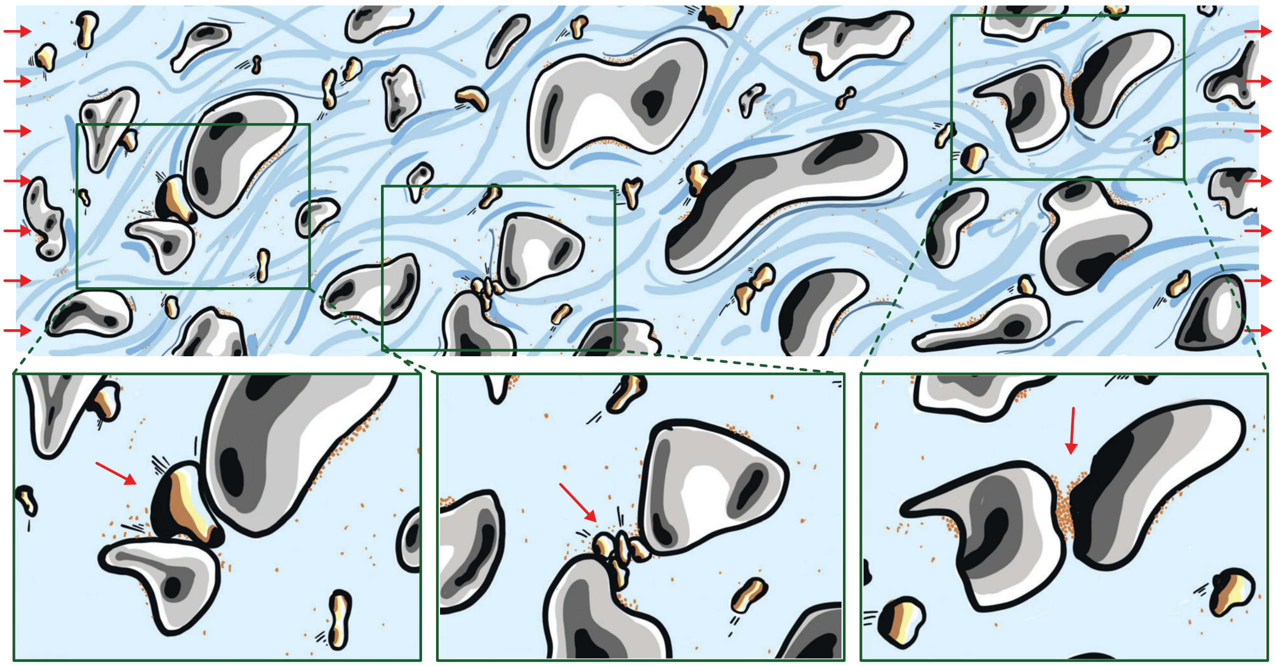

FIGURE 2. A SUSPENSION of particles flowing in a confined system, like this porous medium, can become clogged at constrictions through different mechanisms that depend on the properties of the particles and pores. From left to right: Sieving by a particle with one dimension larger than the width of the constriction; bridging by the formation of an arch of particles arriving simultaneously at the pore; and progressive aggregation on the channel walls of small particles that eventually clog the pore. Red arrows mark the predominant flow direction. (Courtesy of R. S. Sharma.)

one at a time. But clogging by bridging generally occurs at higher volume fractions when particles arrive at a constriction simultaneously.[9] If too many particles arrive at once, they can jam each other, spontaneously forming a bridge, as illustrated in the three time-lapsed frames in figures 4a–c. An arch is formed when constrictions are of size W—larger than the particle size D, but of the same order of magnitude.

For spherical noncohesive particles, researchers have observed bridging experimentally only when $W/D < 5$. For highly anisotropic particles, such as fibers, flakes, or cohesive particles, such as powders, that threshold can be higher because of differences in the particles' arrangement and the resulting force network at the bridge. Clogging by bridging shares many features with the clogging of silos, in which particles smaller than the constriction can form stable arches. The main difference is that silo clogs occur only at large packing densities because the dry particles are subject to gravity.

An approach commonly used to describe such systems is to measure the number of particles s or the volume of suspension that flows through the constriction before a bridge is formed. The two relevant quantities are the average number of particles $\langle s \rangle$ (or the average volume of suspension) before clogging occurs and the resulting distribution of the number of particles escaping. The latter exhibits an exponential decay because of the constant probability of clogging during the flow.[10] As a result, the probability of clogging also follows an exponential distribution, illustrated in figure 4d.

An approach to predict the average number of particles, or the average volume of fluid, flowing through the constriction before bridging occurs is to assume a random distribution of particles in the channel and imagine that a sufficient number of them reach the constriction at the same time. For instance, in a 2D system and particles of diameter D, a constriction of width W will clog by bridging if the number of particles arriving simultaneously is greater than or equal to floor$(W/D + 1)$. For a given particle density, it is then possible to show that before the system clogs the average volume of fluid will increase if the width of the constriction is increased (figure 4e). Similarly, clogging will be delayed if one decreases the volume fraction of the suspension.[11] Clogging by bridging exhibits a particular feature of intermittency, in which the flow clogs and unclogs periodically, when some perturbations exist in the system. Those conditions provide a framework to minimize clogging by bridging.

Too sticky to flow

Very small particles can stick to surfaces and to each other. If a particle attaches to the wall of a constriction, that constriction becomes a little smaller,[12] as shown in figure 5. When the deposition happens repeatedly, particles aggregate, eventually leading to severely reduced constrictions that are more susceptible to both bridging and sieving.[13] Although initial deposition depends on the interaction between the particle and the wall, interparticle interactions can significantly increase the aggregation. The particle–fluid interaction is also an important parameter, because the flow determines how quickly particles will arrive and the shear forces they experience. And that force may influence whether or not the particles can be eroded.

For particles such as sediment or microplastics, aggregation is primarily caused by van der Waals forces, which are short-range forces from distance-dependent interactions between atoms and molecules. Other small particles, such as bacteria and algae, can also be sticky. While still subject to van der Waals forces, bioparticles are often decorated by a variety of adhesion molecules on their exterior, which allow them to attach to surfaces

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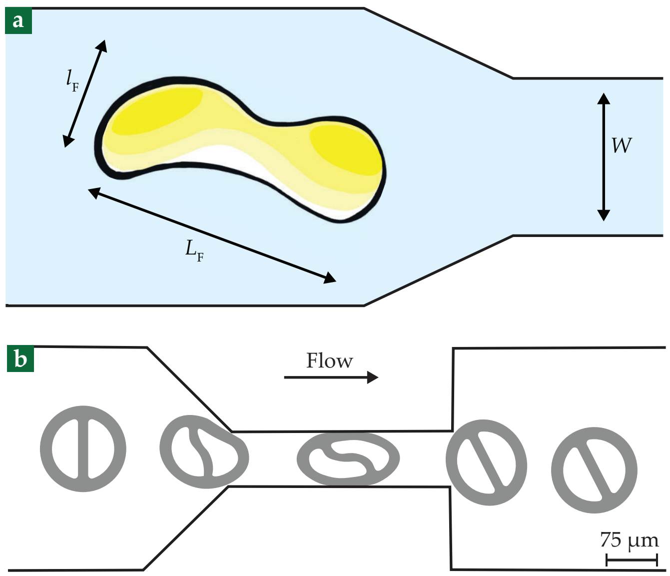

FIGURE 3. GETTING A GRIP on deformable particles. **(a)** Anisotropic and deformable particles have minimal and maximal Feret diameters l_F and L_F, respectively—a Feret diameter refers to the measure of an object along a specified direction. The particle shown here flows toward a constriction of width *W*. (Courtesy of R. S. Sharma.) **(b)** A flexible particle can squeeze through a constriction smaller than its size if the input pressure is large enough. (Adapted from L. Chen, K. X. Wang, P. S. Doyle, *Soft Matter* **13**, 1920, 2017.)

or each other with greater force than abiotic particles. Once attached, many bioparticles can also multiply along the surface while excreting chemicals that serve as a glue to bind them there.

Sieving and bridging are governed primarily by interactions caused by spatial arrangements, but aggregation is more complicated and sensitive to chemistry. For particles in pure water, aggregation is often limited by an electric double-layer repulsion. But pure water is extremely rare outside of specialized applications, such as wafer processing and scientific research. Changes in pH or the addition of salt increase ion availability in suspensions and can drastically reduce double-layer repulsion, allowing van der Waals interactions to dominate. Even small concentrations (<0.1 mol/l) of monovalent salt can significantly increase the aggregation rate.[14] Usually, clogging by aggregation can be observed even for constrictions much larger than the particle diameter and for very dilute suspensions. This clogging mechanism, however, usually takes place over long periods of time—from hours to years.

The flow must go on

Because clogging is such a problem in a broad range of fluid systems, much of contemporary research investigates new techniques for preventing or mitigating it. Just as different systems experience different clogging dynamics, techniques to prevent sieving, bridging, and aggregation also vary depending on the predominant mechanism at work.

A common way to prevent sieving is to filter particles upstream. Most suspensions, however, are not ideal. Many particles, such as cells or protein aggregates, are anisotropic in shape and may be deformable. Nonetheless, those imperfections are actually opportunities to prevent clogging.

For deformable particles, or rigid particles flowing through a deformable constriction, elevated pressure can squeeze them through the passageway.[7] When that happens, the deformation of the particle, constriction, or both results in an adjustment of *W*/*D* that allows the particle to pass. Humans and other mammals rely on that phenomenon, as red blood cells must deform to flow through capillaries. In fact, numerous diseases alter the deformability of red blood cells, increasing the risk of blood clots and stroke if those cells become so stiff that they can no longer flow freely through small capillaries.

Highly anisotropic particles may clog a constriction in one orientation but flow freely in another orientation. To prevent sieving in that case, the particle must become aligned so that it can pass the constriction. For some shapes, particularly those with high aspect ratios, hydrodynamics provides a mechanism. At low volume fractions, slender particles subject to a shear flow tend to align their longest dimension with the flow direction. At higher volume fractions or turbulent, high flow rates, however, the motion of anisotropic particles in confined systems is less certain and remains an active research topic.

The simplest way to prevent bridging is to ensure that the suspension volume fraction is sufficiently low and the constriction is sufficiently large. In the case of grain silos or emergency exits, however, achieving either may be impractical or even impossible. Fortunately, other ways help prevent suspended particles from bridging. Indeed, once a bridge has formed in a static system, all the kinetic energy dissipates and the bridge remains stable with an unclogging probability of zero. But the stability of that bridge can be broken by introducing perturbations to the system.

One way to periodically perturb dry granular media is through vibrations using a piezoelectric device or, in the case of a liquid suspension, by adding fluctuations to the flow. Researchers have shown that, depending on its frequency and intensity, such vibration increases the unclogging probability. Thus, systems that rely on vibration to break bridges often exhibit an intermittent flow, which reflects both clogged and unclogged states.

Another passive method to prevent bridging in silos is to place an obstacle just upstream of the constriction. Researchers have shown that proper placement reduces the bridging probability by a factor of 100 without reducing the flow rate. Furthermore, that technique works for both passive particles, such as grains in a silo, as well as active particles, such as sheep or humans rushing through a constriction.[15] The addition of an obstacle reduces the pressure upstream of the outlet and modifies the conditions for bridging, with the ultimate effect of reduced bridging probability, even for dense suspensions.

Preventing aggregation has proven to be a more difficult task thus far. Nevertheless, there are some promising techniques. For a long time, the best way to prevent aggregation has been to introduce chemicals into a system. Some examples include adjusting the system's pH to reduce mineral precipitation in hard water, or adding biocides, such as chlorine, which kill bacteria and algae and prevent them from proliferating. Adding chemicals is far from ideal, however, as many chemicals are only compatible with specific systems. Furthermore, adding chemicals to large flows presents an environmental risk,

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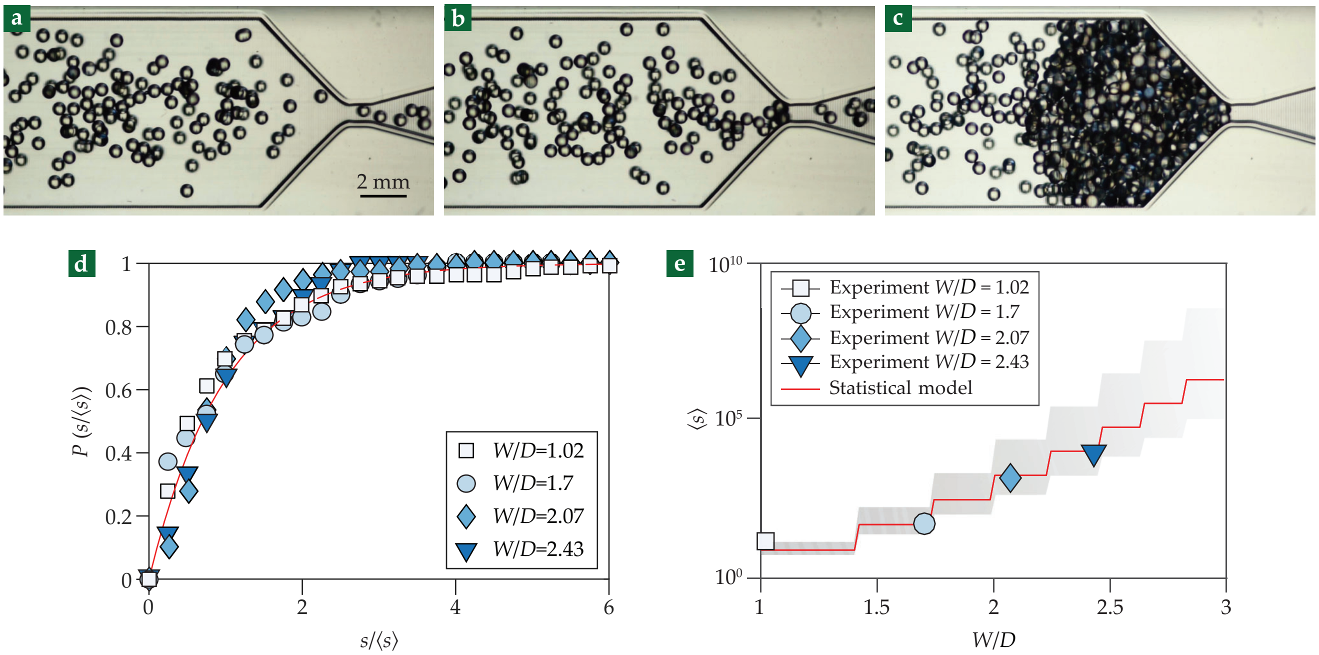

FIGURE 4. PARTICLES BRIDGE at a constriction. **(a)** Particles flow through the channel until **(b)** a sufficient number of them reach the constriction at the same time to clog it. **(c)** The clog prevents the flow of particles, which then form a filter cake. **(d)** This chart shows the probability *P* of clogging after *s* particles have escaped the constriction for differently sized particles *D* and constriction widths *W*. **(e)** The average number of particles <*s*> that can pass through the constriction before clogging it varies with the size ratio of the constriction width to particle diameter, *W*/*D*. (Adapted from ref. 10.)

because they could run off and invade nearby ecosystems. More robust techniques are therefore being investigated.

In some cases, surface treatment can help prevent aggregation. Modifying the surface roughness or surface energy—and often both—significantly reduces the aggregation rate. But it is difficult to develop surface treatments that maintain anticlogging properties for a long time, because of either erosion or fouling of the surface.

Another technique that researchers have proposed leverages capillary forces to remove particles.[16] For instance, passing a slow-moving bubble through a system can do the trick. As the bubble passes over particles, it exerts an inward capillary pressure that can peel particles from the surface. The process of capillary peeling has been shown to work for both inert particles and bioparticles. And although researchers have demonstrated the process for short-term removal of particles, no one has yet tested it as a long-term solution to curb aggregation. Additional methods to locally increase the fluid shear are being developed for future applications.

Finally, yet another promising solution to mitigate clogging is to incorporate pulsating flows into the system.[17] Studies dating as far back as the 1980s report on their anticlogging potential. Over time, researchers have observed that the unsteady shear environment associated with pulsatile flows may help mitigate all three mechanisms of clogging. With pulsation, anisotropic particles can rotate so that they pass a constriction and do not sieve. And although particle bridges are often stable in a steady flow, pulsation can reorient or break apart a bridge and restore flow to the channel. The mechanism is similar to how vibrations prevent bridging. Finally, pulsatile flows may mitigate aggregation by periodically increasing the fluid velocity and eroding particles with a temporarily elevated shear.

Eyes on the future

Many different systems can clog in distinctly different ways, so no one-size-fits-all solution exists, and a lot of work remains to obtain a unified picture of how it happens. Understanding the impact of different parameters on clogging is important for designing resilient systems, thus saving time, money, and energy.

Ideally, as our understanding of clogging becomes increasingly comprehensive, general guidelines for its risk can be established. For bridging and sieving, we know that the size ratio *W*/*D* and the volume fraction Φ are the dominant parameters

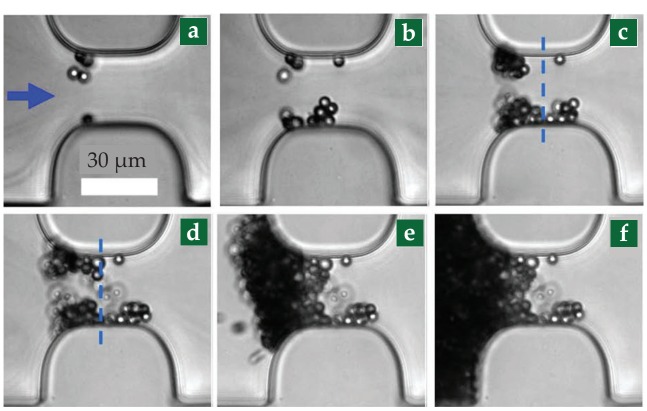

FIGURE 5. THE SUCCESSIVE DEPOSITION of particles at a constriction eventually clogs it. Images correspond to the following times: 4, 9, 12, 16, 22.5, and 24 minutes. Every minute 68 000 particles pass through the pore. The blue arrow signifies the flow direction and dashed blue lines correspond to the middle of the pore. (Adapted from ref. 12.)

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that determine whether or not a system will clog. Therefore, it may soon be possible to describe a phase diagram for the phenomenon. Eventually, parameters such as roughness, particle anisotropy, and deformability may be incorporated into such a diagram. The influence of channel geometry, such as the angle of a constriction, needs to be considered as well.

Aggregation is more complex, but it may be handled in a similar way. We can assume that $W/D \ll 1$, which makes the constriction width a less important consideration for an aggregation phase diagram, though it would change the time it takes the channel to become fully clogged. Similarly, increasing the volume fraction Φ should simply increase the aggregation rate. The proper phase diagram would indicate when to expect aggregation, given the competition between attachment forces—due to a combination of van der Waals forces and an additional adhesive force—and erosion forces from the shear exerted by the fluid. If the erosion force exceeds the attachment force, we would expect minimal aggregation or an upper limit to the size of the average aggregate. But if the attachment force exceeds the erosion force, we would expect continual aggregation and eventually a complete clog.

To fully understand those processes requires an interdisciplinary approach. Clogging can be sensitive to hydrodynamics, biology, chemistry, and physics all at once. Suspensions may contain billions or more of polydisperse particles with varying properties, and their specific locations in the suspension are unknown. Thus, as in turbulence modeling, advanced clogging models require extensive validation and iteration to be predictive. And although simplified systems are essential for isolating specific aspects of clogging, complex systems must be investigated as well. Real suspensions are polydisperse and flow through a wide variety of geometries. Field research and case studies that focus on such real systems should be extremely useful for helping scientists design relevant experiments while also serving as validation sources for clogging models.

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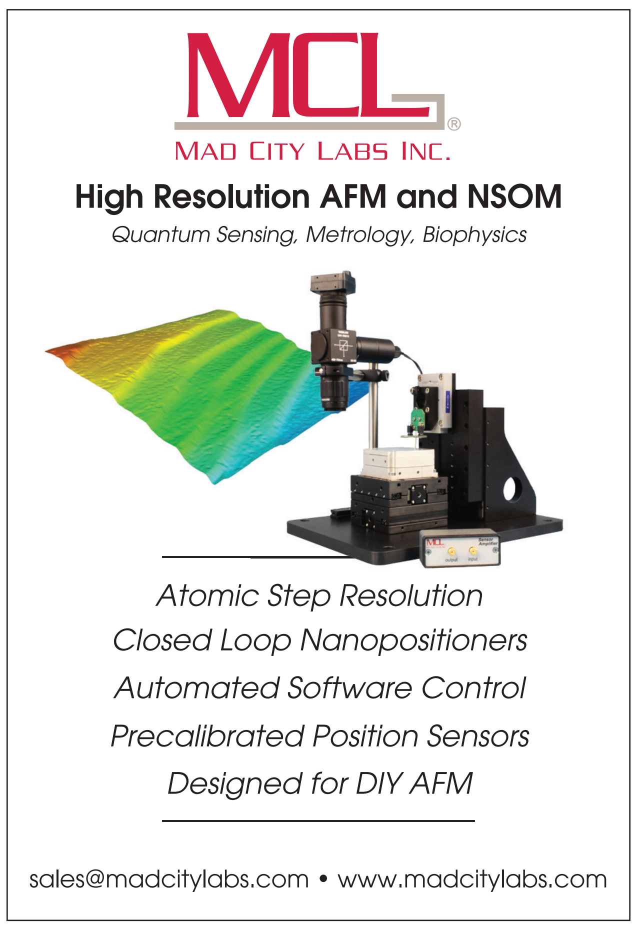

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