# Engineered Symmetries Force Process Efficiencies

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## Introduction

The goal of this paper is to present a new general approach to understanding and implementing process efficiencies. This approach is based on the concept of symmetry. Results can be used to improve processes and to drive innovations.

## Symmetry discussion

Is there a general analytical tool which is applicable to many of the diverse aspects of process efficiency? This paper will argue that symmetry provides such a tool. Symmetry can be defined as immunity to possible change. Figure 1 illustrates this concept with examples of plane symmetries.

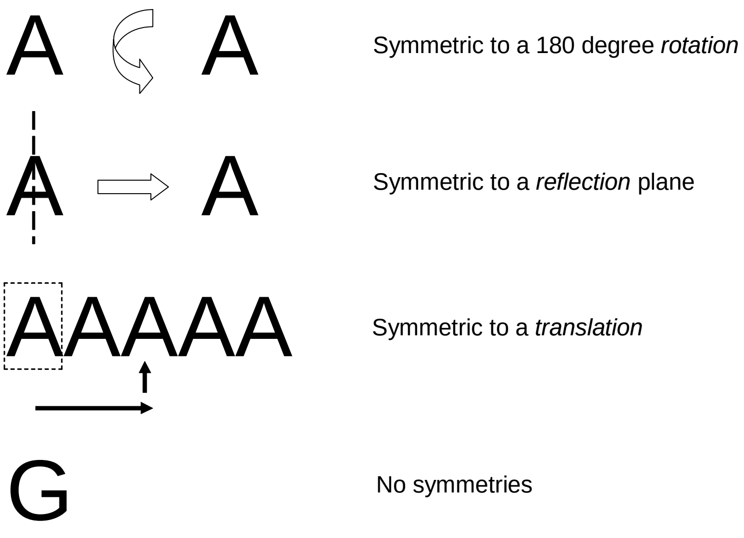


Figure 1. Example of plane symmetries.

Another example is illustrated in Figure 2. In this case a checkerboard pattern increases in symmetry as smaller and smaller squares are used for the pattern.

Figure 2. Checkerboard symmetry increases as squares are made smaller. The number of possible symmetry operations which leave the checkerboard the same increases. At infinitely small squares, the checkerboard is completely symmetric to all translations for any arbitrarily small square size.

Symmetry applies not only to geometric objects, but rather, to any characteristic under consideration. For example, a sine wave exhibits symmetry with to respect time. A symmetric translation of the wave from trough to trough can be made (Figure 3).

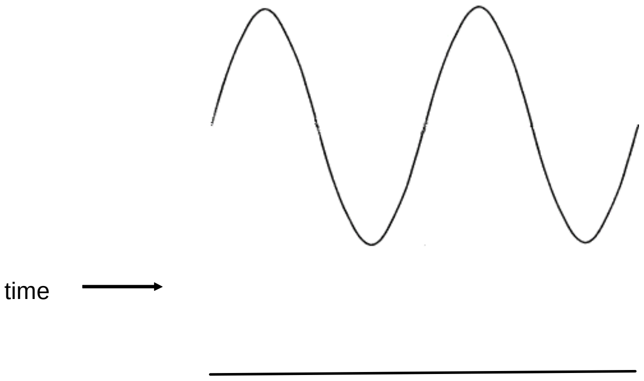


Figure 3. A sine wave exhibits symmetry over time, but less symmetry than the straight line which is symmetric to translation of any point to any other point.

As another disparate example, a very useful symmetry to an astrophysicist is symmetry of the Universe with respect to the laws of nature. A laboratory transported to any location in the Universe would determine the same laws. In general, a particular aspect of a situation can be chosen and if this particular aspect remains the same under a change, the situation is symmetric under the change with respect to that aspect (1).

## Process efficiencies

For this paper, process refers to any process or series of actions in general, not only engineering unit processes. Efficiency improvements are considered to cover a broad range and include, among others:

Less energy use
Smaller equipment
Ease of operation
Higher productivity
Lower costs
Reduced material handling
Ease of process scale-up
Simpler process control hardware and software
Simpler process analysis and modeling
Simpler process description and understanding
Reduction of human/computer time and effort

## Process elements

For this paper, process elements are defined as any disparate aspects of a process which can be evaluated with symmetry concepts. This is essentially anything to do with the process. For example, processing elements may be flow configuration, control software, equipment layout, chemical media, operating mode, etc.

## Symmetry analysis of a process

What does the alteration of aspects of a situation such that the result is the same as the initial situation have to do with process efficiency? To understand this, an argument will be made with the use of a specific example. Symmetries will be described for elements of an ion exchange system. For each symmetry, the specific, ordinarily understood explanation for the process improvement is described. In each case the improvement is a symmetry increase.

### 1. Vessel flow

Figure 4 illustrates two possible ion exchange column configurations. The small dark rectangles represent some type of fluid distributor and collector. The figure to the left represents the ion exchange column operating with flow in the horizontal direction while in the column to the right the flow is vertical. In the column to the left, without high pressure drop, the flow will be uneven. The ion exchange resin could also classify in an undesirable way. The purpose of this example is to demonstrate that even in this obvious case the much preferred configuration of the flow is one in which the process exhibits symmetry. The preferred vessel flow configuration is one which is symmetric with respect to the gravitational field.

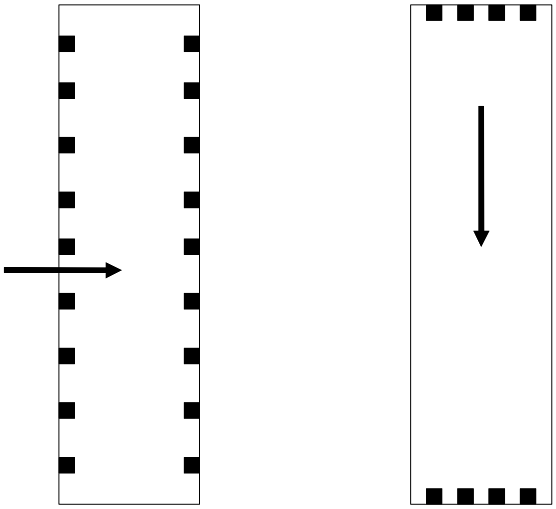


Figure 4. Possible flow directions in a vessel.

*Symmetry increase 1: Vessel flow symmetry*

*Process efficiency in vessel design is increased by configuring the vessel with flow symmetric with respect to the gravitational field.*

## 2. Distributor flow

Conventional fluid distributors and collectors, such as radial or lateral types, are generally designed using pressure drop considerations. Figure 5, to the left, illustrates such a distributor. In this case flow travels to orifices located along the laterals. These devices have different path length and hydraulics to the various orifices. They operate best over a narrow range of flowrates. Because ion exchange involves steps at variable flow rates, this can be detrimental to operation. Also, at too slow flow rate, the majority of the liquid may exit the orifices closest to the main plenum. Further, exiting fluid will exhibit a time lag between exit points due to the variable path length to exit points so the distributed fluids can be somewhat "bowed" as they enter the system. This can result in a spreading of concentrations of the exiting fluids. For example, the waste regenerant may be more dilute and a larger volume than necessary.

Such devices can be replaced by a distributor which depends upon symmetry rather than the expenditure of energy. Figure 5, to the right, illustrates a simple symmetric distributor. Fluid enters the center of the device and travels with equal path length and hydraulic symmetry to the eight exit points. The device is not dependent upon flow rate and pressure drop can be negligible. (Note: Only the hydraulic symmetry concept is illustrated, less exits are shown for the symmetric distributor - this can be increased using more symmetric "legs").

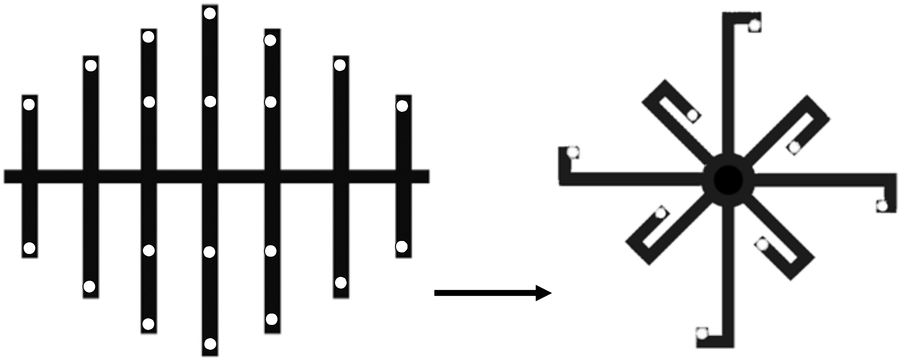


Figure 5. An asymmetric distributor is replaced with a hydraulically symmetric distributor in order to provide flow equally to all exits and to eliminate energy use.

*Symmetry Increase 2: Distributor hydraulic symmetry*

*Process efficiency due to distributor performance is increased by using a distributor based on symmetry rather than pressure drop. A very large flow turndown is provided, distributor "bowing" caused by time lag to exit points is eliminated and energy use is reduced.*

### 3. Resin size

Monospheric resins are preferred for highest efficiency. A reason is that the diffusion path length in a population of monospheric resin will be the same so that the exiting profiles, such as regenerant rinse, will be relatively sharp compared with those obtained using a resin population containing a variety of bead size. The result can be less dilute liquid fractions and less liquid quantities. This can save evaporation costs, handling/transportation costs, downstream equipment size etc. A monospheric population of beads is symmetric with respect to bead size. Figure 6 illustrates bead populations with a large spread of bead size and to the right, a monosphere population.

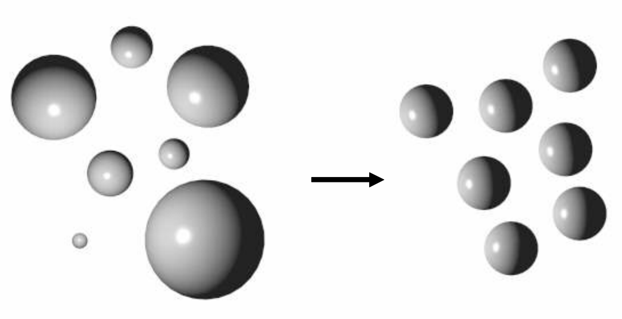


Figure 6. The resin population to the left is asymmetric with respect to size. The population to the right is symmetric to size.

*Symmetry Increase 3: Resin size symmetry*

*Process efficiency related to product quantity and concentration is increased by using a resin symmetric to size. Pressure drop is also reduced.*

### 4. Resin-void

An ion exchange resin can be made more efficient by using smaller particle size. Because of shorter diffusion path and higher surface area, kinetics are quicker and a smaller amount of resin can be used with shorter cycle time. System size can be decreased. The smaller resin size can also provide sharper exiting stream profiles. This leads to more concentrated material and less quantity. These are energy and handling reductions.

A smaller bead population has greater resin-void symmetry than a larger bead population. This can be understood by comparing the large and small bead populations in Figure 7. The small bead population has many more possible bead translations which will leave the population the same. This increase in symmetry can also be recognized by comparison with increasing checkerboard symmetry.

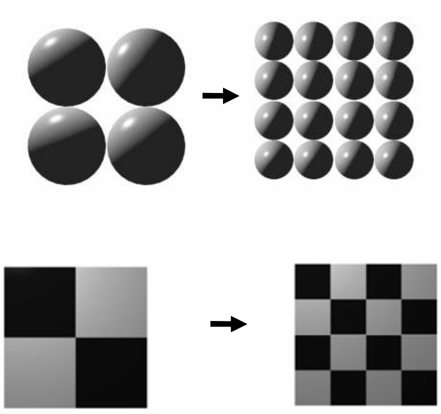


Figure 7. Resin-void symmetry increase.

*Symmetry Increase 4: Resin-void symmetry*

*Process efficiency related to product quality and quantity and energy use is improved by increasing the resin-void symmetry.*

### 5. Resin bed pressure

The system improvements discussed to this point tend to drive the design towards implementation of another symmetry. Although the system has very fast kinetics, primarily due to the small resin, it may not be possible to take advantage of the configuration due to high pressure drop developed as the specific processing rate is increased. By using smaller resin and higher flow rate, a pressure asymmetry will be forced on the resin bed (pressure drop). It will be necessary to consider adding another symmetry in order to continue the optimization.

How is a symmetry added to the now problematic pressure profile of the resin bed? One way pressure symmetry can be imposed is by spreading out the resin in a flat , horizontal configuration. For the same specific flow rate, this reduces the linear velocity and provides a shorter distance for pressure drop to develop. The bed will now exhibit close to the same pressure at any resin bed location. Therefore, pressure drop does not exist. Figure 8 illustrates the reduction of bed depth and subsequent increase in resin bed pressure symmetry. A sample of pressure taken anywhere in the short resin bed can be expected to be about the same as the pressure taken anywhere else in the bed.

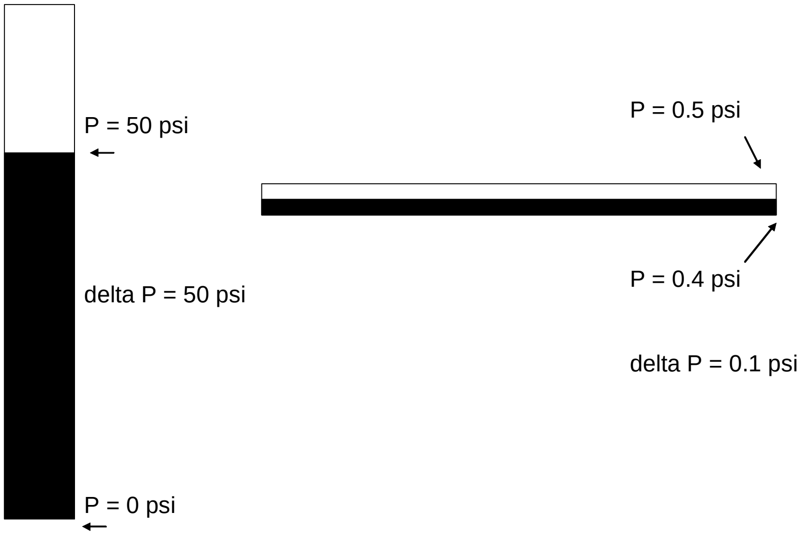


Figure 8. Pressure symmetry is increased in an ion exchange resin bed by using a spread-out flat configuration.

*Symmetry Increase 5: Bed pressure symmetry*

*Process efficiency related to bed pressure drop is increased due to an increase in bed pressure symmetry. The system can operate with less pressure drop so the ion exchange system can operate at a higher specific flow rate (flow rate per unit of resin), system size is reduced and less energy is used. Overall system pressure is lower so the vessel can use thinner walls and less structural support - reducing material and construction costs.*

### 6. Fluid momentum and turbulence

As bed depth is reduced to take advantage of smaller resin, the effect of poor distribution becomes critical. Flow may channel or resin dead spots may exist due to a poor coverage of the bed by a small number of distributor exits. Turbulence due to jetting of the high flow from distributor exits will disturb the bed and cause leakage and a spreading of exiting concentration profiles. High flow rate through the small number of exits in the symmetric distributor of Figure 5 will certainly exhibit these problems. Additional symmetry is now needed for this process element. In particular, the flow momentum within the column should be symmetric.

This problem can be addressed by adding additional smaller iterations of symmetric structure to an existing symmetric distributor. Figure 9 illustrates the progressive construction of smaller scale structure added to an initial "H" type symmetric distributor (the "H" type is easier to illustrate than the symmetric distributor in figure 5). This provides an increase in fluid momentum symmetry over the exit plane of the distributor. Symmetry operations - rotations, reflections and translations are used for this construction. Figure 10 illustrates the increasing symmetry of the fluid flow from the exit plane of the distributor.

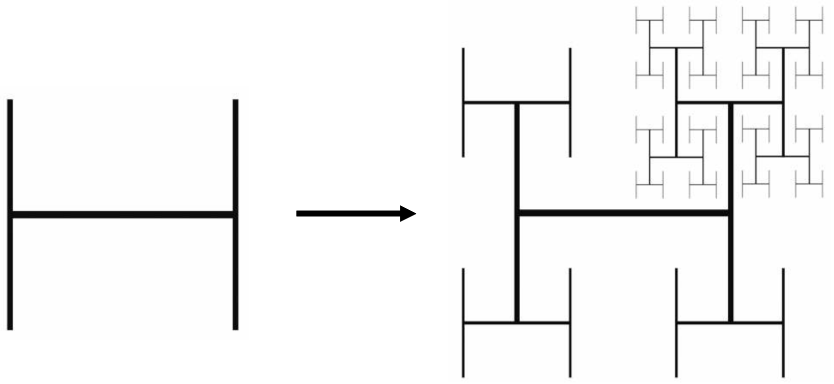


Figure 9. The progressive increase in distributor symmetry by addition of smaller scale symmetric structure. The result is a fractal.

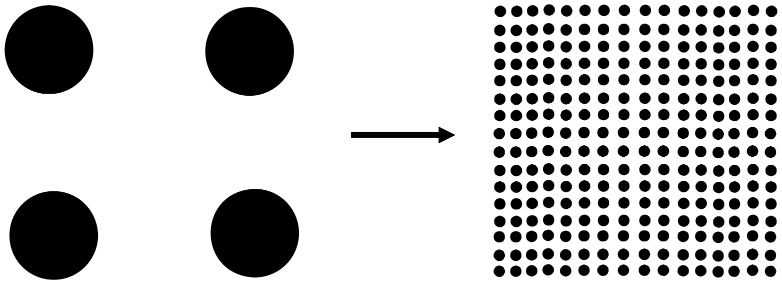


Figure 10. As smaller scale symmetric structure is added to the distributor, the exit plane flow symmetry increases (compare checkerboard symmetry). The size of dots represents fluid momentum from each exit (not the size of an exit). In this example, the exiting momentum from an exit point is reduced by the factor 1/64. As a result, turbulence is significantly reduced.

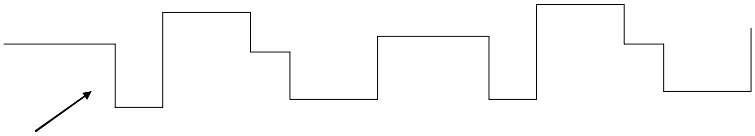
### *Symmetry Increase 6: Flow momentum symmetry*

*Process efficiency related to fluid distribution can be improved by adding smaller and smaller scale hydraulically symmetric structure. The flow momentum becomes progressively more symmetric (gentle flow at any point rather than variable velocities). Turbulence - a very asymmetric and energy dissipative phenomena - is progressively eliminated.*

Observation: Note that in the last two examples the motivation for introducing increased symmetries was the appearance of new asymmetries caused by symmetry additions. The use of smaller resin revealed a bed pressure asymmetry which was addressed to provide additional efficiency and the "flat" resin bed revealed a serious flow momentum asymmetry which was also addressed. This procedure of adding new symmetries to reveal asymmetries with subsequent addition of more symmetries can drive a process toward higher and higher efficiency.

## 7. Operating mode

Continuous systems are preferred to batch processes. The advantages include consistent product quality and ease of operation. For ion exchange the benefits also include less regenerant, less waste and higher exiting concentrations. In Figure 11 a repeating ion exchange batch process is illustrated. The measurement illustrated may be a particular flowrate or other parameter. The process exhibits symmetry over time as seen in the repeating pattern. This time based symmetry can be increased by using a continuous process. A continuous process for the same parameter is shown as a straight line below the batch process. A translation of any point on the time function can be translated to any other point. Although not ordinarily described in this manner, this is an increase in symmetry.



A repeating batch process

A continuous process - The process has increased symmetry over time

Figure 11. A comparison of batch and continuous operation symmetry.

*Symmetry Increase 7: Operating mode symmetry*

*Process efficiency related to consistent product quality and regenerant use can be improved by increasing the symmetry of the operating mode.*

## 8. Control loop tuning

Certainly any flow rates, tank levels etc. associated with an ion exchange system will be tuned as a matter of course. Tuning a PID loop to obtain a constant flowrate is simply the introduction of a symmetry over time. Figure 12 illustrates a tuned and untuned PID loop.

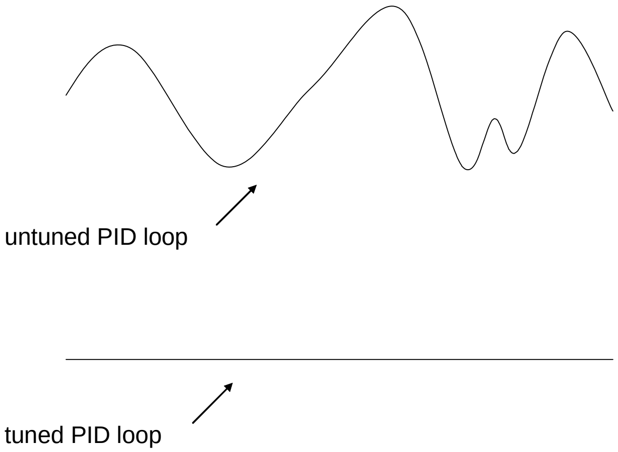


Figure 12. Tuning control loops is introducing process symmetries over time.

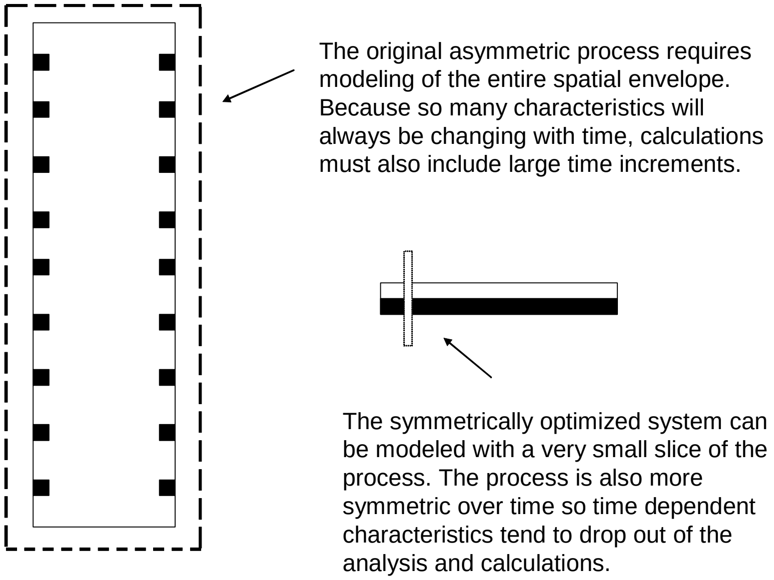
*Symmetry Increase 8: Control loop symmetry*

*Process efficiency related to consistent operation can be improved by increasing the symmetry of the control loops. Additional symmetry over time is introduced.*

## 9. System analysis and CFD modeling

Although a CFD (computational fluid dynamics) model of the original ion exchange system with large turbulent jets, large pressure gradients, channeling and other chaotic aspects would be very interesting, it would also be extremely difficult and time consuming to develop and solve. On the other hand, if the entire process were symmetric over small volumes and short periods of time, which the final improved design approaches, a relatively simple analysis can be done. Figure 13 illustrates the relative amount of the process which must be modeled for the initial asymmetric ion exchange process versus the symmetric process.

Note that the reduction of effort is in both the spatial dimension (smaller volumes used for analysis since all characteristics of volumes are the same) and in the temporal dimension (since the process is the same at any time). This saves both human and computer effort. This is another example of how symmetries add efficiencies to the overall process - in this case, the associated analysis and modeling.



The original asymmetric process requires modeling of the entire spatial envelope. Because so many characteristics will always be changing with time, calculations must also include large time increments.

The symmetrically optimized system can be modeled with a very small slice of the process. The process is also more symmetric over time so time dependent characteristics tend to drop out of the analysis and calculations.

Figure 13. Comparison of symmetric and asymmetric analysis/modeling.

Similarly, symmetry results in the process being described in a simpler manner and it is easier to understand the process.

*Symmetry Increase 9: Modeling/analysis symmetry*

*Process efficiency related to analysis and modeling can be improved by increasing the symmetries of the process. Analysis/calculations become simpler. Process description is simpler and easier to understand.*

## 10. Process scale-up

Scale-up of processes is often a difficulty. Efficiency can be lost as a process moves from lab scale to pilot scale to full scale. For example, the operation of the lateral distributor in Figure 5 becomes worse with scale-up because exit points become more and more hydraulically differentiated.

Maintaining smallest scale symmetry provides a logical path to process scale-up. The distributor in Figure 9 can be easily scaled-up by maintaining the illustrated smallest scale symmetric structure and simply adding larger scale "feeder" symmetric structure. In this case, additional "H" type structure can be added. By this means, the desired flow momentum symmetry will be maintained for any size device.

Another way to understand the use of "smallest scale symmetric structure" is with reference to Figure 13. The small slice of the symmetric process can simply be repeated to produce a device larger and larger in size while maintaining the symmetry of the original slice.

*Symmetry Increase 10: Scale-up symmetry*

*Process efficiency related to process scale-up can be improved by maintaining smallest scale symmetries. Symmetry provides a logical path to scale-up.*

## A symmetry based fractal weak cation ion exchange softener

Full scale weak cation softeners have been constructed which incorporate most of the symmetries, but not all, discussed above(2). For example, these are batch systems not continuous. These softeners typically operate with exhaustion as high as 500 bed volumes per hour. A conventional weak cation softener typically operates at about 50 bed volumes/hour. The resulting softener is about 10% the size of a conventional weak cation softener and about 2% the size of a conventional strong cation softener.

There is no measurable pressure drop across the hydraulically symmetric fractal distributors. Although specific flow rate is extremely fast, bed pressure drop is negligible. Due to fluid momentum symmetry within the vessel, there is no disturbance of the resin bed from turbulence. Internal pressures are so low that a non-coded vessel may be used and flow can be provided by a head tank rather than by pump. Processes based on symmetry principles may appear quite different in appearance compared with conventional equipment. Figure 14 illustrates a short bed "fractal softener". This unit is 5 feet across with a six inch resin bed depth. It operates at a maximum of 700 gpm.

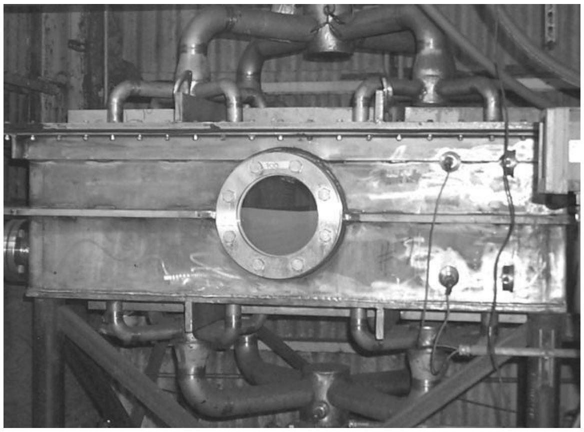


Figure 14. The fractal softener involves the use of several symmetries including bed pressure symmetry and flow momentum symmetry (Amalgamated Research Inc.).

## The symmetry-efficiency connection

The ion exchange discussion demonstrates the broad connection between symmetry and process efficiency. What is generally responsible for this connection? It is helpful to consider a simple description of what the addition of symmetry does. It makes everything "the same" for the aspect of interest.

If the interest is pressure drop through a resin bed, absolute pressure symmetry of the bed, by definition, means pressure is the same everywhere so pressure drop cannot exist. Therefore energy will be saved. Absolutely symmetric PID control loops are, by definition, the same over time. Therefore the system is under control and a consistent product will be produced. An absolutely symmetric fractal distributor provides, by definition, the same exiting fluid momentum at any point on the exit plane. So there is no inhomogeniety of the flow. An absolutely symmetric monosphere resin will, by definition, exhibit the same diffusion characteristics for all beads. Therefore there will be less spreading of exiting fluid profiles and less energy will be used for concentration.

For some cases, Figure 15 provides a useful way of understanding the symmetry-efficiency connection. This figure illustrates that a less spread parameter (narrower distribution) is more symmetric to a measured value. For example, the decreasing spread could represent the exiting concentration of an ion exchange regeneration rinse profile with increasing symmetry caused by using a monosphere resin or a smaller resin size. Or it could represent measurement of profiles for calculation of theoretical plates resulting in increased efficiency in a chromatography application. Or, as in Figure 16, the profiles could represent the increasing flow symmetry and efficiency as smaller scale structure is added to a fractal distributor. Evaluating the outcome of process elements in such a manner can reveal system asymmetries and help provide an understanding of symmetry effects. The outcome is a reflection of the symmetry of the process element leading to the outcome.

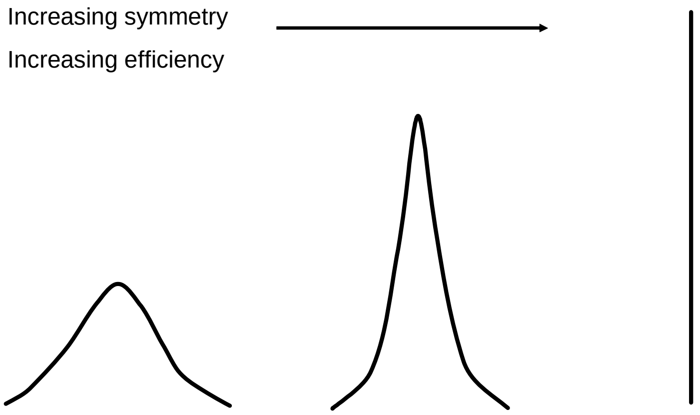


Figure 15: A less spread profile of a parameter is more symmetric to the measured value. This can be either a spatial or temporal symmetry.

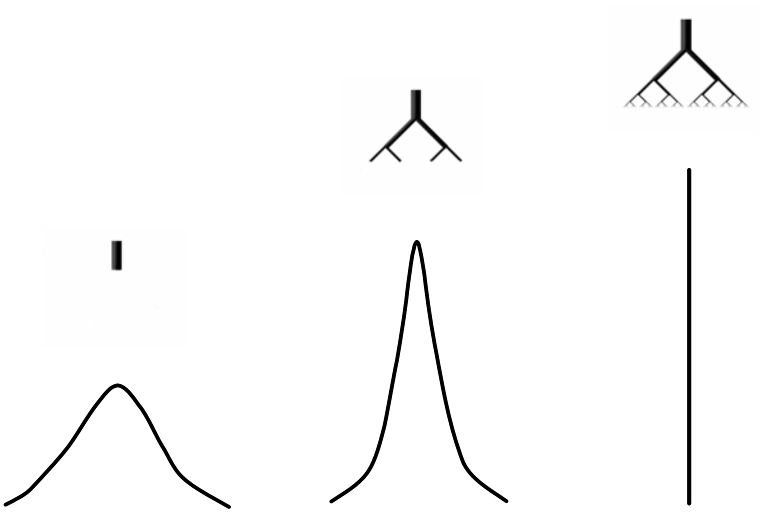


Figure 16: Increasing fractal distributor symmetry (adding smaller scale structure) narrows the distribution of fluid properties such as velocities (turbulence), bubble size, etc.

So far in this discussion, for every case of symmetry increase, the desired outcome of the process element was symmetric. Later in this paper, the special case of necessary asymmetric outcomes will be discussed.

**Process innovation - symmetries and process disappearance**

As an example of the innovation enabling effect of symmetries, with the fractal weak cation softener a design loop can be evaluated wherein increases in symmetry allow the resin bed to approach zero size.

First in conventional terms:

```
BEGIN:
Reduce resin size to obtain faster kinetics.
Reduce resin bed depth to reduce pressure drop due to the smaller resin. Do this by eliminating resin.
Add additional fractal distributor scaling for better distribution and less turbulence over the shorter bed.
Shorten cycles.
GOTO BEGIN
```

Stated in symmetry terms:

```
BEGIN:
Increase resin/void symmetry.
Increase bed pressure symmetry.
Increase fractal distributor symmetry.
Shorten cycles.
GOTO BEGIN
```

A practical decision must be made concerning when to stop shrinking the resin bed. Note that in the loop above, peripherals such as pipe and valves do not change in size so there is no benefit with respect to these items. Also, cycle times become shorter and shorter and there are good reasons not to exhaust the bed every half second with associated valves opening and closing so quickly.

On the other hand, and perhaps the most useful aspect of the disappearance via symmetry observation, entirely new system designs may come into play which specifically take advantage of the new symmetries and allow process intensification to continue. The use of deep symmetry allows an engineer to work within a large range of possibilities for the design of an efficient and practical device.

(Note: The "disappearance" effect is common when symmetries are added and extend to process aspects which are ordinarily not clearly connected. For example, recall the reduction in CFD/analysis effort required for the symmetric process in Figure 9).

## Fluid turbulence

This section will discuss in detail a particular instance of asymmetry in order to make the argument of this paper more clear. This asymmetry is turbulence - the exemplar of asymmetric phenomena. It is interesting, in light of the conclusions in this paper, that it is employed to obtain outcomes which are symmetric. To understand this point, refer to Figure 17. In this case, an impeller transfers large amounts of energy to a vessel for mixing components A and B. Energetic, asymmetric turbulent eddies are forced on the system. The end result is a symmetric outcome - the solution is mixed. The eddies eventually dissipate as heat. If faster mixing is desired with the same equipment, the procedure is usually to create even more energetic turbulence. With respect to efficiency, this method is in direct contradiction to the premise of this paper that a symmetric outcome can be obtained more efficiently by increasing the symmetry of the appropriate process elements.

Recall the asymmetric lateral distributor. Its design is based on pressure drop and therefore energy loss in order to operate properly. Another example was the use of an asymmetric population of resin. Such a resin can result in spread out exit profiles and more dilute, voluminous products which require additional energy to concentrate, handle or transport. This paper argues that efficiencies related to energy use are hindered whenever a less symmetric approach is used to force a symmetric outcome. If the symmetry hypothesis is correct, using turbulence for mixing is inefficient (this is not to disregard the usefulness of turbulence at the smallest scales, where heat and mass transfer occur or where conditions require the use of turbulence for practical reasons).

In addition to high energy use, turbulence can result in inhomogeneous process conditions. For example, in a large impeller mixed reactor, temperature, concentrations and reaction conditions may be quite variable throughout the volume.

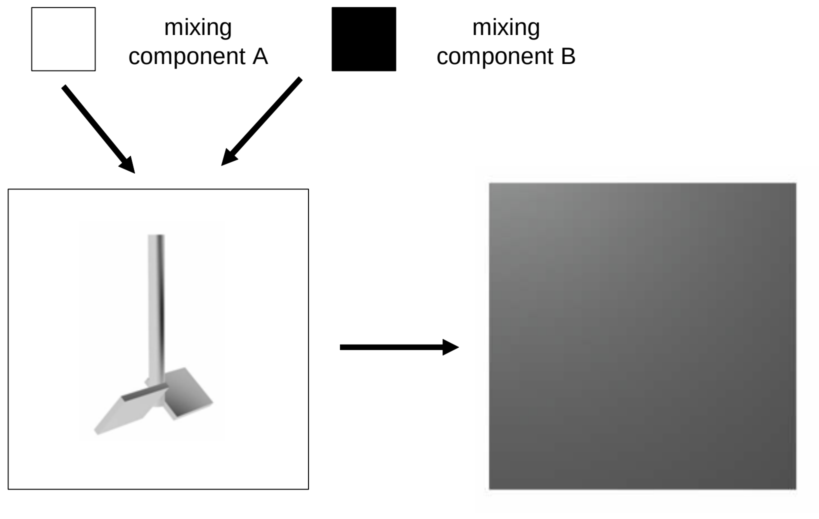
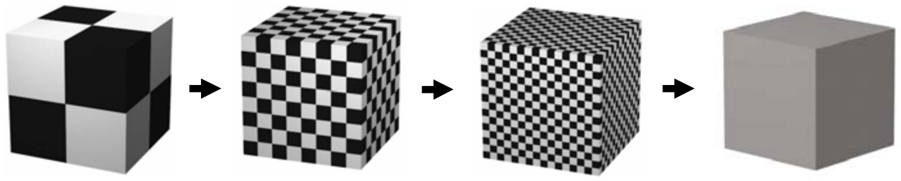


Figure 17. Asymmetric, energy intensive impeller mixing results in a product symmetric to the distribution of A and B.

The symmetry hypothesis of this paper suggests that addition of symmetries to the mixing process will be beneficial. Figure 18 illustrates a favorable increase in the symmetry of mixing components A and B *prior* to employing an asymmetric process element (turbulence). For example, this could represent an increase in symmetry occurring by some presently undefined procedure *before* turning on an impeller.

Consider how little subsequent turbulent energy would be required if the initial conditions were, for example, Symmetry 3. In fact, Symmetry 4 is the completely mixed state with no turbulence used at all. Of course, the problem is how to actually approximate these states.



Symmetry 1 Symmetry 2 Symmetry 3 Symmetry 4

Figure 18. Initial conditions for mixing components A and B *prior* to using turbulence for final mixing.

A solution discussed in previous papers is to use structures referred to as "turbulence alternatives"(3,4,5). These are low pressure drop symmetric fractals. They substitute symmetric scaling and distribution for the asymmetric scaling and distribution of turbulence. Figure 19 illustrates a fractal appropriate for increasing the symmetry of a mixture prior to final mixing. For example, the device can be used to distribute fluid A into fluid B while at the same time spinning as a low energy impeller (Note that the checkerboard pattern in this and all following examples is just a qualitative indication of an increase in symmetry - no such patterns could actually form).

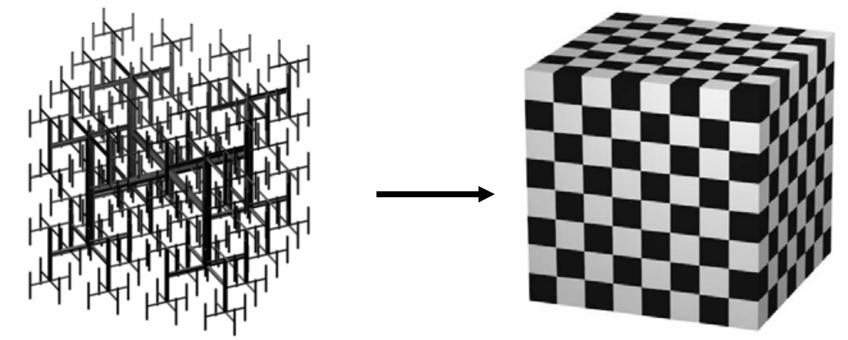


Figure 19. A low pressure drop fractal used as a fluid distributor and impeller can provide a more symmetric mixture prior to energy addition. Therefore overall energy required is reduced.

Figure 20 illustrates a second method to force symmetry on a mixing system. In this case, two fluids are simultaneously scaled prior to mixing by the use of offset fractals. Note that both fluids are "mixed" before they contact one another. By adding symmetry to both fluids in the system, the asymmetry of turbulence is avoided and mixing is more efficient with respect to energy use. The symmetry eliminates the non-uniformities observed with impeller driven mixing. These non-uniformities can include concentration, temperature, turbulent intensity etc.

Also, because of the overall system symmetry, a desired change in mixing/reactor conditions can be realized nearly instantaneously as opposed to an asymmetric system where system inertia and inhomogeniety may require a significant amount of time before a change is observed everywhere in a vessel. This means the fractal mixer/reactor is more symmetric over time - a change in conditions, such as temperature or concentration occurs everywhere at the same time.

Finally, it was previously indicated that faster mixing is obtained with turbulent methods by increasing the energy input per unit time (if the same device is used). For example, impeller RPM is increased or components are shaken more violently. How is the mixing rate increased with a fractal mixer? This is accomplished by increasing the symmetry of the device. For example, by using smaller and smaller structure allowing closer approximation of a completely symmetric checkerboard. Figure 21 is a close-up photograph of an offset fractal mixer/reactor.

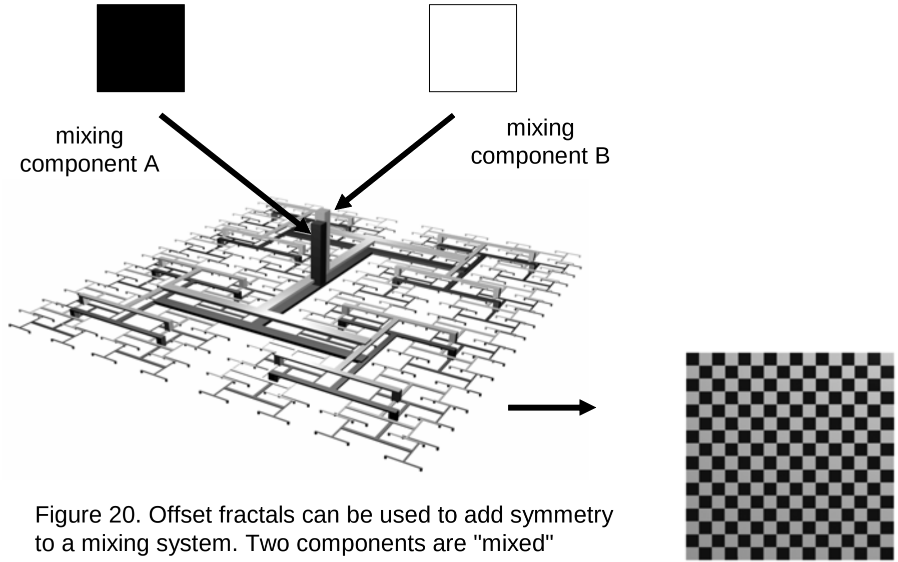


Figure 20. Offset fractals can be used to add symmetry to a mixing system. Two components are "mixed" before they contact one another.

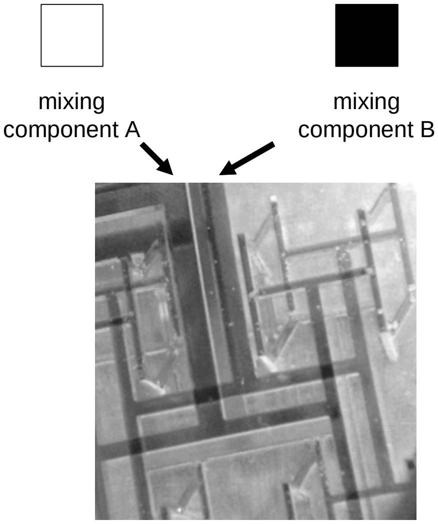


Figure 21. Close-up photograph of the final channels of an offset fractal mixer/reactor (Amalgamated Research Inc.).

Although fractals were used in these mixing examples, they are only one category of structure for forcing symmetry on an otherwise turbulent process. It is suggested that the usual way of using large scale turbulence does not contradict the symmetry/efficiency hypothesis. It is perhaps more likely that large scale turbulence is very often used in an unnecessary, inefficient manner.

## Asymmetric processes

There are processes which require an asymmetric outcome. For these cases, the process forcing should address the asymmetry. An interesting example is clarification (separation of solids from liquids) because this process can gain efficiency by both increasing the symmetry of elements for which a symmetric outcome is desired and by increasing the asymmetry for elements for which an asymmetric outcome is desired. Figure 22 illustrates a continuous introduction of clarifier feed wherein the incoming fluid forms a completely symmetric surface with respect to velocity (no turbulence disturbance).

If this symmetry could be practically implemented, it would lead to much smaller equipment operating under rapid separating conditions. However, for a clarifier, it is also necessary that the subsequent final outcome be asymmetric. Solids move to the bottom of the clarifier and clear liquid moves to the top. This final solids/liquid distribution is asymmetric compared to the starting homogeneous solid/liquid feed material.

Where an asymmetry is required, forcing asymmetries is appropriate. Note that an asymmetry is not desired in velocities of the fluid (turbulence and its associated chaotic accoutrements are not desired) but rather between the liquid/solid components. The liquid-solids difference in density provides an asymmetry which will lead to separation in a gravitational field. The asymmetry can be increased by a settling aid which further reduces the liquid-solids symmetry of the solution (Figure 23).

Summarizing some of the main process elements for improved clarification in terms of symmetry:

1. Create a symmetric velocity condition for the fluid introduction.
2. Use settling aid to increase asymmetry in the liquid-solids mixture.
3. Use gravity to completely eliminate the liquid-solids symmetry.

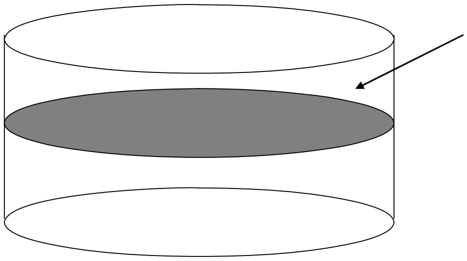


Figure 22. Clarifier operation can gain efficiency by increasing the velocity symmetry of the fluid introduction. Additional symmetry can be added by including symmetric collection of liquid and solids.

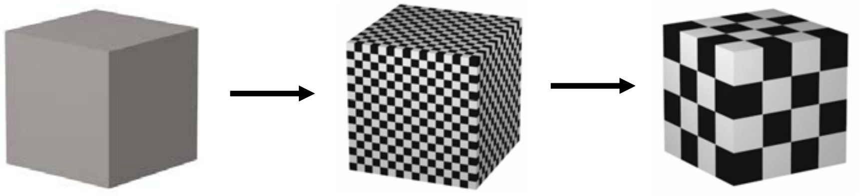


Figure 23. Adding a settling aid to a clarifier solution increases solution liquid-solids asymmetry and increases the efficiency of settling.

Processes which contain an asymmetric element include separations, such as clarification and chromatography. Essentially all the process elements in chromatography require a symmetric outcome, many the same as in the ion exchange example. Only the differential migration of components through the chromatographic media is a desired asymmetry. If the asymmetry of the media with respect to component affinities can be increased or by some other manner magnify the asymmetry, the chromatography process will be more efficient.

## Conclusions

A commonality has been determined which applies to diverse aspects of process efficiency. This commonality is symmetry. As a working hypothesis, this paper proposes that increasing symmetries or asymmetries is a general manner of addressing a wide variety of disparate process efficiencies.

It is suggested that a process be separated into individual elements and these elements be evaluated for two cases:

Case 1.

The desired outcome of the process element is symmetric. In this case, process efficiency is improved by increasing the symmetry of the process element.

Case 2.

The desired outcome of the process element is asymmetric. In this case, process efficiency is improved by increasing the asymmetry of the process element.

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