

*Why engineer fractals? / Engineering rationale*

We have recently proposed using engineered fluid transporting fractals in a wide range of applications(1,2). In general, fractals can be considered when fluid scaling and distribution is a process requirement. Fluid scaling is a necessary phenomena in many unit processes such as mixing or when the geometry of a fluid must be altered.

Figure 1 illustrates two examples. Process “a” represents the introduction of a fluid into the top of a column, thereafter the fluid travels downward. This figure could represent a chromatography process where it is preferable to avoid axial mixing. Process “b” represents the progressive mixing of two components. It is not ordinarily recognized that process “a”, a non-mixing process, and process “b”, specifically a mixing process, share a common characteristic. However for this article the common characteristic is of central importance. This shared feature is fluid *scaling*. In process "a", the flow at the entrance of the column must be scaled, as indicated by arrow length, and distributed in order for the fluid to approximate a homogeneous surface. In process "b" the components must be scaled and distributed in order to be mixed. The ubiquity of scaling as a processing requirement suggests that precise manipulation of the scaling of fluids may be beneficial and widely applicable.

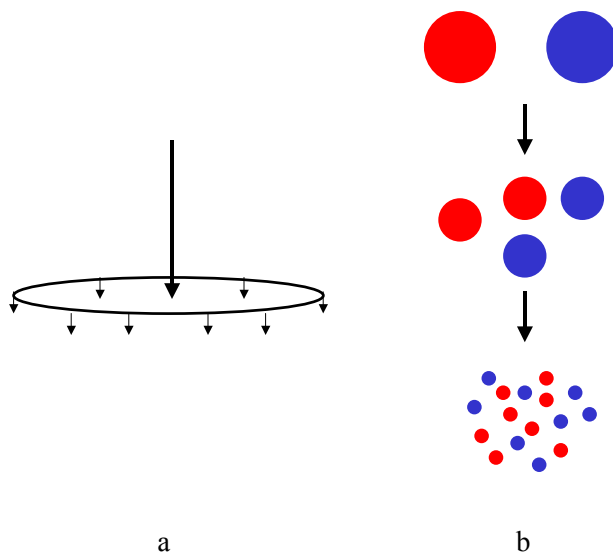


Figure 1. Widely disparate processes such as distributing fluid to a column and fluid mixing have a common characteristic. This characteristic is fluid scaling.

The engineered scaling provided by fractals can narrow the broad distribution of fluid properties ordinarily encountered when turbulent or inefficient scaling methods are used. These properties include concentration, velocity, pressure, temperature,

particle/bubble size, and eddy size. Fractals can also scale fluids with reduced energy loss compared with turbulence (turbulence is inherently an energy dissipation process). For these reasons, fractals can potentially benefit processes via reduction of energy use, decrease in equipment size, uniformity of flow and efficiency of mass and heat transfer.

There has been very little purposeful engineering of fractals (fractal antennas are one exception(3)). It is remarkable that fractals are ubiquitous in nature but are so rarely found in engineered structure. However there must be specific practical reasons to construct fractal devices. During the early and mid 1990s, Amalgamated Research Inc. developed the general rationale for engineering fluid transporting fractals

The initial argument can be made as follows:

1. Scaling of fluids is a common necessity in a variety of fluid processes.
2. Precise control of fluid scaling should be beneficial in many respects. Strict scaling control will narrow the broad distribution of fluid properties which can give rise to process inefficiencies,
3. Fractals are intrinsically scaling structures and can be engineered in a precise, defined manner,
4. Engineered fractals are therefore a logical solution to the problem of fluid scaling.

Turbulence is the most widespread fluid scaling method. A key characteristic of turbulence is the scaling of fluid motion from large to small scales - the turbulent, or eddy cascade. Turbulence inducing equipment is ubiquitous. While a valuable and often necessary tool, turbulence by its very nature implies uncontrolled characteristics and there are certain processing situations where this uncontrolled aspect is detrimental to efficiency. Furthermore, turbulence is an energy dissipation process so that using it for scaling can be unfavorable in this respect. For example, only a small fraction of the energy used to create surface area in mass transfer operations in two-phase flows (e.g., pulsed liquid-liquid extraction) is ordinarily useful. The rest contributes to axial mixing and therefore reduces overall process efficiency. Furthermore, the presence of eddies of variable size contributes to non-uniformity of liquid scaling and results in poor control of the droplet population.

There is a functional equivalence for turbulence and flow through engineered fractals with respect to scaling and distribution. Figure 2 illustrates a qualitative comparison of scaling via a turbulent cascade and scaling via a fluid transporting fractal. Turbulence is an uncontrolled method of scaling while engineered fractals provide the opportunity for precise scaling control.

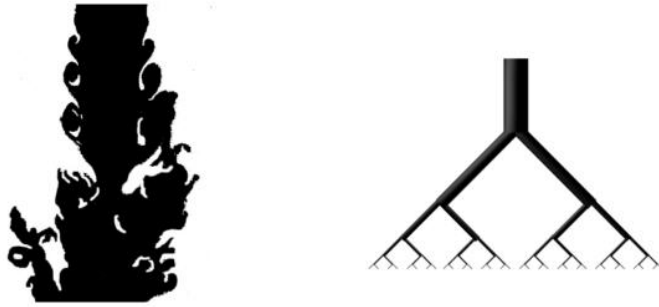


Figure 2. A turbulent cascade versus flow through an engineered fractal.

Fractals can attenuate a turbulent or otherwise unfavorable distribution of fluid properties and provide a progressively exact scaling. Additionally, although there will be an energy loss across a fractal, it can be less than that incurred when scaling is by means of free turbulence. Figure 3 illustrates qualitatively the progressive narrowing of the distribution of a fluid property as a fractal is iterated to smaller and smaller scale. Sharpening a distribution can lead to smaller equipment requirements, energy reduction, improved reactor yield etc. The distribution in Figure 3 could represent, for example, the concentration band broadening that occurs as a fluid is introduced into a chromatography column, the distribution of fluid velocities entering a process, particle or bubble size distributions, or eddy size distribution in a mixing process. In all these examples a sharper distribution will be beneficial.

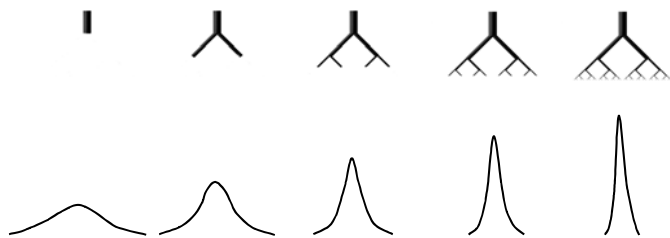


Figure 3. Progressive narrowing of fluid properties as a fractal is iterated.

A large variety of standard devices are ordinarily used to scale fluid in one way or another. A typical example is mechanical equipment which scales by inducing free turbulence. Other devices can generally be identified as providing scaling precision at a level somewhere between inducing free turbulence (although often using some turbulence) and the potentially precise control provided by engineered fractals. Because of the turbulence/fractal functional equivalence, a possible fractal application can often be recognized by simply noting if turbulence is a necessary but detrimental characteristic of a process and considering the use of a fractal in its place.

Figure 4 illustrates a comparison of mixing devices - an impeller for mechanically inducing turbulence and an engineered fractal. Note that fluid scaling and distribution is the goal in each case, however a fractal may provide a more controlled and predictable process, at least down to the minimum size channels attainable by the fractal.

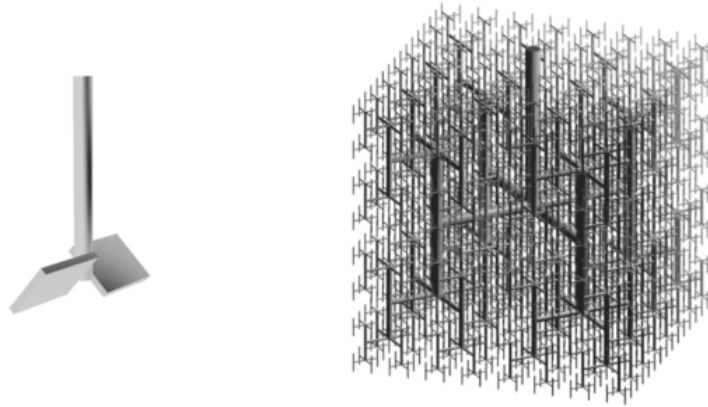


Figure 4. Mixing devices. An impeller versus an engineered fractal.

A common problem with process scale-up is the appearance of scale dependent inefficiencies. For example, larger equipment size can result in unfavorable effects due to higher Reynolds number. Fractals can scale-down some of these effects. One example is mixing. We use the term "non-contact mixing" to describe how fluids can be scaled and intermingled using fractal structure prior to contact with one another. Non-contact mixing may allow large and unfavorable eddy size to be eliminated entirely from a mixing or reaction process.

In some cases, a fractal may allow localized mixing of components, that is, because a fractal can scale with a low level of turbulence, mixing or distribution may be constrained to a localized volume within or near the fractal boundary.

Questions which may lead to consideration of an engineered fractal include the following:

- What unit processes in an operation require scaling?
- Is fluid scaling a necessity but presently under poor control?
- Can benefits be gained if the distribution of a fluid property is narrowed?
- Is energy being wasted by using turbulence for scaling?
- Can some or most of the induced turbulence in a process be replaced with an engineered fractal?
- Does process scale-up result in inefficiencies which can be countered with the scale-down characteristic of an engineered fractal.
- Does a process require the rapid formation of a particular fluid geometry?
- Is very rapid but precise scaling required?
- Will introduction of symmetries to the scaling process be beneficial?
- Can scaling homogeneity be beneficial?
- Can a process benefit from scaling to a particular fractal dimension?
- Can a process benefit from scaling control which changes as a function of time?
- Is there a benefit to localized mixing of one fluid within another?
- Can a fractal retro-fit to a process be useful or should a process be entirely reconfigured with a fractal as a key design element?
- Can a process benefit from a combination of a fractal together with turbulent scaling?

The use of a fractal in any particular application will involve a number of practical considerations. Certainly engineered fractal scaling will not always be appropriate. Because fractals are used to scale flow over a wide range of size, manufacturing techniques are required which allow small functional structure to be fabricated. The ability to construct complex 3D objects can also be important (recall that what is conventionally called a "3D" object may have an integer or non-integer fractal dimension).

A separate problem related to the scaling function of engineered fractals is plugging. If a fractal is designed with channel size small enough to be plugged with feed

components, then it must be possible to intermittently clean the fractal or the feed material must be appropriately filtered prior to use. Otherwise the smallest channel size (the lower cutoff scale) must be made larger. Design considerations can also be dependent upon the scale of the device's operation. Surface tension, for example, can become a concern at small scales.

For some processes, fractals may only be a partial solution to scaling problems. A fractal may be useful for initial controlled scaling with the remaining process goals dependent upon small scale turbulence.

### Examples

A true fractal is a mathematical entity with scaling proceeding ad infinitum. Any engineered or natural fractal is an approximation which will eventually reach a point of scaling cutoff. Furthermore, the "lines" which make up engineered fractals will actually be conduit or other materials with an associated thickness. It is important to keep these approximation characteristics in mind when engineered fractals are being described.

Figure 5 illustrates a fractal appropriate for introduction and collection of fluids from columns. As a distributor, the purpose of this device is to rapidly form a homogeneous non-turbulent surface. Flow is from a center inlet, then through 6-way, 3-way and 7-way dividers, and finally through a fractal pattern where the fractal dimension is  $\sim 2$ . As bifurcations (branches to new channels) are added to the fractal pattern, turbulence is progressively reduced at fluid exit and a two dimensional surface is more closely approximated. The lower fractal cutoff is determined by practical constraints or by the scale beyond which further scaling is not necessary.



Figure 5. An engineered fractal for distribution and collection of fluids.

As opposed to using turbulence as the scaling and distribution means (for example distributing fluid as jets from an orifice dependent device), the cascade has been designed to be extremely symmetrical. The deep scaling and high level of symmetry provides a rapid and precise transition of a fluid's geometry as it passes through the fractal. Note that because of symmetry the fluid pathways exhibit hydraulic equivalence. This means that the time of passage and the pressure drop are equivalent for all paths. Therefore, in addition to fluid surface homogeneity and a low level of turbulence, the device also has a very large turndown ratio. There is no preference for fluid to flow to any specific area as flow rate or pressure drop are varied. The device is also massively parallel and the total cross sectional area is increasing at the smaller scales. Therefore, pressure drop is very low. Distributors and collectors of this type are in service in columns with diameters ranging from a few centimeters to over 6 meters. Applied to industrial scale chromatography, the fractal's function is to reduce the band broadening which can occur at distributor inlet and outlet and therefore decrease the distributor's contribution to HETP.

A similar flow-through fractal has been prototyped for countercurrent gas-liquid operation(4). Again, only minimal pressure drop is required to maintain uniform distribution. Testing has indicated that the turndown ratio for this device can be as high as 10:1.

Table 1 lists the results of a comparison test of an ion exchange process using conventional and fractal distribution. The process is weak cation exchange softening. The goal of the testing was to demonstrate that using fractals for the distribution and collection of fluid would allow a softener to be configured as a small, flat bed and consequently be operated at very high productivity. Fractals enable the operation of a flat bed because they quickly introduce a homogeneous non-turbulent surface of fluid. The fractal bed was configured with a high width to height ratio in order to maintain linear velocity appropriate for the resin kinetics. Using the fractal softener in a quick cycling mode it was possible to operate at 10 times the conventional flow rate (per unit of resin). The benefits observed included a very small column, a correspondingly small amount of resin, a reduction of construction material/expense constraints and small peripheral equipment. Although operating at 10 times the flow rate used on the conventional system, the fractal softener column pressure and bed pressure drop were very low.

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

	Conventional IX	Fractal IX
Resin bed depth (m)	1.0	0.15
Exhaustion flow rate (Bed volumes/hour)	50	500
Maximum resin bed pressure drop (kg/cm <sup>2</sup> )	3.5 - 5.6	0.1 or less
Relative process size	10	1

This particular use for a fractal should be applicable to a number of other processes, for example, to alleviate problems with compressible beds, to reduce the amount of expensive media required or to significantly decrease equipment size. The possibility of minimizing equipment size by using short columns (together with other factors) has been theoretically examined for various applications (e.g., Wankat (5)). Fractals should contribute to the possibility of constructing such devices.

We have constructed functional prototypes of the fractal illustrated in Figure 6. This particular device was designed to be geometrically self-similar, that is, all iterations yield exact copies of the initiator. Magnification by a factor of 2 reveals 8 new copies. The fractal dimension can be determined from the self-similarity dimension (see equation 3 in "What are fractals?" discussion):

$$(1) \quad D = \log(8)/\log(2) = 3.0$$

Because of scale cutoff and conduit thickness the actual object is only an approximation to a fractal dimension of 3, but it should be clear from the figure that the device fills space in a dense and homogeneous manner. Additional iterations would cause the object to appear to be a solid cube. A smaller fractal dimension with the same initiator will yield a more open and less homogeneous structure.

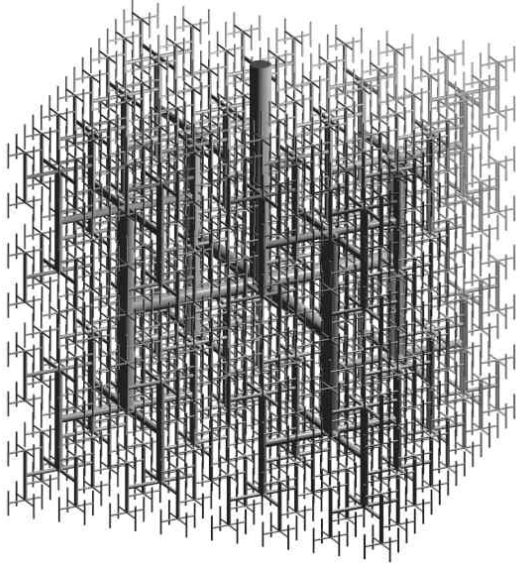


Figure 6. An engineered space filling fractal.

An overall process may benefit by implementing fractals in several unit processes. As an industrial example, fractals have been introduced into three different processes at the Amalgamated Sugar Company LLC plant in Nampa, Idaho . A 2 m diameter fractal is used in an ion exchange system. 5 m diameter fractals are used for fluid distribution and collection in 16 simulated moving bed chromatography columns. A third type of fractal is used for air distribution in a 12 m diameter silo. There are candidates for fractal scaling in several other processes at this particular plant. For example, it may be possible to increase the capacity of the solid-liquid clarification unit by using a fractal to decrease the turbulence at the fluid introduction. The gas-liquid reactors may benefit by improving control of the gas bubble size.

Because there can be a large number of fluid geometry transitions required across a set of unit processes, it can be helpful to outline the required scaling as a set of fractals linked to one another. This is simply a convenient way to overview a process from a scaling point of view. Figure 7 illustrates such a diagram.

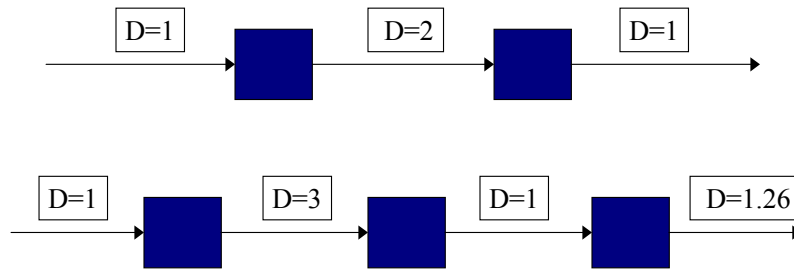


Figure 7. Fractal scaling transitions including lines, surfaces, volumes and non-integer patterns.

### Related applications

Because fluids so often exhibit or require scaling, there are a variety of possible uses for engineered fractals in addition to the fluid transport discussed here. Many fields of engineering involve fluids and engineered scaling control by the use of fractals should be generally applicable.

As one example, the University of Cambridge Department of Math and Theoretical Physics has recently initiated a study to establish the feasibility of modifying the multiple scale structure of turbulence in a controlled manner using fractal grids (6). We have constructed a number of fractal objects of varying dimension for these studies.

### Conclusions

Scaling and distribution are very general fluid handling requirements and apply to processes which require mixing and/or geometry transitions. Fractals are by definition deeply scaled and therefore address certain problems of scaling in a direct and logical manner. In some cases, an engineered fractal can be an effective functional substitute for turbulence. In general, engineered fractals can provide precise control of scaling and distribution and therefore can enhance the efficiency of fluid processes.

## References

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