Scale-Up Of Rotor-Stator Equipment

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Rotor-stator mixers, due to their high-shear capabilities, are increasing in popularity. As a result, there are a wide range of designs available on the market. They can be used as batch (in-tank) units or as continuous in-line devices and they typically consist of a high-speed rotor rotating in a fixed stator. Any liquid or solid-liquid mixture passing through this style of mixer is subjected to high shear forces and turbulence. Their high shear rates, high energy dissipation rates, versatile nature, and cost efficiency make them ideal for processes requiring rapid disintegration, homogenization, dissolving, emulsification, and dispersions.

When specifying a pump or agitator it is possible to predict, with a high degree of certainty, the size and configuration of the machine required to carry out a given task. Technical advances such as Computational Fluid Dynamics (CFD), Laser Doppler Anemometry (LDA), and Particle Induced Velocimetry even allow process engineers to model the performance of equipment based on factors such as vessel geometry, batch size, and product viscosity, providing accurate scale-up information without always having to carry out extensive laboratory or pilot scale trials.

By contrast, scale-up of high shear devices such as rotor-stator mixers is still very much based on a practical approach rather than a theoretical one; users have to rely on their own experience and that of the equipment supplier when specifying a mixer, and laboratory or pilot scale testing is still central to the selection process. From the manufacturer's point of view, design and development of new techniques and equipment is similarly based on the same practical approach which has been employed since the emergence of rotor-stator mixers in mass food production during the post war years. The continuing evolution and success of this type of mixer across industries as diverse as food, chemicals, pharmaceuticals, petrochemicals, and cosmetics suggests that there is nothing wrong with this approach in itself. However, there is a growing expectation on the part of users for the provision of scientific data (of a similar nature to that given for pumps and agitators, for example) to enable them to make better informed decisions when specifying a mixing system.

Equipment manufacturers are seeking to employ the latest technology to streamline the development and scale-up process. To this end, manufacturers are working in partnership with academic and research institutions on various projects such as the University of Maryland's High Shear Mixing Research Program in the United States and the British Hydromechanics Research Group (BHRG) at Cranfield University in the United Kingdom to develop a more scientific understanding of the operational parameters of rotor-stator mixers and to find ways in which to apply this knowledge in areas such as scale-up and design.

The first point to consider is that the hydrodynamic forces inside the rotor-stator workhead are far more complex than those which occur with agitation or pumping. Furthermore, a pump or agitator is simply moving the product, whereas rotor-stator devices process the product, that is, they bring about a change in it through a number of operations which can include particle size reduction, homogenization, solubilization, emulsification, and reaction acceleration. Many of these can be occurring simultaneously in a single operation, meaning that a range of operational or hydrodynamic variables can apply in any given application; it is too simplistic to merely select any one criterion to predict scale-up. It is also important to keep in mind that the physical properties of materials and process conditions will also affect calculations, for example where the rheology of the product undergoes a significant change during processing. The generation of correlations based on physical and scientific concepts has been very difficult as there are many parameters that have an effect on the mixer's performance. At present, a combination of the following parameters is generally thought to provide the most reliable results:

(i) Energy dissipation (power per unit volume)
(ii) Tip speed
(iii) Shear frequency
(iv) Throughput
(v) Open area.

Energy Dissipation Rates, ε

Due to its complex nature, the flow in a rotor-stator mixer is highly turbulent. If turbulent conditions are prevalent in a mixing system, scale-up can be achieved by maintaining a constant power per unit volume. A percentage of this power will be expended in turbulent energy dissipation, and these figures can then be used in correlations to predict such desired results as droplet sizes in emulsions.

However, it is increasingly becoming apparent that rotor-stator mixers exhibit laminar flow tendencies (especially with fluids with higher viscosities). Rotor-stator mixers are often operating in the laminar regime where viscous shear is more prominent. Therefore, the identification of the operating regime in a rotor-stator mixer will help in the understanding of the mixing mechanisms involved.

A method of determining the flow regime is to determine the dependence of the power draw of the unit on rotational speed. If the power is found to be proportional to rotation speed raised to the power of 3, then turbulent conditions will apply. If the power is related to rotational speed raised to the power of 2, then the flow will be laminar.

To successfully investigate the usefulness of energy dissipation in scale-up, the power has to be monitored while mixing to determine the effects of the fluid physical properties on power draw. The most effective method of doing this is to incorporate a torque transducer onto the shaft of the mixer to measure the shaft torque (and effectively the total energy supplied to the mixture).

The energy dissipation, ε (W/m^3), also referred to as the power per unit volume can be estimated using the following expression:

$$\varepsilon = \frac{P_{Fluid}}{V}$$

P_{Fluid} Total power expended to the fluid (W)

V Volume of the mixer (m^3)

Many applications require more than one pass through in an in-line rotor-stator mixer to achieve the desired concentration or particle or droplet size. This is because the distribution of energy dissipation in the rotor-stator mixer is variable. This would suggest that this technique is dependent on the accurate evaluation of localized energy dissipation in the mixer — for which there is very little information currently available.

Tip Speed And Gap Shear Rate, γ_{gap}, (s^{-1})

Tip speed, V_{tip} (m/s), can be used to evaluate the kinetic energy imparted to the fluid from the tip of the rotorblade as well as determining the shear stress and rates imparted to the fluid.

$$V_{tip} = \bullet ND$$

N = Rotational speed (revs per sec)
D = Diameter of rotor (m)

A direct function of V_{tip} is the shear rate in the gap between the rotor and stator, γ_{gap}, (s^{-1}). The highest values of shear rate are in this region of the mixer and consequently the main mixing mechanisms will be characterized in this region. The values for the shear rate in the shear gap, γ_{gap}, (s^{-1}), can be estimated using the following expression.

$$\gamma_{gap} \quad \frac{V_{tip}}{\delta}$$

δ – shear gap (gap between the rotor and stator), m

The γ_{gap} will become more significant at higher viscosities as the velocity gradient will increase. At lower viscosities the flow patterns in the gap will not exhibit simple shear flow and will become more turbulent in which case turbulent energy dissipation may become more significant.

Although scale-up using values of shear rate and tip speed work well in some applications involving agitators and stirrers, they are not always applicable to rotor-stators. The reason for this is that the flow from the rotor (and consequently any particles or drops being carried with it) is assumed to travel at the same speed as the rotor tip. It then undergoes a sudden deceleration as it impacts the stator wall, and it is the losses in kinetic energy during this process that contribute to dispersion/emulsification. The tip speed in addition to the rotor-stator geometry (and physical properties of the fluids) will have a larger bearing on scale-up issues. This leads to another parameter that is commonly used called the 'shear frequency,' which is a function of rotational speed and the geometry of the rotor and the stator.

Shear Frequency, *sf* (s^{-1})

The interaction between the flow from the rotor and the geometry of the screen play a significant role in the turbulent and shear characteristic in the gap. CFD models indicate that the high energy dissipation regions (energy contributed to mixing) occur when the rotor passes a hole or a slot. The way the fluid impinges on the stator wall and the resultant turbulent eddies that occur are governed by the number of holes/slots and the number of blades/teeth on the rotor. This is the reason for the number of stator designs ranging from circular holes and slots to stators with square holes that are available for differing applications.

Changing from a Slotted Head (SLDH) to a Square Hole High Shear Screen (SQHS) and the corresponding increase in *sf* (from 480,000 min^{-1} to 8 x 10^6 min^{-1}) reduces the rate of particle size reduction but nevertheless results in a smaller particle size (the magnitude of which is product dependant).

This is due to the fact that there are a greater number of shearing events where the losses in kinetic energy occur in the SQHS than in the slotted head. Another factor to consider is that the SQHS has a slightly smaller open area than the SLDH, thus the residence time of the particles in the areas of highest shear is greater. An area of low pressure will exist on the trailing edge of the rotor which will draw material back into the shear gap and rotor region further increasing the residence time of the particles in the areas of highest shear. The smaller open area will also increase the velocity of the fluid travelling through the holes (or slots) which will aid breakup due to attrition. This gives rise to two or more parameters that may affect scale-up — velocity of jets through holes, V_{jet} (m/s), and residence time in the various regions of the mixer, t_{res} (s).

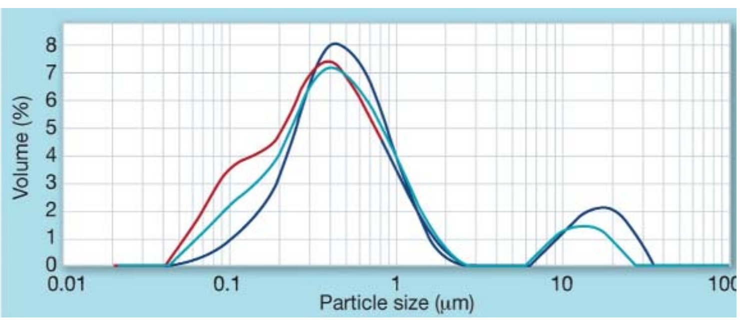
$$V_{jet} = \frac{Q_v}{A} \qquad t_{Res} = \frac{Qv}{V}$$

Q_v = Volumetric flowrate (m^3/s)

A = Open area of screen (m^2)

V = Volume of region in mixer (m^3)

The effect of the velocity of the jets will be small relative to the amount of shear and energy generated in other regions of the mixer. This will depend on the mode of operation and if the flow through the mixer is increased by use of a pump, *Vjet* is a function of flowrate. In general, it is recommended that pump-assisted, rotor-stator mixers are not operated at throughputs significantly beyond their natural pumping capabilities, as the corresponding reduction in residence time can compromise the efficiency of the machine, and could potentially lead to mechanical problems.



This graph shows particle size analysis based on titanium dioxide slurry trials.

Residence Times

The residence time is an important parameter when considering scale-up as the break-up of both particles and droplets is time dependant (they will only break if they are exposed to the high shear/energy areas for a sufficient amount of time). The mixer can be divided into the following sections: (a) the rotor region; (b) the shear gap; (c) the stator region (volume of the openings in the stator); and (d) the volute.

These regions can be put into the following order of residence times: shear gap < stator < rotor < volute. The very short residence times in the shear gap and the fact the regions of high localized energy dissipation are very small indicates that a percentage of the fluid mixture bypasses this region. It is important to note that increasing the residence time in the gap by making it larger will not increase the areas of high energy as the flow interactions between the rotor and stator will not change. Also a larger gap width will lead to greater leakage where the fluid will pass out of the top of the gap and not through the screens. Increasing the number of holes or slots will increase the rotor-stator interaction and, in turn, increase the number of high energy regions. This can be done by changing the screen. This has also led to the advent of multi-stage mixers (consisting of an array of concentrically arranged rotors and stators) illustrated below.

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The estimation of nominal residence times can be coupled with a Reynolds analysis, where the Reynolds number is the ratio of turbulent forces to viscous (laminar) forces present in a system. This would make it possible to investigate whether inertial (turbulent) or viscous (laminar) forces are likely to be responsible for mixing in each of the regions.

An understanding of the flow patterns within each of the regions of the rotor-stator mixer will give an appreciation of the areas of high energy dissipation and the types of break-up mechanisms that would be induced as a result. The High Shear Program at the University of Maryland has employed techniques such as Computational Fluid Dynamics, Laser Doppler Anemometry, and Particle Induced Velocimetry to model the complex flows in the rotor-stator mixer.

It is important to understand that all the parameters mentioned are simplistic descriptions of what is occurring in the head at any one time. It must also be emphasized that the material being mixed will play a significant role in the ability to scale-up from laboratory or pilot scale to full production. For this reason many end users have developed their own scale-up criteria based on a mixer's performance on one specific product. However, they have found this criterion difficult to transfer from one application to another because a mixer will not necessarily yield the same results for another product. The desired particle or droplet size will also play an important role in the development of scale-up rules. If the final particle size is small, break up will be mainly achieved by attrition and the velocity through the holes/slots may prove to be more significant. ●