Cracking the Scaleup Challenge with Engineered Fractals

***Steve Peacock** explains how fractal design principles are helping engineers achieve uniform flow, predictable mixing and more reliable routes to commercialisation*

PROCESSES that perform well at pilot scale often fail when scaled up due to poor fluid distribution or mixing. These challenges can introduce significant technical and commercial risk. Engineered fractals offer one approach to addressing this problem, enabling more consistent performance across scales. They are now being applied in areas including direct lithium extraction (DLE) and metals recovery from recycled battery materials.

WHAT ARE ENGINEERED FRACTALS FOR FLUID DISTRIBUTION AND MIXING?

In simple terms, fractals are recurring geometrical patterns that repeat themselves at ever-smaller scales. Fractal-like structures are very common in nature – for example in leaf veins, blood vessels or river networks. In engineering, fractals can be created by iteratively following a set of "generative rules". One example might be to split a single line segment into two-line segments at a T-shaped junction and repeat this process at smaller scales. Following similar generative rules creates the diagrams shown in Figure 1 and Figure 2.

In fluid distribution, this approach allows a single inlet stream to be divided into many outlets that are hydraulically equivalent. Each flow path has the same length and number of turns, supporting consistent distribution across a surface or volume.

QUICK READ

- **Scaleup without surprises:** Fractal designs replicate identical flow paths, helping pilot performance translate reliably to full scale
- **Fixing flow and mixing:** Uniform distribution and controlled mixing reduce channelling and underperformance in large equipment
- **Cutting cost and risk:** More predictable scaleup can reduce reliance on expensive demonstration plants and speed up commercialisation

Figure 1: Fractal-based distribution of fluid from a point source along a one-dimensional line

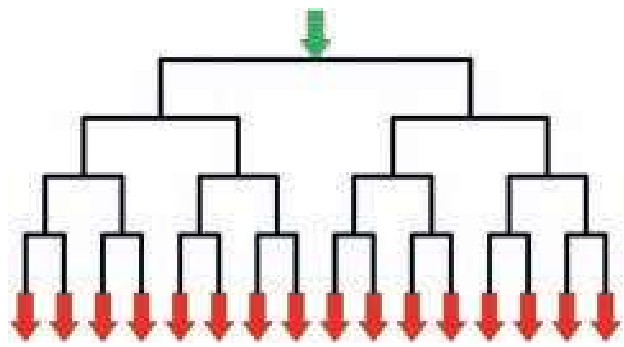


Figure 2: Fractal-based distribution of fluid from a point source over a two-dimensional surface

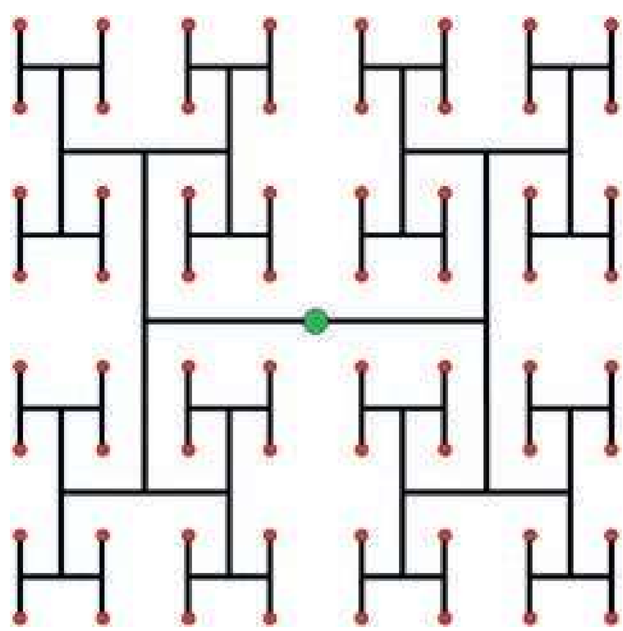
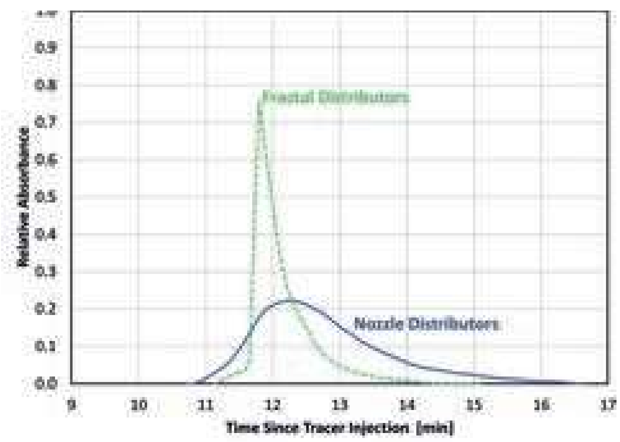
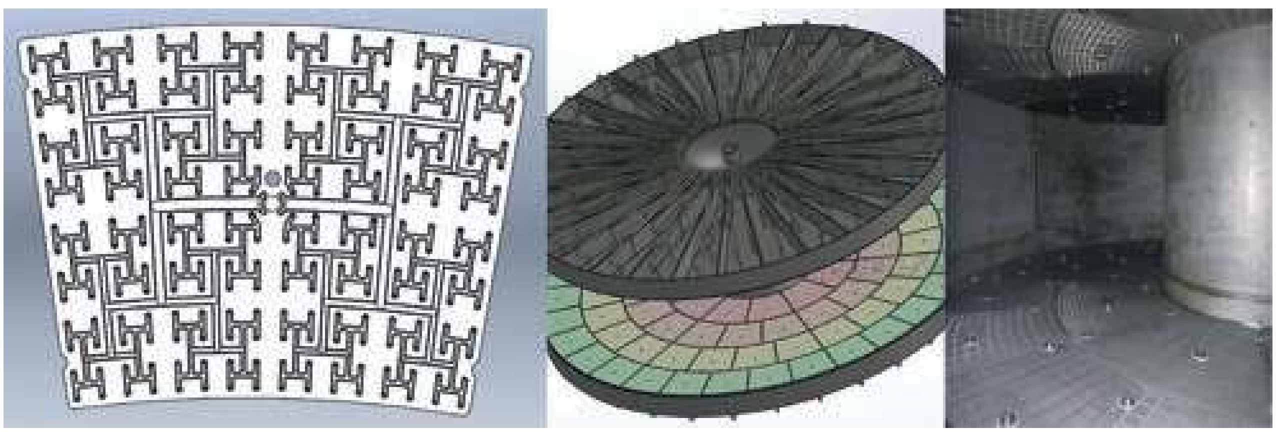


Figure 3: Tracer test results comparing distributor types in an industrial chromatography system

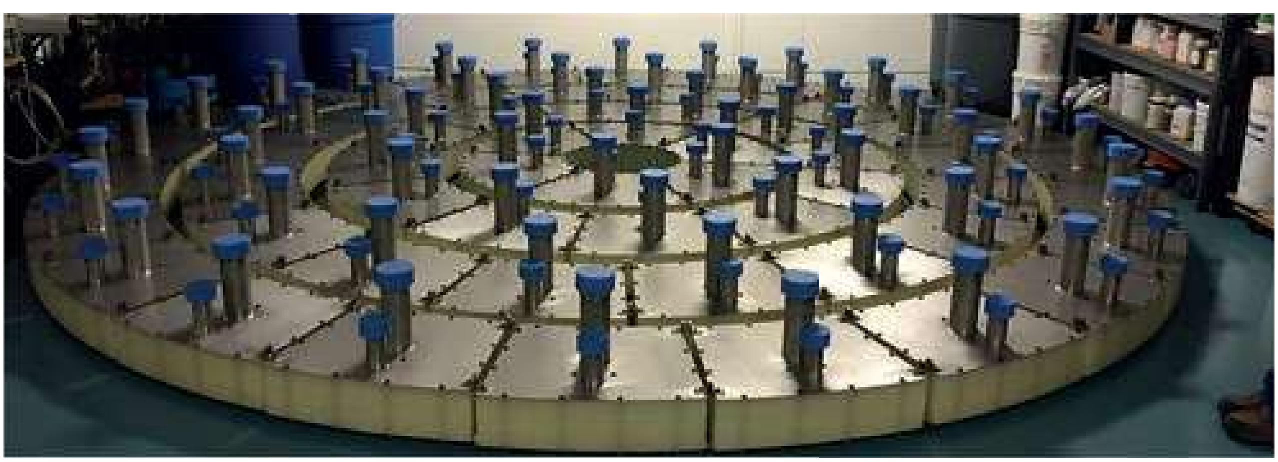


Engineered fractals have been employed for fluid distribution in industrial equipment since the early 1990s. One early example involved replacing nozzle distributors in a simulated moving bed chromatography system in a US beet sugar factory, where performance had deteriorated on scaleup. Tracer testing using a food-grade dye showed that the original distributors led to significant maldistribution. A clear improvement in the plug flow nature of the fluid was seen after the installation of the fractal distributors. Following subsequent replacement of the distributors in all eight of the resin columns within the chromatography system, the separator performance matched the levels seen at pilot scale.

High-quality plug flow is particularly important in packed-bed unit operations such as chromatography, ion exchange and adsorption but fractal distributors can also be applied to absorption, distillation, extraction, mixing and reaction processes. Typically, fractal distributors within large industrial process



(From left to right) **Fractal tile design; vessel showing fractal installation details; the inside of an industrial ion exchange column showing installed fractal tiles**



Fractal tiles for the mixing of two immiscible fluids at 8,000 m³/h in an industrial chemical reactor

vessels are implemented in the form of "tiles" which cover the entire top and bottom of the vessel.

In applications requiring very high-quality plug flow fluid distribution, fractals are typically installed within vessels having flat tops and bottoms. In less-demanding applications, fractals can be fitted into traditional dished-end vessels. Because fractal distributors are based on symmetry rather than on pressure drop, these systems can operate with relatively low energy input and can tolerate wide flow turndown ratios.

Fractal concepts can also be applied to mixing. By distributing two fluids separately through parallel fractal pathways and combining them at many small outlets, mixing can be controlled at a defined length scale. This can be advantageous in large vessels, where conventional turbulence-based approaches can be difficult and energy-intensive.

REDUCING SCALEUP RISK

Scaleup during commercialisation can be expensive, time-consuming and prone to failure. Organisations typically work through a series of pre-commercial project phases to validate and derisk the technology before spending large sums of money on a commercial plant which may fail (often by gradually increasing the scale of the process until failure occurs, implementing the necessary corrections and then increasing the scale again).

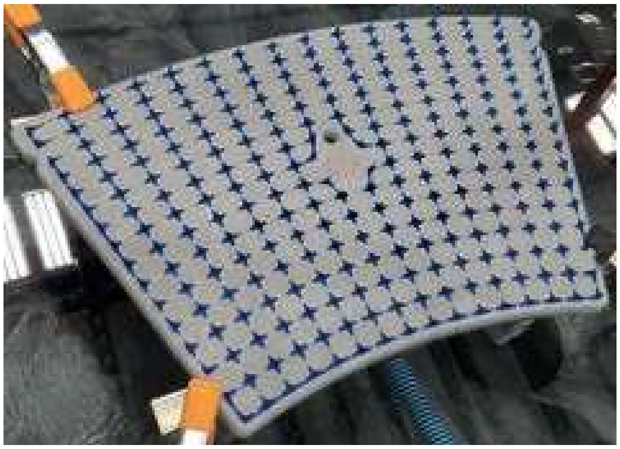
In particular, the demonstration-scale stage of development (at perhaps 5–20 times smaller than the full commercial scale) can be very capital-intensive and the plant usually has no residual value once the process development is complete. Even if the core process is validated at pilot- or demonstration-scale, behaviour can change. Maintaining uniform conditions at larger scales is challenging and maldistribution or poor mixing are common causes of underperformance. Conventional distributor designs can lead to channelling, where fluid preferentially flows through parts of a vessel while other regions remain under-utilised. This effect often becomes more pronounced as equipment size increases.

Since each flow path through a fractal distributor or mixer is hydraulically equivalent, each behaves identically, regardless of the size of the distributor or the total number of flow paths. As a result, performance can be maintained as systems scale by replicating the same flow geometry in parallel. This provides a more predictable route to scaleup than approaches that rely on iterative redesign at each scale.

In some applications, this allows the costly demonstration-scale phase of the commercialisation process to be eliminated. For example, in ion exchange, adsorption and industrial chromatography applications, decades of experience have been obtained in successfully scaling new processes directly from pilot scale (with resin or adsorbent columns having a diameter of only 7.5 cm) to full commercial installations having vessel diameters greater than 6 m.

In the beet sugar industry, fractal-based equipment for sugar recovery from molasses dominates the industry worldwide.

Blue dye tracer testing of a conventional radial fluid distributor, showing poor performance



Blue dye tracer testing of a fractal fluid distribution tile, providing a dense and uniform distribution

A simulated moving bed chromatography system for manufacture of an organic acid (*with permission from Escon GmbH***)**

More than 25 large-scale industrial chromatography systems have been fitted with fractal fluid distributors, in systems having a total adsorbent volume of 1,000 m^3 or more.

CASE STUDY – DIRECT LITHIUM EXTRACTION

Direct lithium extraction (DLE) is an adsorption-based process which makes use of packed beds of lithium-specific adsorbents operated in a continuous multi-column process. Lithium ions are adsorbed from the brine feedstock and subsequently eluted from the adsorbent bed (using pure water as the eluent) to produce an eluate stream containing relatively pure lithium chloride that is further processed into the solid lithium carbonate or lithium hydroxide form for battery use. Due to the low concentration of lithium in the feed brine (typically 500 ppm or less), the DLE adsorption process is carried out at a substantial and capital-intensive scale.

The DLE process is very sensitive to the quality of the fluid distribution that is achieved in the adsorption columns. Due to the nature of the process, the loading step of the DLE adsorption cycle is of relatively short duration, which means that changes in the process fluid being introduced into each column (such as feed brine, water to displace spent brine or to elute the bound lithium and any recycled impure product fractions) occur much more frequently than in a more-traditional ion exchange or adsorption process. If the fluid distributor in each column does not achieve a high-quality of plug flow, then some degree of mixing between these various process fluids will occur at each change of process step in the adsorption cycle. This is particularly detrimental to the quality of the lithium-rich eluate produced, as the concentration of lithium is so low that even minor contamination with other components of the feed brine can make the process uneconomic. This becomes increasingly problematic as the scale of processing increases, making the scaleup of the DLE process to larger sizes challenging and risky.

Some developers have addressed this by capping the size of adsorption vessels but this restricts the ability to benefit from economies of scale.

Fractal fluid distribution provides an alternative approach, enabling larger vessels to be used while maintaining uniform flow through the adsorbent bed.

This approach has been demonstrated in a commercial-scale DLE adsorption system in South America, which employs fractal fluid distribution in 16 vessels, each having a diameter of approximately 4 m. This system was successfully scaled to commercial size based on engineering data obtained on a pilot-scale test unit having columns of only three inches in diameter, fitted with fractal fluid distributors.

SCALING WITH CONFIDENCE

Scaleup and commercialisation remain challenging, particularly where fluid distribution and mixing are critical to performance. Engineered fractals offer a geometrically based approach to addressing these issues, improving flow distribution and mixing performance.

By replicating hydraulically equivalent flow paths, fractal designs can reduce uncertainty during scaleup and, in some cases, simplify the transition from pilot to commercial operation. Their application in areas such as lithium extraction highlights their relevance to emerging technologies linked to the energy transition.

While not a universal solution, fractal-based distribution and mixing provide a practical tool for engineers seeking to reduce scaleup risk. ■

Steve Peacock is technical director at Amalgamated Research in Twin Falls, Idaho, US

44-47 Features - Engineered fractals_1020 June 2026_The Chemical Engineer.indd 47 22/05/2026 09:42