LIQUID AGITATION TECHNOLOGY

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1. INTRODUCTION

Agitation is one of the basic Unit Operations in industry, used to dissolve, disperse or suspend solids in liquids, mix miscible/immiscible liquids, disperse gases in liquids, mix solids together, promote mass and heat transfer, reduce particle agglomerates, etc.

In this particular Technical Paper, we will address the main aspects of the agitation processes of Newtonian liquids and the theoretical concepts that underpin this operation.

2. BASIC CONCEPT

In liquid agitation, the aim is to promote the best mixing, in the shortest possible time and with the lowest energy consumption. To achieve maximum agitation efficiency, a series of factors must be taken into consideration, both in relation to the characteristics of the liquid being agitated, the relation to the geometry of the tank and to the agitator itself.

The power required to move an agitator through a homogeneous liquid at a given rotation can be estimated by the following equation:

$$P = Po \, . N^3 \, . D^5 \, . \rho \qquad \text{(Equation 1)}$$

P = Power (Watts)

N = Speed of the agitator (revolutions per second = s^{-1})

D = diameter of the agitator (m)

ρ = Density of the Liquid (kg/m^3)

Po = Power Number ➔ dimensionless number, specific for every configuration involving the dimensions of the tank and agitator and the Agitation Reynolds Number (Re_A).

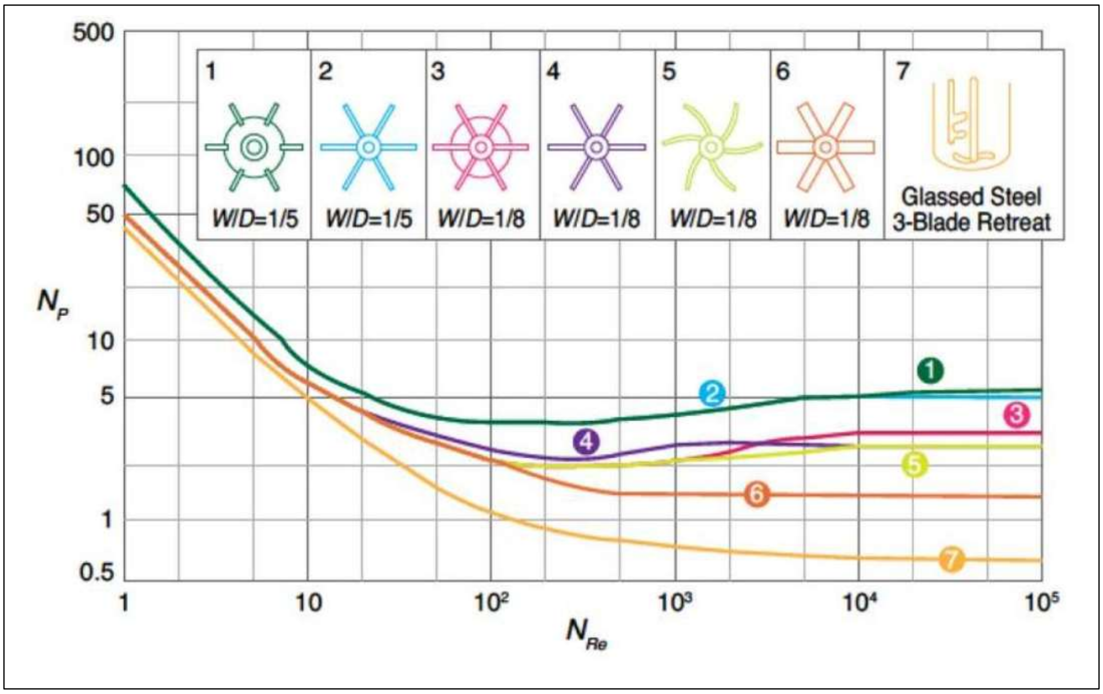
The power calculated by Equation 1 is the so-called “shaft-end power”, that is, the power that must be supplied to the agitator submerged in the liquid. When sizing the motor to be connected to the agitator, due consideration must be given to the additional power required to move the couplings, speed reducers, pulleys, etc.

Note the great effect that the agitator diameter has on the result of the power calculation, which is also influenced, to a lesser extent, by the agitator rotation speed.

The Power Number "Po" can be obtained from specific graphs, like the one shown in Figure 1 below, which brings the correlation between the Power Number and the Agitation Reynolds Number (Re_A). These graphs are often obtained from practical experiments developed by universities or companies specialized in agitation systems. For each type of agitator, tank configuration, accessories installed in the tanks, etc., there is a specific Power Number and, therefore, sometimes it is not easy to find the appropriated Power Number in open literature, given the large investment of time and financial resources required to obtain them.

Some guidance on the Power Number is presented in the section 3 of this document, where the Power Numbers for different kinds of agitators can be found and used as a reference for a first estimation of the power needed for the agitation of a specific case.

FIGURE 1 – Example of Power Number Graph



On the other hand, the Agitation Reynolds Number (Re_A) can easily be calculated from the following equation:

$$Re_A = \frac{N \,.\, D^2 \,.\rho}{\mu} \qquad \text{(Equation 2)}$$

Re_A = Agitation Reynolds Number (dimensionless)

N = Speed of the agitator (revolutions per second = s^{-1})

D = diameter of the agitator (m)

ρ = Density of the Liquid (kg/m^3)

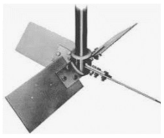
μ = Viscosity of the Liquid (kg/m.s)

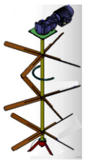
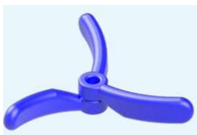
OBS: 1 cP = 0,001 kg/m.s

3. POWER NUMBER

The Figure 2 below brings a quick refence guide to get the Power Number for different types of agitators. However, as previously mentioned, the accurate Power Number for a specific tank, type of agitator and speed of agitation can only be obtained from specific graphs.

FIGURE 2 – Examples of Power Number

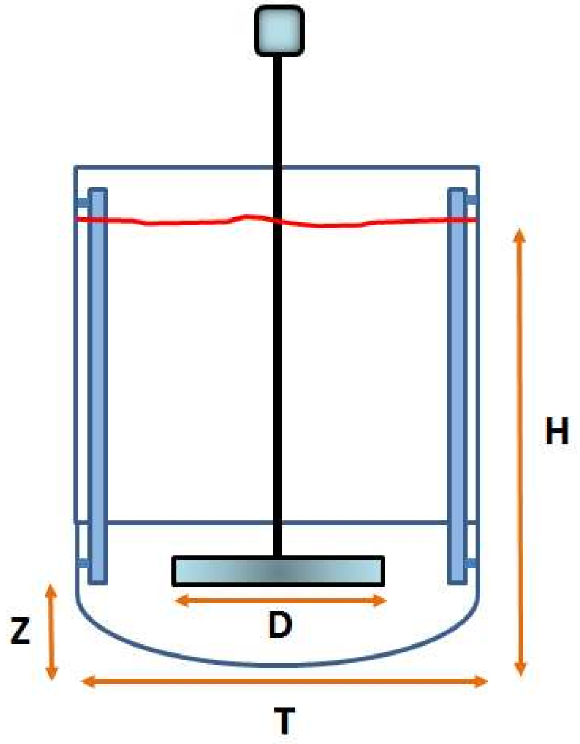
Agitator		POWER NUMBER (Po)	Observation
PBAT Tank with Baffles 1 set of agitators **4 Blades @ 45°**		**1,3**	Valid for $Re_A > 8 \times 10^2$
PBAT Tank with Baffles 1 set of agitators **4 Blades @ 60°**		**3,5**	Valid for $Re_A > 10^2$

Agitator		POWER NUMBER (Po)	Observations
PBAT Tank with Baffles **2 set of agitators** 4 Blades @ 60°		**5,5**	Valid for $Re_A > 10^3$
PBAT Tank with Baffles **3 set of agitators** 4 Blades @ 60°		**7,0**	Valid for $Re_A > 2 \times 10^3$
FLAT BLADES Tank with Baffles 1 set of agitators 4 Flat Blades		**3,6**	Valid for $Re_A > 10^2$
RUSHTON DISK Tank with Baffles 1 set of agitators 6 Blades		**5,0**	Valid for $Re_A > 3 \times 10^3$
SMITH DISK Tank with Baffles 1 set of agitators 6 Blades		**3,0**	Valid for $Re_A > 3 \times 10^3$
MARINE PROPELLER Tank with Baffles 1 set of agitators 4 Blades Pitch = 2D		**1,0**	Valid for $Re_A > 10^3$
FLAT GLASS LINED Glass Lined Tank 2 Baffles 1 set of agitators 3 curved blades		**0,9**	Valid for $Re_A > 5 \times 10^2$
COWLES DISK Tank with Baffles **1 set of agitators** Standard Disk		**1,0 – 2,3**	Valid for Re_A between 35 to 55 Use P_o = 1,0 for low viscosity liquids (< 10.000 cP). For higher viscosities, use P_o = 2,3 or an intermediate value.

Agitator		POWER NUMBER (Po)	Observation
COWLES DISK Tank with Baffles **2 set of agitators** Standard Disk		**1,8 – 3,5**	Valid for Re_A between 35 to 55 Use P_o = 1,8 for low viscosity liquids (< 10.000 cP). For higher viscosities, use P_o = 3,5 or an intermediate value.
HYDROFOIL – TYPE 1		**0,3**	Valid for liquids with low solid content
HYDROFOIL – TYPE 2		**0,7**	Valid for liquids with some quantity of solids content.
HYDROFOIL – TYPE 3		**0,3**	Valid for de-glomeration operations.
HELICOIDAL AGITATOR			$N_{Po} = \frac{150}{Re}\left(\frac{H_i}{D}\right)^{-0,28}\left(\frac{p}{D}\right)^{-0,53}\left(\frac{h}{D}\right)\left(\frac{W}{D}\right)^{0,33} n_b^{0,54}$ Valid for Re_A in the laminar region and viscous fluids. H_i = blade distance from the bottom of the tank D = external diameter of the blade p = pitch h = height of the agitator W = width of the blades n_b = number of blades
GATE AGITATOR			$N_{Po} = \frac{85}{Re}\left(\frac{H_i}{T}\right)^{-0,31}\left(\frac{h}{D}\right)^{0,48}$ Valid for Re_A in the laminar region and viscous fluids. H_i = blade distance from the bottom of the tank D = external diameter of the blade T = diameter of the tank h = height of the agitator

4. RECOMMENDED TANK GEOMETRY

To achieve an efficient agitation, the following recommendations should be followed as far as possible concerning the tank geometry:



D = Diameter of the agitator (m)

H = Height of liquid inside the Tank (m)

T = Tank diameter (m)

Z = Clearance between the agitator and the bottom of the Tank (m)

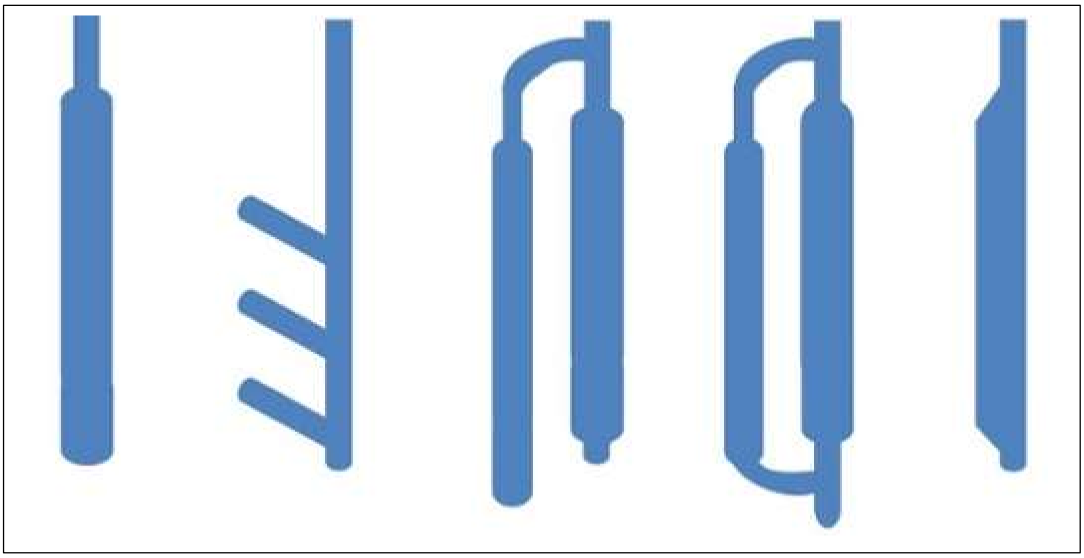
Recommended ratios:

$0,8 < H < 1,2\ T$ $Z = H/4$ $D < T/2$

a) The vessel must have baffles – normally 4, with a width of T/10. This prevents the liquid from circulating on the vessel walls and minimizes vortex formation. It is recommended that there be a space between the baffle and the vessel wall to prevent solids from accumulating behind the baffles.

b) For tanks with large diameter agitators, such as anchor, gate, helicoidal or similar types, the installation of conventional baffles may be impossible due to lack of physical space for the installation. In these cases, other types of baffles may be used, as shown in Figure 3. (finger type, beavertail type, etc.).

Figure 3 – Examples of alternative Baffle configuration (in sequence: Beaver tail, Finger type, H type, D type and Fin type)



c) The preferred agitator is the turbine type with inclined blades (45°). The liquid pumping direction must preferably be towards the bottom of the vessel to “sweep” the particles that settle there and move them upwards.

d) The movement of liquid by a disc-type agitator with flat blades is not very efficient in relation to the movement of particles that are at the bottom of the vessel. This type of agitator requires about 10 times more power than inclined blade turbines to achieve the same level of solids suspension and for this reason they are not recommended for work involving solids suspension.

e) For vessels that are not too tall, with H/T <1,2, an agitator positioned at a height of H/4 above the bottom of the vessel is sufficient. For taller vessels, with H/T between 1,2 and 1,8, it is recommended to install a set of 2 agitators positioned T/4 and 2H/3 above the bottom of the vessel.

f) The power required to move particles from the bottom of the vessel increases as the distance from the agitator to the bottom of the vessel also increases. On the other hand, if the agitator is too close to the bottom of the vessel, there will be restrictions on liquid circulation and therefore, the distance of H/4 is an excellent parameter.

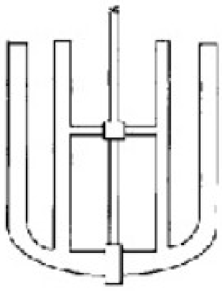
g) The size of the agitator should not exceed half the diameter of the vessel. Very large agitators interfere with the circulation of liquid inside the vessel, compromising the uniformity of the solution. In addition, they require a large torque, which increases the cost of the motorization.

h) Tanks may have flat, elliptical, torispherical, domed, semi-spherical or slightly conical bottoms. Tanks with highly conical bottoms should be avoided, due to the great difficulty in promoting efficient agitation in this geometry and the possibility of stagnation of solid materials at the bottom of the tank.

5. TYPES OF AGITATORS

There are 3 main categories of agitator:

LARGE AGITATORS: Agitators that are relatively wide in relation to the diameter of the tank, i.e., with a ratio between 0,7 and 0,9 T. Examples of these agitators are the anchor, gate, helicoidal and paddle types. They are generally used in systems involving liquids with high viscosity (> 5.000 cP) and they can promote the movement of large quantities of mass, with low shear, with movement almost entirely vertical or lateral. They are also characterized by a very high Mixing Time and although the axe rotation speed is normally low, there is a very high speed at the external tip of the agitator (Tip Speed), due to the large diameter of these agitators.



Gate type agitator

Anchor type agitator

MEDIUM-SIZE AGITATORS: Medium-sized agitators have a diameter between 0,3 and 0,5 T, with Tip Speed between 2-5 m/s, and are used in low or medium viscosity liquids (below 5.000 cP). Examples of these agitators are the turbine type with flat or inclined blades (Pitch Blade Angle Turbine = PBAT), hydrofoils, marine propellers, etc. These agitators promote a good mass flow during agitation and present moderate shear. The use of multiple agitators on the same shaft is sometimes employed to increase the agitation effect, especially in tanks with great height. The agitation promoted by these agitators is greatly influenced by the presence of baffles, without which they produce significant vortexes on the surface of the liquid.

Marine Propeller

Pitched Blade Angle Turbine (PBAT)

Flat Blade Disk

SMALL AGITATORS: Small diameter agitators (0,05 – 0,2 T) normally have a high Tip Speed (5 – 15 m/s) and operate in low viscosity liquids (< 1,000 cP). Examples of these agitators include Cowles, Silverson, Perforated Disc, etc. These agitators promote very high shear in the region close to the agitator, moderate movement of fluid mass, with high energy consumption. They are used primarily in the dispersion of materials and formation of colloids.

Cowles agitator

Perforated Disk

General observations regarding the agitators:

• The liquid flow produced by disc-type agitators is not very efficient if one wishes to prevent any particles from accumulating at the bottom of the tank. Disc-type agitators require about 10 times more energy than PBAT agitators to achieve the same result in terms of particle suspension.

• It is recommended that the direction of rotation of the agitators be such that the liquid is pumped downwards in the centre of the tank, to clean the bottom of the tank and to cause any solids to be raised into the liquid being agitated.

• For shallow tanks, with an H/T ratio of up to 1,2, an agitator positioned at H/4 above the bottom of the tank will be sufficient. In deeper tanks, with H/T between 1,2 and 1,8, if the height of the liquid above the agitator is very high, the upper part of the liquid is not sufficiently agitated, so that a deep vessel will require more than one set of agitators. Therefore, it is recommended to install two agitators, positioned at T/2 and 2H/3 above the bottom of the tank.

• The power required to sweep particles from the bottom of the tank increases as the separation between the agitator and the bottom of the tank is increased; however, if the agitator is too close to the bottom of the tank, the circulation of the liquid will be impaired. A height of H/4 represents an adequate positioning.

• The diameter of medium or small agitators should never exceed half the diameter of the vessel. An agitator that is too large will interfere with the circulation pattern. In addition, large diameter agitators require greater torque, which usually leads to high horsepower motors, increasing the cost of the installation.

6. INTENSITY OF THE AGITATION

As a general rule, the power dissipated by an agitator working with low viscosity liquids is in the range of 0,2 to 5,0 W/kg. In applications where a high energy load is required (such as in processes requiring high mass transfer, emulsification processes, etc.) it may be necessary to use powers of up to 10 W/kg. Powers above this value are not common and can only be found in very specific applications, such as in the case of polyethylene manufacturing reactors, where powers of the order of 100-200 W/kg are used.

The following table shows the power levels commonly found for various intensities of mixing:

Power (W/kg)	Agitation level
0,2	Mild
0,5	Moderate
1,0	Vigorous
5,0	Intense

Regarding the "Tip Speed", the speeds normally found and recommended are shown in the following tables:

LIQUID – LIQUID SYSTEMS	
Tip Speed (m/s)	**Recommendations**
0,3 – 0,7	Low level of agitation, used for: • Homogenization of miscible liquids to uniformity, when the density difference is less than 0,1 • Homogenization of miscible liquids to uniformity, when the viscosity difference is up to 100 times • Obtaining liquid movement through the tank • Production of a flat liquid surface, but with movement
1,0 – 2,0	The most common level of agitation used in the industry for: • Homogenization of miscible liquids to uniformity when the density difference is less than 0,6 • Homogenization of miscible liquids to uniformity when the viscosity difference is up to 10.000 times • Suspension of solids (< 2%) with sedimentation velocities between 0,01 and 0,02 m/s • Creation of waves on the surface of low viscosity liquids
2,3 – 3,3	High level of agitation, used for: • Homogenization of miscible liquids to uniformity when the density difference is less than 1,0 • Homogenization of miscible liquids to uniformity when the viscosity difference is up to 100.000 times • Suspension of solids (< 2%) with sedimentation velocities between 0,02 and 0,03 m/s • Creation of a central vortex and elevation of the liquid level on the vessel walls in low viscosity liquids

SOLIDS SUSPENSION	
Tip Speed (m/s)	**Recommendations**
0,3 – 0,7	Minimum suspension of solids. • Produces only a minimum movement of solids • Moves solids deposited at the bottom of the tank, suspending them intermittently
1,0 – 1,6	The most used level of agitation used in the industry for: • Suspension of all solids from the bottom of the tank • Promotion of liquid uniformity up to at least 1/3 of the tank volume
2,0 – 2,6	Level of agitation recommended when a complete and uniform distribution of solids must be obtained. • Suspension of all solids from the bottom of the tank • Promotion of liquid uniformity up to at least 95% of the tank volume
3,0 – 3,3	Used when it is necessary to achieve a maximum uniformity of solids distribution. • Suspension of all solids from the bottom of the tank • Promotion of liquid uniformity up to at least 98% of the tank volume

GAS DISPERSION	
Tip Speed (m/s)	**Recommendations**
0,3 – 0,7	Used when the degree of the dispersion is not critical to the process. • Gross dispersion of gas bubbles • Typical for situations where the mass transference is not a critical factor
1,0 – 1,6	Used when a moderate degree of dispersion is required for the process. • Allows small bubbles to reach the tank wall • Promotes the recirculation of dispersed bubbles back to the agitator
2,0 – 3,3	Used when a rapid mass transference is necessary to the process. • Maximizes the bubbles interfacial area throughout the liquid

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