

Vessel geometry considerations for bottom-mount magnetically driven agitators in the biopharmaceutical industry

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ABSTRACT The performance of an agitator mounted on a process vessel is strongly related to the relations between vessel geometry, baffles and impeller characteristics (shape, diameter and location inside the vessel). Magnetically driven agitators have been used widely in the biopharmaceutical industry due to their ability to offer high levels of containment and isolation. Most designs are bottom mount and capable of mixing relatively low volumes inside a pressure vessel in a multi-use system, or inside a bag in a single-use system. In order to be able to mix the lowest possible levels, these designs are typically shaft-less, with the impeller sitting right on top of the bearing assembly. This feature restricts the number of impellers that can be used to one, which in turn restricts even further the possible vessel geometries that can be used to obtain efficient mixing. Furthermore, while in most industries baffles are used to improve mixing pattern, these are uncommon in bioprocess due to the difficulty to clean them. Instead, mixers are installed offset from the center of the vessel to prevent the swirling of the fluid. This also limits the number of possible locations for a bottom mount mixer. This article discusses the recommended vessel geometries for working with bottom mount agitators, as well as the need to create or avoid pulling a vortex.

DISCUSSION

Bottom mount magnetically driven agitators feature an impeller that is driven by a magnetic coupling, rather than physically connected to a shaft. This means that the need to penetrate a process vessel is not required, eliminating the need for mechanical seals and reducing the risk of leaks. By not having a shaft, it is easy to design the process contact surfaces for effective cleaning and steaming in place (CIP, SIP). Once a shaft has been eliminated from the design, the agitator is limited to having just one impeller sitting near the bottom of the vessel. The distance from the bottom may vary from different manufacturers, but it is often no more than 5 mm. Therefore, the impeller can only pump up, which is achieved by a radial flow out of the impellers that would hit the vessel walls, turning in to axial flow. Once the flow gets to the surface, it would come down back to the impeller and out again radially. See figure 1.

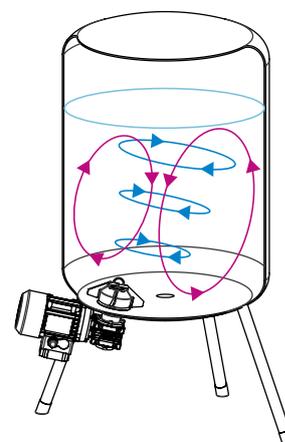


Figure 1 Bottom mount magnetically driven mixer flow pattern.

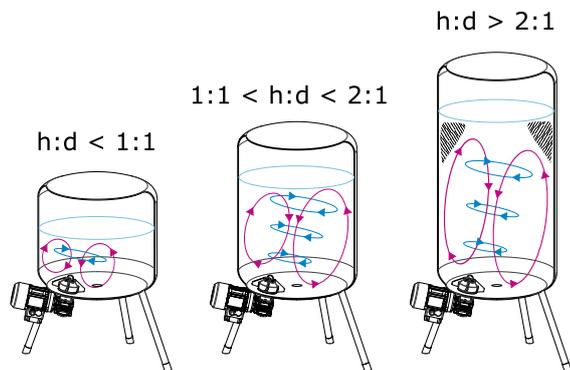


Figure 2 Effects of the h:d ratio on the flow pattern.

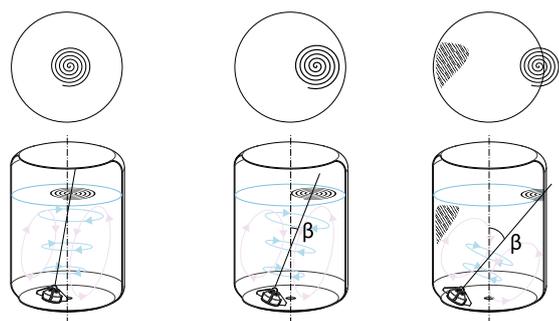


Figure 3 Effects of impeller placement on the flow pattern. From left to right: a) The vortex is along the centerline. The fluid in the tank will predominantly rotate, with reduced mixing performance as a result. b) The center of the vortex is at $\frac{1}{4}d$, rotation and axial flow combine to yield the optimal mixing performance. c) The mixer is too close to the tank wall, this will lead to a 'dead zone' (hatched) where mixing performance is reduced.

Vessel internal diameter and liquid height relationship

For most applications, a ratio of liquid height (h) to vessel internal diameter (d) of 1.5:1 is ideal for unbaffled vessels. A range of h:d from 1:1 to 2:1 is recommended. Refer to figure 2.

Outside of this range, different conditions may occur. If the ratio is below one and the impeller is properly sized considering the vessel internal diameter, a good degree of mixing can be expected, but this configuration inhibits a vortex formation. If the ratio is above 2, for bottom mount magnetic coupled mixers this would mean that it is not possible to create enough momentum in the flow to reach the surface, thus potentially creating zones of different concentration at the top, against the walls. When working with mixer designs without a shaft, this condition should be avoided. Figure 2 shows more details of the results of the different ratios in terms of the mixing flow pattern. In water-like applications, the dead zones depicted (zones with limited movement) are eliminated and the flow is typically turbulent. As viscosity increases (often beyond 1,000 cP, depending on the specific fluid rheology), these dead zones would start to appear and would be more prominent as the viscosity increases and the flow regime turns into laminar. The location of the mixer in the bottom dish also affects the resulting mixing pattern. Refer to figure 3.

A placement in the half radius would give the best location for mixing performance. However, other considerations may be relevant when choosing placement, such as low level mixing. In this case, if trying to optimize low level mixing the impeller would be placed as close as possible to the outlet valve and some loss on mixing efficiency would occur.

Vortex formation considerations

The need to generate a vortex is application dependent. A vortex is not a sign of 'better mixing'. In many cases, a vortex should be avoided as it may entrain air. Process fluids with a tendency to foam are particularly sensitive to this condition. The exception to this rule is when dealing with light powder's incorporation. Solids that tend to float, are hydrophobic and/or can clump would require a vortex to be sucked down towards the impeller. If that is required by the application, then it is extremely important that the h:d ratio selected is not below 1:1, as this will inhibit the mixer's ability to form a vortex. This is a common mistake seen when designing agitated vessels in the biopharmaceutical industry. As there are multiple factors that may govern the vessel geometry, it is important to prioritize those that may have a larger effect on the mixing results. After all, an expensive biopharmaceutical-grade, agitated pressure vessel will become useless if the flow pattern cannot achieve the desired mixing outcome (e.g. incorporation of light solids into solution). Some of the main reasons vessels are designed with a h:d below the 1:1 ratio are related to head room, since the same working volume can be achieved with a shorter vessel. However, the consequences to the process shall be considered carefully. Vortex shape and depth is dependent on the agitator suction rate, the liquid viscosity and the vessel geometry. The dimensionless Froude number is used to describe surface condition and can be related to the formation of surface vortices. It represents the ratio of flow inertial forces to gravitational forces. For agitated vessels, the Froude number can be expressed as (nomenclature explanation in the end of this white paper):

$$Fr = \frac{n^2 2t}{g} \quad (1)$$

Higher Froude numbers would be more conducive to the formation of surface vortices. However, this is a complex phenomenon that requires considering various additional parameters. Every appurtenance in the agitated vessel can potentially change the flow dynamics and help or inhibit vortex formation. A common case in biopharmaceutical vessels where this occurs is due to the use of dip tubes for ingredient additions. Depending on the length of it, the dip tube can effectively act as a baffle and can inhibit vortex formation even on the vessels with the recommended h:d ratio. The impeller shape has an influence in the ability to break a vortex. Given the same impeller diameter, some impeller shapes may be more conducive to create a vortex than others. Typically, higher wings may help in forming a stable vortex, even when close or slightly below the 1:1 ratio. Figure 4 shows common modifications done to impeller wing shape for obtaining different changes in the flow pattern.

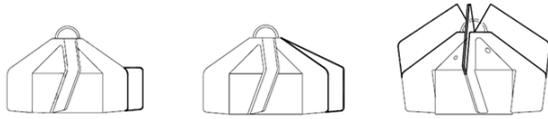


Figure 4 Common impeller modifications that alter the flow pattern. From left to right: a) and b) Increased wing diameter increases pumping at low rpm. c) Higher wings help vortex formation.

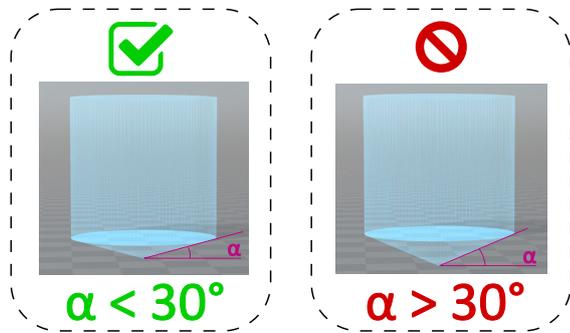


Figure 5 Typical range of angles recommended for conical bottoms in combination with the use of bottom mount magnetic coupled mixers.

Vessel bottom geometry considerations

Figure 1 depicts an agitator in a vessel with a dished bottom. This is the most common bottom shape used in bioprocess (in most cases a ASME flange and dish head is used). Other bottom shapes are used in certain processes, such as conical. With magnetically driven agitators, the angle of the cone may be restricted to avoid uneven loads on the bearings. In general terms, the angle is no more than 30 degrees from the horizontal line (see figure 5). Other type bottoms, such as flat ones are uncommon due to their inability to provide a self-draining vessel (needed to effectively steam in place).

Hemispherical bottoms have been used with bottom mount mag mixers, but are not common. These may offer a lower minimum mixing volume than dished bottoms. Alternatively, tulip vessels are often used for processes where there are concentration steps (such as various filtration systems). See figure 6. Tulip vessels create an additional degree of complexity when trying to use bottom mount mag mixers. The difference between the small and large diameter, as well as the depth of the tulip shall be considered. For the tulip, the same vessel geometry rules apply, so the ratio of h:d should be maintained as recommended. In particular, deep and narrow tulips should be avoided if using a bottom entry mag mixer. When the small and large diameter ratio is closer to one, it is often possible to mix the entire vessel with one mixer installed in the bottom. As the difference between diameters increases, the ability to mix the entire volume with one mixer is reduced and in some instances, two impellers may be used (one installed in the bottom and one installed on the side of the larger diameter).

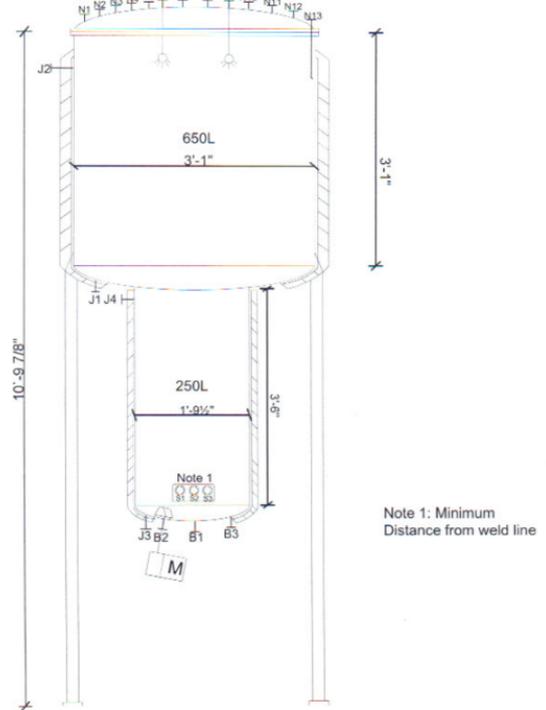


Figure 6 Example of a tulip vessel configuration.

CONCLUSION

An agitated vessel is a system that comprises a vessel with a given geometry and an agitator that act together to obtain the required mixing purpose of the application. When using bottom entry magnetically driven mixers, the following vessel geometry considerations shall be evaluated when designing vessels and selecting the proper agitator:

- The h:d ratio shall be within the recommended ratio of 1:1 to 2:1. Values below 1:1 can provide appropriate mixing flow pattern, but will inhibit vortex formation. Values above 2:1 shall be avoided.
- The position of the impeller in the bottom dish affects flow pattern and mixer efficiency. The half radius position would provide the best mixing performance.
- If vortex formation is required by the application (such as with incorporation of light powders), h:d ratios below one shall be avoided. Some impeller configurations may enhance the ability to break a vortex in the surface.
- The shape of the bottom dish shall be considered. Some shapes may not be recommended when working with bottom entry mag mixers.

NOMENCLATURE

d : vessel internal diameter

Fr : Froude number (dimensionless)

g : gravity

h : liquid height

n : impeller rotational speed in revolutions per minute (rpm)

t : impeller outside diameter

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