Understand Flow Patterns in Glass-Lined Reactors

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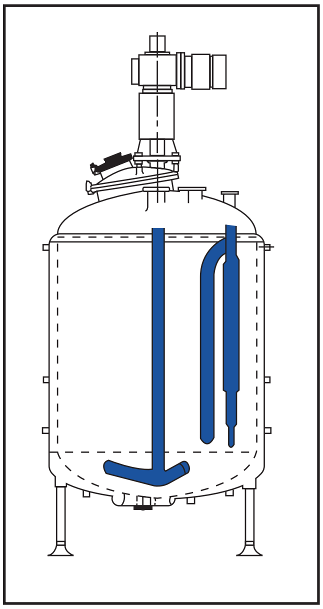
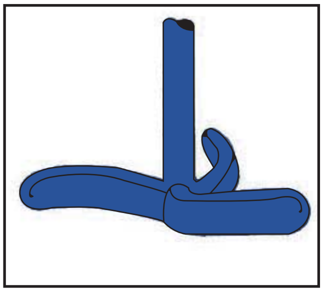
Physical modeling and computer simulation provide insights into the performance of a glass-lined reactor equipped with a retreat curve impeller and finger baffle.

Glass-lined reactors are essential process equipment in the pharmaceutical and specialty chemicals industries. A typical glass-lined reactor (Figure 1) includes a retreat curve impeller (RCI; Figure 2) near the bottom of the vessel and usually a single baffle mounted through a nozzle in the vessel head. The RCI with rounded blade corners may limit harmful turbulence effects while maintaining circulation throughout the vessel. Glass lining (the term "lining" is used to refer to the glass coating on the agitator and the inside of the tank) provides corrosion resistance, is easy to clean, and eliminates product contamination.





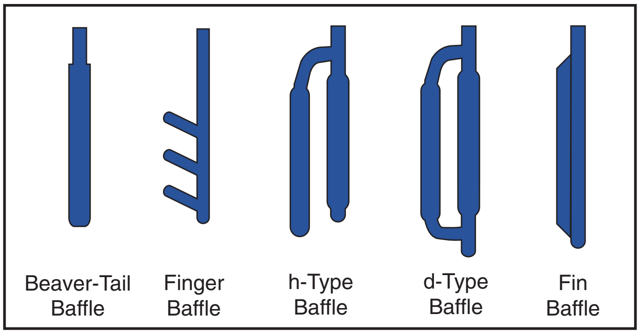
■ Figure 1 (left). Typical glass-lined reactor contains a retreat curve impeller, shown in Figure 2 (right), and a single baffle.

The retreat curve of the RCI blades provides better radial flow than radial flow impellers with similar power characteristics. The impeller is placed near the bottom of the vessel to maximize the allowable range of liquid levels and to produce circulation from the bottom to the top of the vessel. The baffle (occasionally two baffles) is mounted from a nozzle in the top head because mounting to the side of a glass-lined vessel is difficult. The impeller and baffle always have a rounded cross-section without sharp corners because high stresses in the glass can cause the brittle coating to fail.

In recent years, improvements in mixing technology and glass formulations have led to new impeller designs. Many of the impeller styles offered in metal alloy mixers are now available in glass-lined reactors.

However, despite the development of new impeller technology, little has been published about the performance characteristics of the mixing equipment. Even such basic information as power number is rarely found for either retreat curve or newer types of glass-lined impellers.

Computational fluid dynamics (CFD) can describe the three-dimensional flow characteristics of a glass-lined reactor. With proper validation, CFD can be used with confidence to study equipment and process variations. Recent articles on the application of CFD modeling to



■ Figure 3. Glass-lined baffle styles.

mixing studies *(1, 2)* discuss some current modeling capabilities. This article looks specifically at the traditional geometry of a glass-lined reactor.

Key parameters

The two basic variables in RCI-equipped reactors are impeller-to-tank-diameter ratio (D/T) and baffle type.

Usually, the largest possible impeller diameter is selected (up to 70% of the tank diameter). Sometimes the size of the vessel access opening limits the impeller diameter to only 30% of the tank diameter. The traditional RCI is a welded fabrication with a one-piece agitator consisting of a shaft and impeller that must fit through an opening in the vessel. With a full-opening flanged head, opening size is not a problem. With a welded head, which is typical of larger reactors, the shaft and impeller must fit through a smaller flanged opening in the top head.

The one-piece agitator design was necessary until recently to allow for complete glass coverage. Developments involving tighter tolerances and cryogenic shrink fitting have made it possible to install an impeller and shaft separately. The added flexibility of in-tank assembly has reduced the limitations on impeller size and expanded opportunities for different impeller designs.

Various baffle designs (Figure 3) have been offered by different manufacturers through the years. Each design has a different influence on baffle performance.

Baffles mounted from the top head with large-diameter impellers can extend only to a depth above the impeller. A single baffle that does not extend to the impeller depth provides less-than-optimal swirl control, especially in the impeller region.

Some of the earliest published technical information about mixers deals with the power requirement for different impellers. Although the power number relationship was developed in the 1930s *(3)*, more recent work *(4)* forms the basis for most modern impeller technology.

The impeller power number, N_P, is usually defined as:

$$N_P \equiv \frac{P}{\rho N^3 D^5} \tag{1}$$

where P is the impeller power, ρ is the fluid density, N is the rotational speed, and D is the impeller diameter.

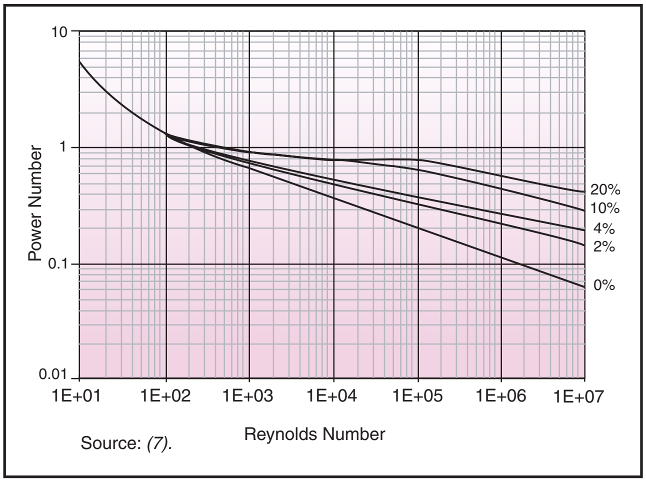
Any coherent set of units or appropriate conversion factors make N_P dimensionless. This dimensionless nature makes the value of N_P independent of absolute size and primarily a function of impeller geometry. The effect of fluid viscosity and any swirling flow is usually handled by an empirical correlation between power number, N_P, and Reynolds number.

The definition of Reynolds number for a mixing impeller differs from a pipe or particle Reynolds number, in that the product of $N \times D$ is used to represent velocity:

$$N_{Re} \equiv \frac{D^2 N \rho}{\mu} \tag{2}$$

where μ is the fluid viscosity. Again, coherent units or appropriate conversion factors will make the Reynolds number dimensionless.

Values for the impeller Reynolds number are also different from other forms of N_{Re}, in that turbulent conditions usually exist for $N_{Re} > 20{,}000$ and laminar conditions occur for $N_{Re} < 10$. The large transition range between turbulent and laminar conditions represents a gradual transition from turbulent conditions near the impeller to laminar conditions near the tank wall. In the transition range, the turbulent regions, especially in the



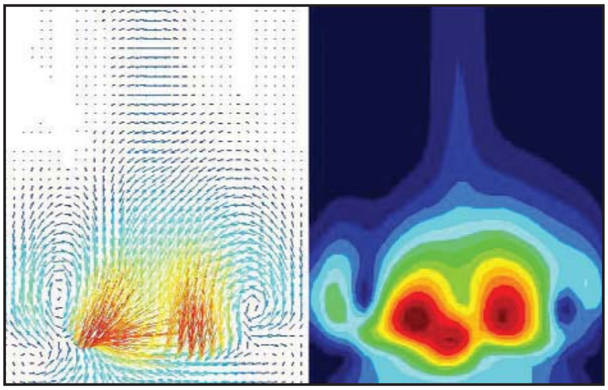
■ Figure 4. Power numbers for retreat curve impellers.

impeller discharge, gradually diminish in size as the Reynolds number becomes smaller.

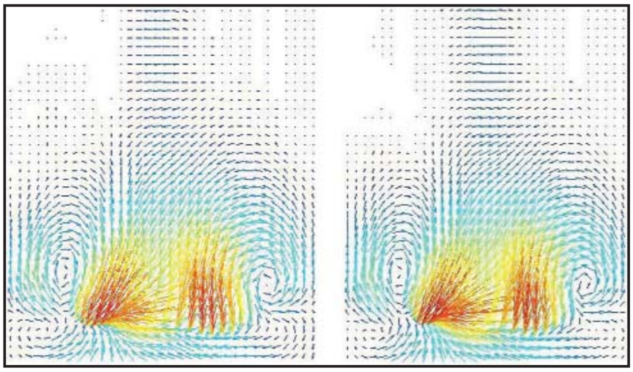
Test results *(4)* show significant differences between impeller power for baffled and unbaffled tanks. The increased power input to a baffled tank is associated with a shift from a rotational flow pattern to a vertical recirculation pattern. Rushton *et al*. *(4)* and Bates *et al*. *(5)* studied straight-blade and curved-blade radial flow turbines. The power numbers for straight- and curved-blade turbines are the same in the turbulent range, with only small differences in the transition range. While the literature provides measured results for many types of fabricated impellers, with and without baffles, little information has been available for the retreat curve impeller traditionally used in glass-lined reactors.

Nagata *(6)* reports power numbers for Pfaudler-style impeller of 0.37 without baffles and 0.73 with baffles. Koen *(7)* provides power numbers for a retreat curve impeller as a function of viscosity (Reynolds number) and baffles, as plotted in Figure 4. Koen looked at baffle width as a percentage of effective area to projected area for a finger baffle. As the baffle width increases, so do the power requirements. Additionally, the power requirements in the turbulent range become nearly constant with larger baffles. This change in power requirements and effect of baffle size must accompany a change in flow pattern. Nagata *(6)* reports pumping numbers (pumping capacity divided by rotational speed and impeller diameter cubed) of 0.23 without baffles and 0.29 with baffles.

Experimental work, especially involving newer impeller or baffle designs, is closely held by the equipment manufacturers.



■ Figure 6. Velocity profile of the experimental system (mean velocity vectors on the left and mean velocity contours on the right).



■ Figure 7. Experimental velocity vectors for baffled (left) and unbaffled (right) systems are nearly the same.

Physical modeling

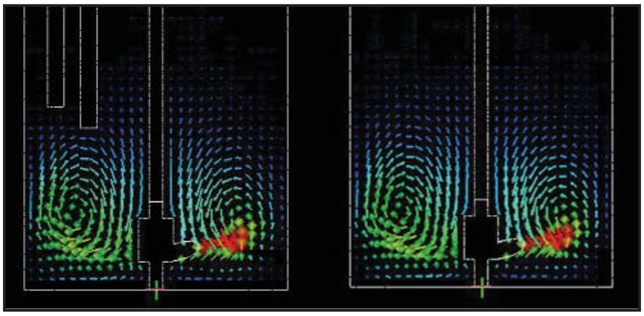
As a means of observing flow patterns and validating the computer model, scale models of the retreat curve impeller and the h-style baffle (Figure 5) were constructed for testing in a 6-in.-dia. (152 mm) vessel. The experiments were carried out with water and a glycerin-type fluid, with two different impeller shaft speeds in baffled and unbaffled configurations. The tests were observed using a particle image velocimetry (PIV) system. Experimental data were taken at several horizontal planes and a vertical plane through the center of the tank. The optical observations were converted into velocity vector diagrams, such as Figure 6. The diagrams were phase-locked with the impeller rotation to observe the flow characteristics with the impeller blades in the same location of the rotation.

■ Figure 5. Impeller and baffle used for experimental physical modeling.

Both optical observations and the vector patterns extracted from the data show strong flow in the impeller region. However, there is almost no difference between the results obtained with and without the baffle (Figure 7). The magnitude of the flow velocities drops rapidly as the distance from the impeller region increases and only shows a significant direction change above the level of the lower tip of the baffle.

The CFD model

The CFD studies were conducted with the program ACUSOLVE; the geometric model and discretization were accomplished using the ICEM/CFD “autohexa” package. A full three-dimensional computational model was employed because of the unsymmetrical arrange-



■ Figure 8. CFD modeling shows that the axial velocity vectors in the impeller region are nearly the same in baffled and unbaffled systems.

ment created by a single baffle. A three-dimensional model of approximately 500,000 tetrahedral elements was constructed to describe the glass-lined reactor problem and numerically describe the fluid motion. Boundary conditions with shapes similar to the retreat curve impeller and h-baffle provided the internal geometry for the model. Both pressure and velocities were calculated at each node (*i.e.,* the apexes of the tetrahedral elements).

The results obtained with the computer model were essentially the same as the results from the experimental model (Figure 8). All of the velocity magnitudes agreed to within 10%. Accurate results were calculated directly without arbitrary parameter tuning for turbulence models, artificial viscosity, etc. The modified parameters were geometric model variations, material rheology models, and tetrahedral element density.

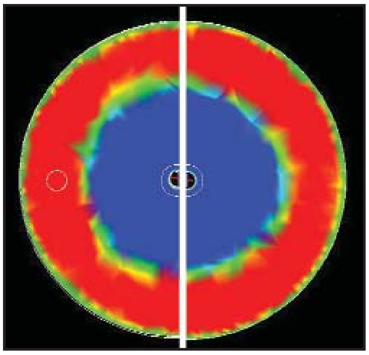
The axial velocities presented in Figure 9 are upward near the wall and downward around the center, as expected with a radial-flow impeller near the bottom of the tank. At a level slightly above the impeller and below the baffle (25% of the liquid level), the velocities with and without a baffle are so similar that they are indistinguishable. The rotational velocities at this level in the tank are also unaffected by the baffle shown in Figure 10.

Higher in the tank, at 40% of the liquid level, the presence of the baffle can be observed in the calculated velocity profiles. The only effect of the baffle on axial velocity magnitude is in the immediate region of the baffle, as illustrated in Figure 11. However, the baffle clearly restricts the rotational velocity in the upper portion of the tank, as shown in Figure 12. This effect of the baffle in the upper portion of the tank is the reason that surface observations do not show a strong swirling motion in the typical glass-lined reactor.

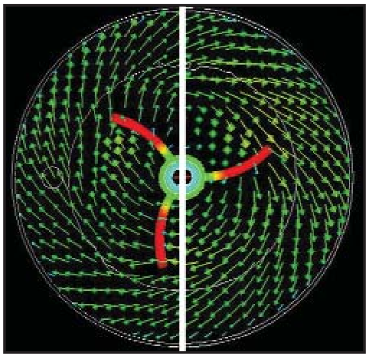
General observations

The fact that both the experimental and computer models reveal little influence of the baffle in the impeller region has both advantages and disadvantages.

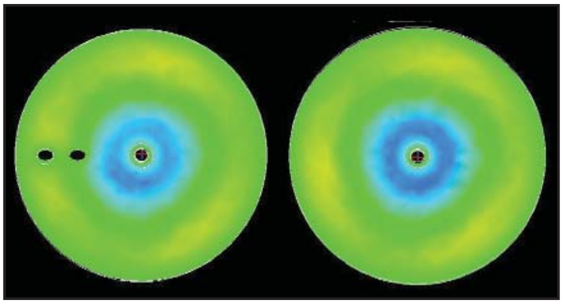
If the baffle controls only the upper portion of the tank, most baffle effects are related to restricted surface motion. Surface motion that creates a strong vortex may have a desired effect of drawing liquid or dry-powder additions into the liquid or an undesired effect of incorporating and dispersing unwanted gas. Control of surface motion is likely to increase with liquid level, but may limit maximum mixing intensity without drawing a vortex.

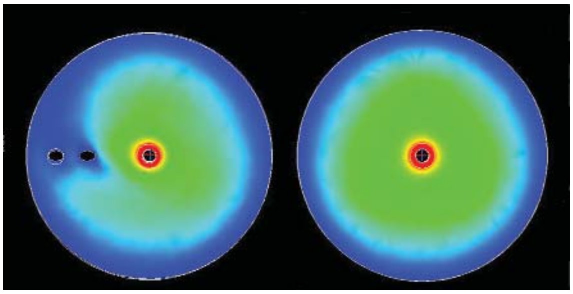


■ Figure 9. Axial velocity magnitudes are almost indistinguishable at 25% of the liquid level (below the baffle).



■ Figure 10. Rotational velocity vectors are unaffected by the baffle at 25% of the liquid level (below the baffle).





■ Figure 11 (above top). The baffle alters the axial velocity magnitudes in the immediate vicinity of the baffle (at 40% of the liquid level).

■ Figure 12 (above bottom). The baffle restricts the rotational velocity in the upper portions of the tank (at 40% of the liquid level).

If the flow patterns in the lower portion of the tank are not influenced by the baffle, then many low-liquid-level mixing characteristics can be similar to full-batch mixing. Turbulent wakes or vortex shedding behind impeller blades, which may influence dispersion characteristics, probably remain unchanged with liquid level. Rapidly settling particles could have a tendency to separate from the liquid swirling in the lower portion of the tank. The rotational momentum of the swirling liquid and the differential mass of the particles would cause separation, as in a centrifuge.

Because the impeller and baffle operate somewhat independently, the type of baffle in a glass-lined reactor may have a stronger influence on process results than in alloy tank applications, where "standard" baffles restrict swirling throughout the tank. The opposite may be true for impeller types, since the rotational motion will develop for any impeller geometry.

Differences in glass-lined and alloy reactor construction also influence mixing characteristics. These differences are both beneficial and detrimental. One of the most perplexing issues is to decide when the differences in mixing performance will affect a process if it must be moved from one type of reactor to another. The more we know about both the mixing and its effect on a process, the more likely a practical solution to a mixing problem can be found.

The work described here, along with Refs. 2 and 8, lends confidence that changes introduced in the model can be used to evaluate other characteristics of glass-lined reactor performance. **CEP**

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