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PROCESS INTENSIFICATION USING ENGINEERED FLUID TRANSPORTING FRACTALS

Mike Kearney, Amalgamated Research Inc.
2531 Orchard Drive East
Twin Falls, Idaho, USA 83301
info@arifractal.com

Presented at the 2003 AIChE Spring National Meeting

Abstract

We have determined that engineered fluid transporting fractals can be used to accomplish many of the goals of process intensification. The fractals are used to control the scaling and distribution of fluids. Fractals allow fluid properties, such as eddy size or concentration distributions, to be adjusted in a highly controlled manner. This control is obtained by introducing symmetries into the fractal structures. In some cases benefits can include order of magnitude reductions in process size, energy use and device design pressure.

Target applications include control of single and multi-phase flows in chromatography, ion exchange, distillation, adsorption, aeration, extraction, mixing and reaction.

Background

As a simple definition, fractals are self similar objects whose pieces are smaller duplications of the whole object. Examples are ubiquitous in nature and include coastlines, clouds, river beds, trees and the blood circulation system (1,2). Fractals are, for the most part, absent from engineered devices.

The usefulness of fractals lies in their controllable scaling characteristics. Scaling, for example from large to small or vice versa, is a common requirement in a number of disparate unit processes. For example, fluid scaling is required when the geometry of a fluid is altered. Fluid entering a large column must be scaled and distributed to approximate a surface. The opposite operation is performed for fluid collection from a column. Mixing is a unit operation with a very different purpose but also requires fluid scaling as a key characteristic wherein fluids are scaled to smaller and smaller parts and interspersed.

It is not ordinarily recognized that scaling is such a central requirement of fluid processes and, as a result, the common methods used for scaling are not generally recognized as inefficient or lacking control. For example, mixing is usually accomplished using turbulence for scaling. The use of an impellor is a typical example of using turbulence to scale and distribute fluids. Turbulence results in broad distributions of fluid properties such as eddy size, bubble size, concentration bands, etc. The use of engineered fractals can narrow the distribution of these fluid properties in a controlled manner and can therefore result in significantly smaller equipment, less energy use and more homogeneous processes (3,4). These results are associated with process intensification.

Figure 1 illustrates a partial view of a fractal structure which can be used to introduce a fluid to a column oriented process. (5,6). Characteristics include:

- Scaling is accomplished using engineered symmetry. A uniform surface of fluid is introduced. This is in contrast to nozzle or orifice pipe type distributors which usually depend upon the uncontrollable characteristic of turbulent scaling to spread a fluid.

- The device is dependent upon fractal scaling and symmetry for proper flow distribution. As a result, the fractal has low energy requirements. Most distributors (such as orifice pipe) are designed using pressure drop to provide proper flow to all exit points.

- Due to symmetry, all the flow paths of the fractal are hydraulically equivalent. The hydraulic path to an exit point near the center is equivalent to the hydraulic path to a point at the outer edge. Therefore, unlike distributors designed using pressure drop criteria, the fractal has a very large turn- down (1 to 10 easily obtained).

- Fractals by definition are scaling structures. As a result, the often difficult problem of process scale-up is alleviated. Figure 2 illustrates how the smallest fractal structure used in small scale tests is maintained as larger fractal iterations are added to create the larger scale device. This method tends to maintain the process characteristics observed at the smallest scale.

Note that as the center of the device is approached, the fractals are scaled by a different percentage depending upon the direction. The fractals appear to be stretched more in one direction than the other. This type of stretched fractal is referred to as self-affine. Self-affine fractals are used in this case to best match the geometric constraints of the vessel.

Fractal manufacturing and use is a practical reality. We have installed over 45,000 ft^2 of the fractal similar to that in figure 1.

Figure 1: A section of a fractal distributor for fluid introduction/collection.

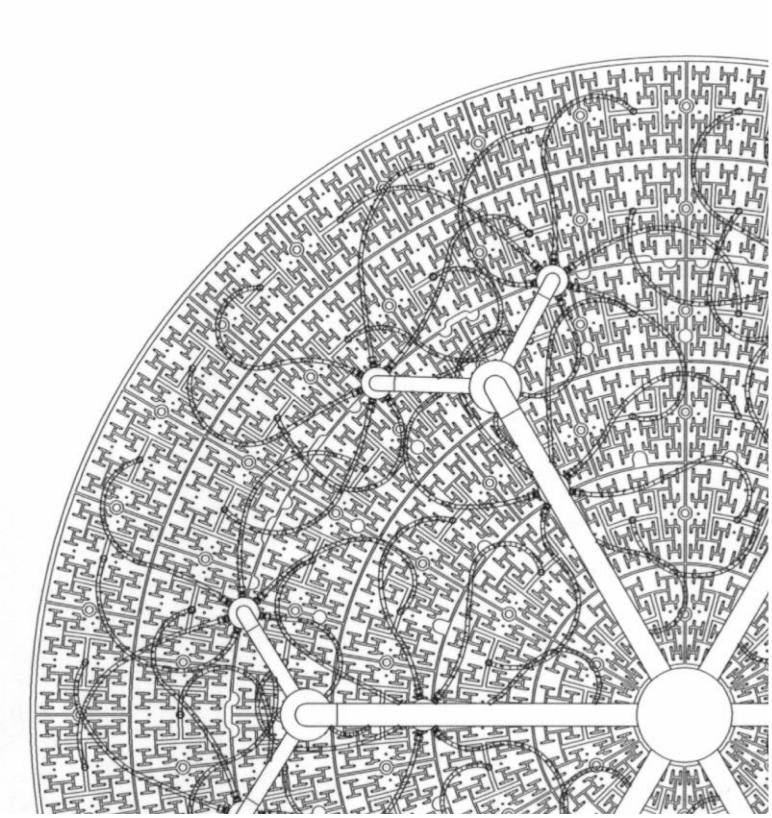
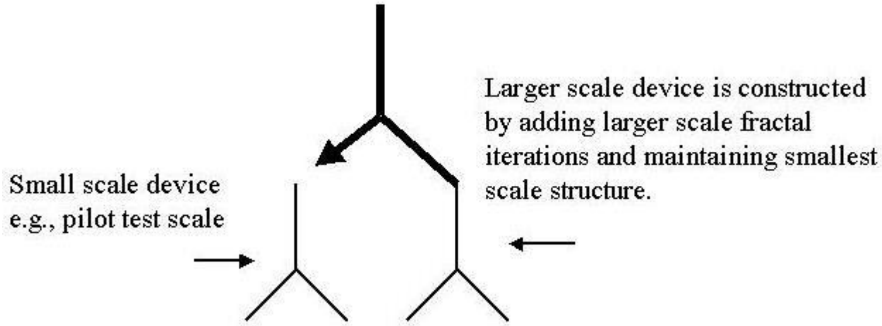


Figure 2: The concept of process scale-up using engineered fractals.



Process intensification example

Figure 3 is a photo of an ion exchange application using fractal distribution and collection. The vessel is 5 ft. diameter x 1 ft. height. The process is weak cation softening of a biomass derived material (juice from sugar beets). The process involves regeneration of the ion exchange resin with sulfuric acid and exhaustion of the resin to Ca^{+2}/Mg^{+2} form. Steps of the process include exhaustion, sweet-off, regeneration, regeneration rinse and backwash. The larger scale fractal structure can be seen above and below the vessel. Layers of progressively finer fractal structure are located inside the vessel.

The fractal introduction and collection of fluid allows extremely high flow rates to be used without turbulent disturbance of the resin bed. This characteristic also allows the bed to be very flat (only 6 inches). Table 1 lists a comparison of operation of the fractal ion exchange vessel and a conventional vessel operating in the same factory. Of particular note is the order of magnitude decrease in resin requirement and the near complete elimination of pressure drop. Other advantages include safety since the fractal vessels operate at low pressure. The low pressure also allows feed by gravity rather than by pump. Small space requirement is another benefit.

Another interesting characteristic concerns the flow in the freeboard above the resin bed. Six inches of freeboard was provided to allow 100% expansion during resin backwash. The Reynolds number associated with the flow through this free area is about 85,000 (700 gpm at 85 C). However, the fractals introduce the fluid in a very controlled, non-turbulent manner. All the fluid momentum across the introductory surface is in the same direction so that the processing can be carried out without the development of visible large scale turbulence. This is an example where a fractal can beneficially introduce a temporary stability into a process operating in the turbulent regime.

Figure 3: A fractal ion exchange vessel.

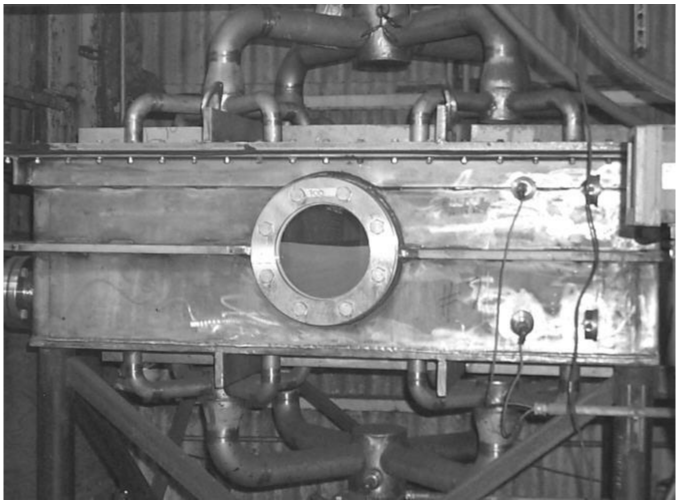


Table 1: A comparison of conventional ion exchange and fractal ion exchange.

	Conventional IX	Fractal IX
Resin bed depth (inches)	40	6
Exhaustion flow rate (Bed volumes/hour)	50	500
Maximum resin bed pressure drop (psi)	50-70	1 or less
Relative process size	10	1

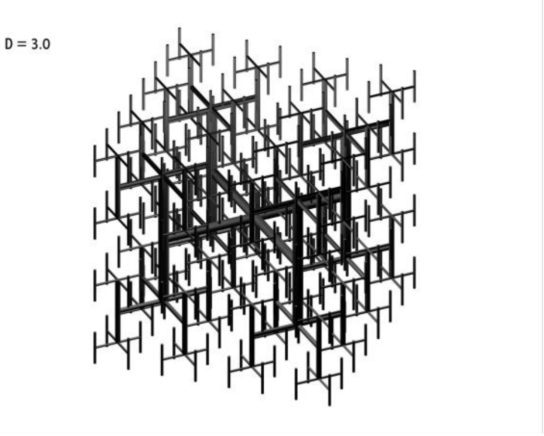
Flexibility of fractal design

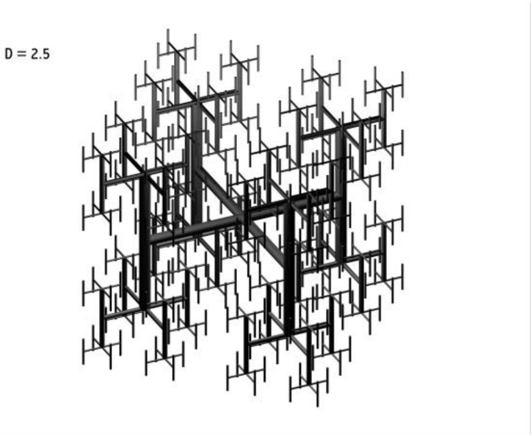
As noted, engineered fractals allow for precise control of the geometry of fluid scaling. Reference 7 describes several ways that fractals can be varied to provide desired scaling and distribution geometry. These methods include:

1. Variation of scale-down factors to modify space filling characteristics.

The fractal dimension is a measure of the space filling characteristics of a fractal. As the calculated dimension is reduced, space is less filled by the object, as can be seen by comparing the fractals in figure 4 with D = 3.0 and 2.5. Therefore, the fractal dimension of an engineered structure is a key design criteria. Because fractals have a dimension associated with them, certain aspects of design are straightforward. Using the fractal dimension, fractals can be designed in a logical manner to approximate surfaces, volumes and non-integer patterns (8).

Figure 4: A comparison of space filling characteristics at different fractal dimension.





2. Variation of the fractal cut-off.

Smaller and smaller iterations of structure are added to an initiator to produce a fractal. The space filling characteristics can be altered by adjusting the number of iterations. The smallest scale used in a device is referred to as the fractal cut-off. In some cases, the cut-off may be constrained by manufacturing limits and cost restrictions rather than design intentions.

3. Variation of the structure with respect to symmetry.

Fractals can be engineered with variations of the object's scaling symmetry. For example, the scaling factor can be different in different directions. The self-affine fractals in figure 1 are an example of this. The scaling factor can also change with change in iteration number. Another related technique is to vary the symmetry characteristics of the initiator. Note that the initiator is the original large scale structure geometry duplicated in the smaller descendent generations.

4. Variation of the structure with respect to the number of branches per node.

Figure 4 illustrates fractals with 8 branches per node. Altering the branch count is a useful design parameter. Techniques 1-4 can, of course, be used in combination.

Offset fractals

Fractals can be constructed such that two or more fractals are offset. This allows design of devices wherein two or more fluids can be scaled simultaneously prior to interaction. In such configurations the separate fractals can scale in the same flow direction or from differing directions before combining. Used as mixers and/or reactors, offset fractals can provide precise control of scaling and distribution of all fluid components.

Combining the use of engineered fractals with process turbulence

While fractals can be thought of as highly controlled functional alternatives for the scaling and distribution feature of turbulence, they can also be used together with turbulence to take advantage of its beneficial characteristics (7). Some examples:

- Fractals can be used to provide an advantageous first stage of distribution prior to final turbulent mixing.

- Fractals can be placed in motion and thus cause turbulence while concurrently distributing fluid.

- Fractals can be used in a turbulent fluid flow passing through the fractal.

- Fractals can be designed to provide turbulent jetting.

- Similarly, fractals can be used as fluid collection devices from turbulent flows.

Literature cited

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