Control of Fluid Dynamics with Engineered Fractal Cascades Adsorption Process Applications

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Control of Fluid Dynamics with Engineered Fractal Cascades - Adsorption Process Applications

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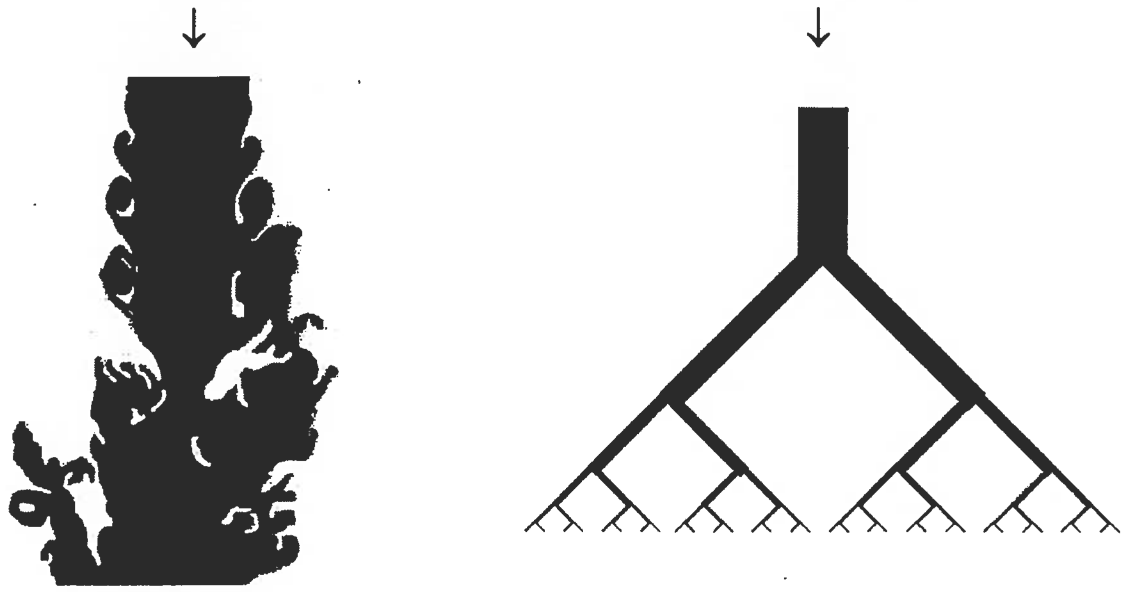
Engineered fluid transporting fractals can be utilized for a broad range of fluid control applications. These applications include use as alternatives to turbulence, controlled formation of fluid geometry and rapid transition of effective fluid dimension. As applied to adsorption processes, fractals can be used to provide rapid and homogeneous distribution of fluids to form surfaces or rapid distribution and collection of volumes.

INTRODUCTION

Engineered fluid transporting fractals have recently been suggested as structures which can be utilized for precise scaling and distribution of fluids[1]. Under this proposal, and as illustrated in Figure 1, fluid scaling and distribution can be regarded as a general phenomena with an underlying range of specific mechanisms. At one end of the mechanism spectrum is free turbulence which is the most familiar and most often used approach for obtaining deep fluid scaling. Turbulence, however, entails very little control of geometry. At the opposite end of the spectrum are fluid transporting fractal structures which also allow deep scaling but can, in addition, provide precise control of the scaling geometry. As with free turbulence, fluid flow through an engineered fractal, from largest to smallest conduit, experiences a continual reduction of spatial scales and a continual dissipation of large scale motion.

Figure 1. Fluid scaling: Turbulence versus flow through a fluid transporting fractal.



Turbulent Jet
Unpredictable Scaling Geometry

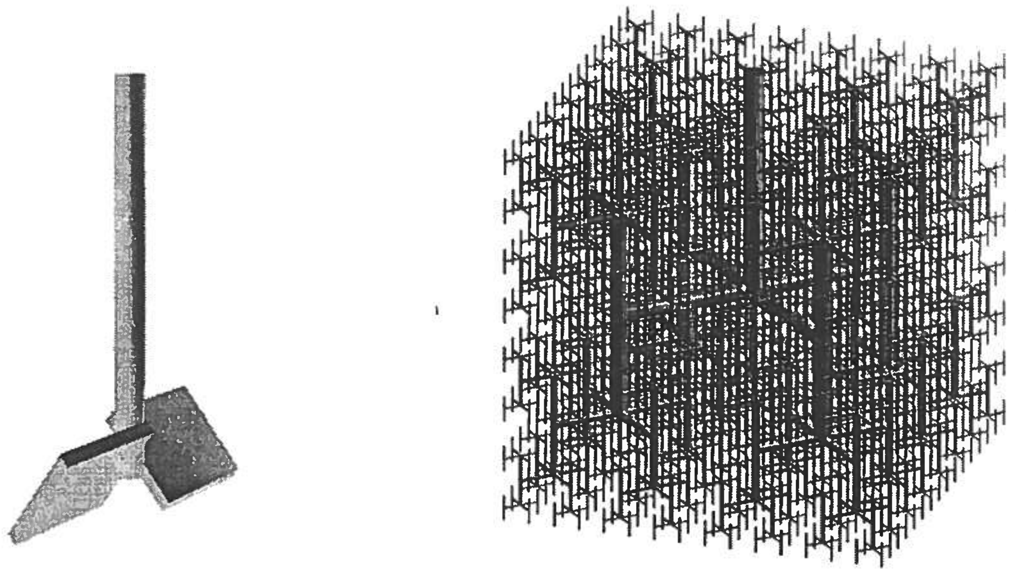
Fluid Transporting Fractal
Precise Scaling Geometry

Engineered fractals can therefore be used as alternatives to turbulence. This is of value when control over the geometry of the scaling and distribution phenomena is advantageous.

The process of mixing serves as a specific example of turbulence substitution. Mixing is generally achieved with turbulence. The hypersensitivity of turbulent fluid systems makes it difficult to control the time evolution and geometry of such processes. For the same reason, the behavior of turbulent mixing systems is difficult to predict[2]. In Figure 2 a mechanical turbulence inducing device is compared with an alternative non-turbulent scaling and distribution fractal (fluid passing through the fractal mixes with surrounding fluid). As opposed to using turbulence, the fractal allows the mixing geometry to be controlled. Unlike the mechanical device where mixing efficiency is generally improved with increasing turbulence, the fractal mixer efficiency increases as smaller scale structure is added and turbulence is progressively eliminated. Consequently, such a device may be useful when constrained mixing geometry is necessary or very homogeneous or low turbulence mixing is required.

While this is only an introductory example, the ubiquity of turbulence as a tool and/or hindrance in chemical processes suggests that a broad range of applications for engineered fractals may be anticipated.

Figure 2. A comparison of mixing mechanisms: Turbulence inducing mechanical equipment versus an engineered fluid transporting fractal. Both devices scale fluids. However the fractal provides control of the scaling geometry.



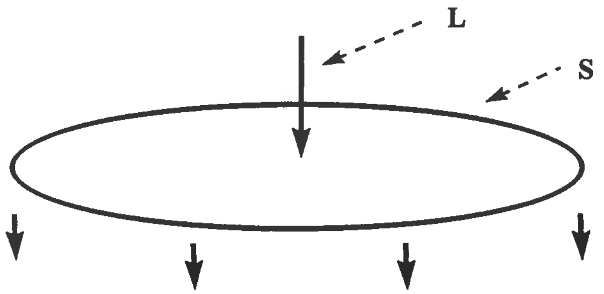
Turbulent Mixer

Non-Turbulent Fractal Mixer

ADSORPTION PROCESS APPLICATIONS - FLUID DISTRIBUTION

With respect to adsorption processes, the controlled distribution and collection of fluids is an excellent application for engineered fractal structure. As with many other unit processes[3], optimized industrial scale adsorption is highly dependent upon distributor performance. In general, a proper distributor should introduce a homogeneous surface of fluid to a column of adsorbent (Figure 3).

Figure 3. A goal of proper fluid distribution is the rapid transition to a homogeneous surface. Geometrically, a line L representing incoming fluid must convert to a surface S which moves through the adsorption bed.



A long list of possible distributor disturbances can be catalogued. As a first example, consider a typical distributor, such as a lateral or radial, where fluid exits orifices along the distributor flow path. Orifices are sized to provide near equivalent flowrate as pressure varies along the distributor. An optional design solution involves variable orifice density along the path to take account of the pressure changes. If orifice sizing or density layout is incorrect, flow rate will vary along the distributor flow path.

Narrow turndown range is another problem which can be encountered with distributors designed using pressure drop criteria. If flowrates vary over time, the orifice layout may become inappropriate for the flowrate changes.

A completely different problem can be attributed to distributor pressure drop itself. Consider a distributor which is dependent on pressure drop and meets all requirements of equivalent flow from all distribution points. Because of pressure drop, such distributors exhibit turbulence. Disadvantages can include the requirement of supplementary column length in order to provide a void space or mixing chamber for turbulence to spread and mix the fluid across the bed diameter. Under utilization of the adsorbent near the top of the bed is another possible problem.

Turbulent distribution can be particularly harmful to chromatographic processes. Turbulent mixing at the distributor interfaces of a chromatographic system will blur the desired component separation. It is unfortunate that proper flowrate design for a pressure drop dependent distributor results in mixing - a result contrary to the very purpose of chromatography.

An additional distribution problem is pattern channeling. Because the flow within a bed of adsorbent is often laminar, patterns of introduced fluid can channel through the bed relatively undisturbed. Both low distribution point density and distribution device patterning will result in absence of plug flow and under utilization of the adsorbent.

In some cases, time lag can become a problem. If a significant differential time lag exists across a distributor, a cross-sectional disturbance across the adsorbent bed can occur which is independent of the other problems discussed above.

Compromises are often made in distributor design simply because of the typical cylindrical column which must contain the distributor. Distributor geometry designed for the bulk of the cross-sectional area may encounter inefficiencies near the outer circular edge. Adsorption process distributors may also be difficult to scale-up. As column diameter increases, significant changes in distributor design may be required as the above problems magnify.

Finally, maldistribution can place limits on the allowable range of useable bed width to height ratio, therefore placing restrictions on adsorption dynamics. Low width to height ratios require larger adsorbent particle size so that pressure drop is acceptable.

ADSORPTION DISTRIBUTOR DESIGN CRITERIA

With reference to the preceding discussion it is possible to list design criteria for an ideal adsorption surface distributor:

1. Minimal turbulence.
2. Rapid formation of a surface.
3. Surface homogeneity, minimal turndown limits, no differential time delay disturbances.
4. No pattern channeling.
5. No distributor-column geometry conflicts.

6. No scale-up limits.
7. Minimal limits on adsorbent bed width to height ratio.

FRACTAL SURFACE DISTRIBUTOR

Fractals provide a straightforward approach to meeting the above requirements.

Minimal turbulence

Because fractals can be used as alternatives to turbulence, such a structure is a logical choice for the general geometry. A fluid transporting fractal can act as an "engineered" eddy cascade, providing the required deep fluid scaling but under geometric control.

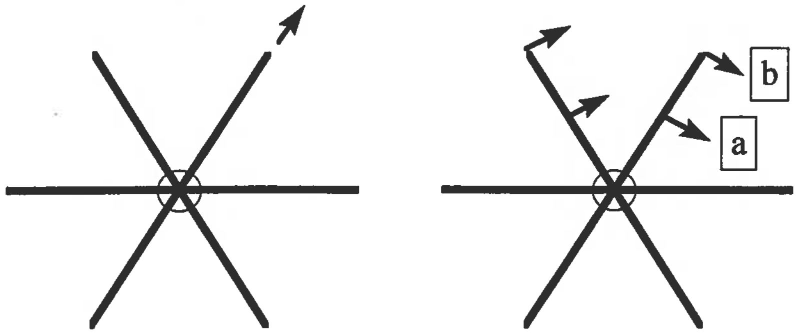
Rapid formation of a surface

The key to transforming an incoming flow to an engineered surface using fractal geometry is that lines with topological dimension=1 can be constructed to have a fractal dimension =2. In effect, a line can be constructed which completely fills a surface. Furthermore, lines of different fractal dimension can be linked to provide dimension transitions. For the case under consideration, a line of fractal dimension = 1 can be linked to a line with fractal dimension =2 to yield a transition from a line to a surface as illustrated in Figure 3. With respect to the real distributor structure, this means that a fluid inlet with an effective dimension=1 will be linked to a conduit layout which fills a surface with effective dimension=2.

Surface homogeneity, minimal turndown limits, no differential time delay

These factors can all be grouped because they will result if there is hydraulic equivalence of flow to all points on the introduced fluid surface. This requirement can be met if the structure exhibits universal flow path symmetry (Figure 4).

Figure 4. Distributors which do and do not exhibit universal path symmetry. All flow paths begin from the center.



A distributor with universal path symmetry. All six pathways can be generated by applying symmetry operations to any single path.

A distributor without universal path symmetry. Path "b" cannot be generated by symmetry operations on path "a".

No pattern channeling

This criteria is met by providing deep scaling for the fractal. The structure should contain many levels of bifurcation so that a surface will be closely approximated.

No scale-up limits

Although there are always practical limits for sizing a structure, fractals by definition are invariant to scaling so that an increase or decrease in size is accommodated by adding or removing iterated structure.

No distributor column conflicts

This requires that the chosen fractal be in the shape of a circle in order to fit the typical cylindrical column.

DESIGN IMPLEMENTATION

Figure 5 illustrates a realization of a fractal surface distributor appropriate for adsorption processes. An earlier paper describes results utilizing this design specifically for simulated moving bed chromatography [4]. Fluid flows from a narrow center inlet, then through 6-way, 3-way and 7-way dividers, and finally through a fractal pattern (Cayley tree) where a dimension=2 can be approximated. The fluid is therefore distributed as a surface. The structure can be thought of conceptually as an engineered eddy cascade with scaling carried out to any desired level (within manufacturing constraints). As bifurcations are added to the fractal pattern, turbulence is progressively reduced at fluid exit and a two dimensional surface is more closely approximated.

As opposed to using turbulence as the deep scaling and distribution mechanism, the cascade has been designed to be extremely symmetrical. Any individual fluid path from the center to an exit point can be used to generate all other paths, to a close approximation, using symmetry operations. The resulting symmetry provides equivalent hydraulics (equivalent flow rate, equivalent time of passage, equivalent pressure drop, etc.) to each exit point. The introduced surface is therefore completely homogeneous.

The entirely uniform, turbulent free distribution also provides opportunities for the use of adsorption columns with unusually large width to height ratios. This allows for the use of very small particles with fast dynamics while maintaining plug flow and low bed pressure drop.

The device can be installed as a column end distributor/collector or for mid-column flow-through service. The scale invariance inherent in the fractal has allowed structures with almost identical geometry to be built and operated successfully over a column diameter range of 15 cm to over 6 m.

NOTES

Detailed accounts of fractal geometry can be found in the literature[5,6,7]. Turbulent jet visualization in Figure 1 is used with permission of the University of Maryland Turbulence Research Laboratory.

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Figure 5. Fractal surface distributor. Scaling can continue indefinitely within manufacturing constraints.