

# Mixing Technology – Fundamentals

By Dr. V.V. Chavan\*

## Introduction

**A**GITATION and mixing are of commercial relevance to several process industries like: chemical, petroleum, plastic, paper, agrobased, food, cosmetic, paint and pharmaceutical. Uptodate knowledge of the tools to steer, manipulate, control, select, develop, design or scale-up a given process is most essential in our competitive world of today. We have put the very purpose, the objective of an agitated system in a perspective. The "criteria" that one should keep in mind for a given agitation job are also outlined here.

## Homogenization

The dictionary meaning of "homogeneous" is "of the same kind". Elaborating it further for the scientific usage, we define 'homogeneous' as "composed of parts which are all of the same kind".

The size of these parts has a special significance when quantifying homogeneity. It represents the scale

The scale of segregation is the dimension that characterises the clumps of an unmixed component in the mixture. The intensity of segregation really accounts for the distribution of these clumps. Physical significance is better explained by an example. In blending of two viscous liquids, the scale of segregation can directly be observed as the thickness of the striation of one liquid into another. Initially, when the two liquids are entirely separate, the intensity of segregation is equal to 'one'.

The scale of segregation is the dimension that characterises the clumps of an unmixed component in the mixture. The intensity of segregation really accounts for the distribution of these clumps. Physical significance is better explained by an example. In blending of two viscous liquids, the scale of segregation can directly be observed as the thickness of the striation of one liquid into another. Initially, when the two liquids are entirely separate, the intensity of segregation is equal to 'one'. Finally when they are totally mixed at the level of the "scale of scrutiny", the intensity of segregation is zero.

In order to define these quantities in precise mathematical terms it is convenient to approach the small and large scale segregations separately.

In dealing with "small scale segregation", our "scale of scrutiny" is also small. Generally, in the mass transport at the molecular level or in chemical reactor problem, we are associated with small scale segregation. In large scale segregation, the scale of scrutiny is larger (mostly greater than a micron). The problems associated with large scale segregation are thus physical, for example: dispersion of pigment in viscous liquids, blending of polymer melts or mixing of powders. Table 2 describes these quantitative measur-

Table 1  
Typical scales of scrutiny

Purpose of mixing	Scale of scrutiny
Mixing pigments in plastics, paints or soap	Resolving power of eye
Mixing ingredients in detergent powder	Weight used for one wash
Mixing ingredient in a pharmaceutical drug	Weight of a tablet
Mixing active additives to rubber before vulcanization	Volume over which an individual grain can be active

at which we scrutinise the mixture. This so called "scale of scrutiny" determines the amount of energy we should put in and the time that we should allow for the mixing.

In quantifying homogeneity, statistics is heavily made use of. Two terms are defined and used; these being:

- scale of segregation, and
- intensity of segregation.

\*Dr. V.V. Chavan is Director of Mixing Equipment Manufacturing Company, Bombay.

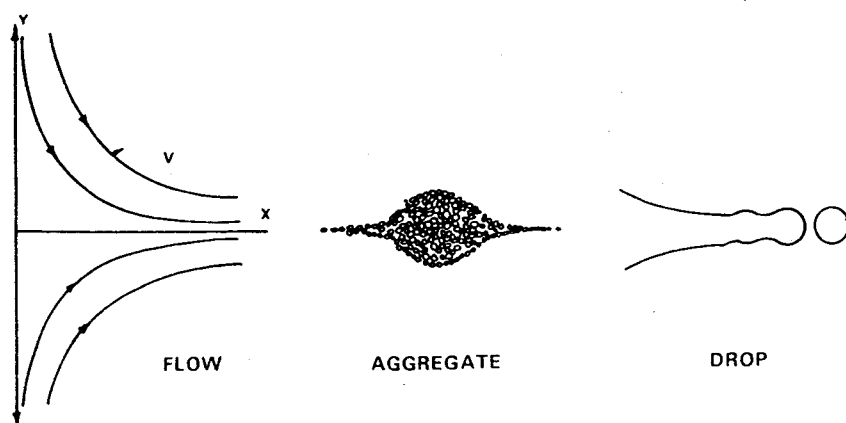


Fig. 1. Effect of stretch flow.

**Table 2**  
**Measures of homogeneity**

Type of segregation	Process situation	Scale of segregation (S)	Intensity of segregation (I)
Small-scale segregation	Mixing or blending usually close to molecular scale. Turbulence is often prevailing. It is, however, not a prerequisite.	Defined by Dankwerts <sup>4)</sup> in term of a correlogram. Not so often used.	Also defined by Dankwerts <sup>4)</sup> as the ratio of variance at the end ( $\sigma^2$ ) to the variance at the start ( $\sigma_0^2$ ) $I = \frac{\sigma^2}{\sigma_0^2}$ $\sigma_0^2 = \bar{c}(1-\bar{c}); \bar{c}$ being the expected mean composition of a component. $\sigma^2$ is estimated as the $\frac{1}{n-1} \sum_{i=1}^n (c_i - \bar{c})^2, c_i$
Large-scale segregation	Blending of viscous liquids, dispersing pigments, in viscous liquids mixing of pastes, mixing of powders.	When blending two liquids scale of segregation can be directly measured or visually observed in terms of thickness of striations ( $r_s$ ) of one liquid into another. For the other cases, Kristensen <sup>6)</sup> proposes a method which requires measurement of variance within a sample together with the variance between sample required to obtain the the intensity of segregation.	being the point value of the concentration. For blending problems sample size should be much larger than $(r_{s, avg})^3$ . Here often, the coefficient of variance is used as a measure of intensity, thus: $I = \frac{\sigma^2}{\bar{c}}$ $\sigma$ and $\bar{c}$ have the same meaning as above. More elaborate statistical tests have been proposed in the literature, especially for solid and paste mixing. The criteria are postulated with an assumption of randomness, which is then checked with t-test or $\chi^2$ - test. Sample size, particle-size distribution or density differences also need to be taken in to account when computing statistical quantities like variance and coefficient of it. The latter is often used as a measure of intensity of mixing is also noted above. Often, in solid Mixing a term, namely: degree of mixedness (M), is used. Physically, this is converse of the intensity of segregation and defined by: $M = 1 - \frac{\sigma^2}{\sigma_0^2} \text{ or } M = 1 - \frac{\sigma}{\sigma_0}$

es of homogeneity.

### Dispersion

Here, we will consider the physical processes that are associated with a dispersion of one phase into another. Often, these phases are insoluble in each other, for example: in dispersion of a pigment in liquid or forming an emulsion or aerating a liquid. Dispersion is also relevant when the phases are soluble in each other; since the contact area and hydrodynamics around these particles will determine the overall mass transfer coefficient. "Dispersion" involves two processes:

- physically breaking one phase down to smaller size and
- dispersing these small units in a continuum.

The second process is quantitatively governed by the same frame-

work and criteria of homogeneity. In the first process, that is the process of breaking, the size of a unit (a particle, a droplet or a bubble) is the criti-

cal factor to watch.

In processes such a break down of agglomerates or flocculates or formation of a droplet or bubble, sever-

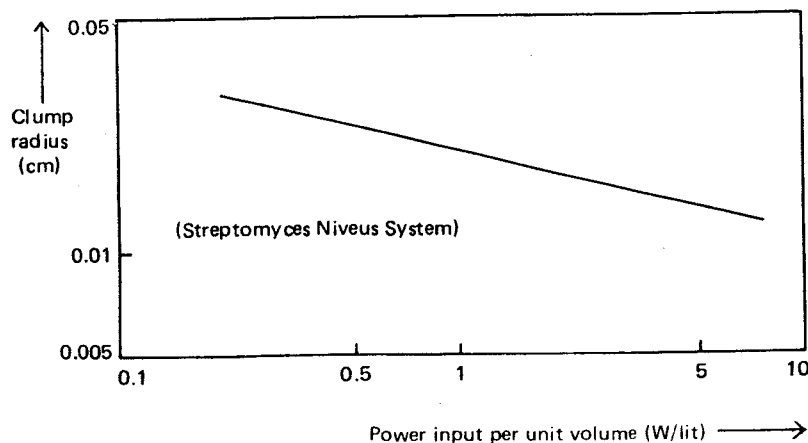
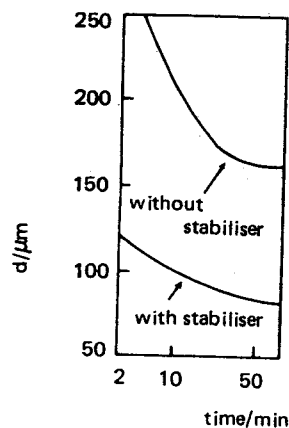
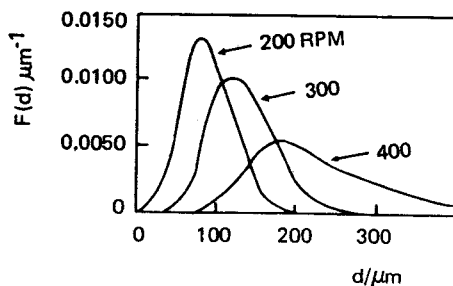


Fig. 2. Effect of power input on size of bacteria clumps.



(a) Mean drop size as a function of time. (Paraffin/water at 60°C, in 1.5 lit vessel with a turbine, PVA as the stabiliser).



(b) Drop size distribution of a dispersion of kerosene in aqueous glycerol at various impeller speeds ( $\mu_c = 3.6$  cP,  $\mu_d = 1.4$  cP,  $\sigma = 31.8$  dyn/cm).

Fig. 3. Typical emulsification results.

al physical aspects become important. For example, it would be the interaction forces between the particles or it would be the colloidal forces like van der Waal attraction force or electrostatic repulsive force or it could be force due to the adsorbed macromolecules on to the particles. In any case, in breaking down of agglomerates or formation of droplet, hydrodynamic plays an extremely important role. It is well-known how that by certain type of flow (illustrated in Fig. 1) you can break an aggregate or form an emulsion with less efforts. This thought provoking picture should make you think on two aspects:

- how to design the impeller and
- where to introduce the second phase.

When the applied shear on aggregate becomes larger than the strength of the aggregate it will naturally break. This simple law should determine the average size of an aggregate that will be present in an agitated vessel provided the hydrodynamics is known. Based on this hypothesis simple scale-up rules could be derived. For Newtonian liquids, the derived equations are given in Table 3. Just to illustrate the use of such arguments a plot of aggregate size against the power per unit volume is shown in Fig. 2.

Emulsification and aeration processes are also governed by similar hydrodynamic phenomena although the forces associated with particles are different. Here, it is the inter-

**Dispersion and aggregation are the two processes that generally go on simultaneously till an equilibrium is reached. Several other physical processes are also involved in making the situation extremely complex.**

Table 3

**Scale-up on aggregate size**

Criteria: applied stress > strength of aggregates

Theoretical results

Laminar flow in vessel

$d_{\text{aggregate}} \propto \text{tip speed}$

Turbulent flow in vessel

(a)  $d_{\text{aggregate}} \propto (P/V)^{-1}$   
for  $d_{\text{aggregate}} \gg \lambda$

(b)  $d_{\text{aggregate}} \propto (P/V)^{-1/2}$   
for  $d_{\text{aggregate}} \approx \lambda$

(c)  $d_{\text{aggregate}}$  independent of  $(P/V)$   
for  $d_{\text{aggregate}} < \lambda$

Note:  $\lambda$  equals  $(\nu^3/(P/V))^{1/4}$

Where:  $d$  - diameter  
 $P$  - power  
 $V$  - volume  
 $\lambda$  - size of energy dissipating eddies  
 $\nu$  - kinematic viscosity ( $\mu/\rho$ ).

facial forces and the physical properties of these interfaces that dominate the physics. The importance of hydrodynamics, however, cannot be underestimated as illustrated in Fig.3. Empirical equations are available in the published literature for

- the critical speed above which a dispersion could be formed, and
- the diameter of a droplet or a bubble.

### Aggregation

This is precisely the opposite phenomenon. Here the particles are required to be brought closer to each other. Practical situations are several, for example: water treatment, oil recovery from oil/water emulsions and deaeration. Again, here the interaction forces and the interfacial forces become important. Now the particles are to be brought closer to each other and thus the repulsive forces need to be overcome. The time needed for the particles to come closer to each other is also an important factor. Thus, the impeller tip velocity and shear rate are important factors in laminar (slow) flows, which is a common mode of operation for this purpose. In turbulent flows, the power per unit volume provides a useful scale-up criterion.

Dispersion and aggregation are the two processes that generally go on simultaneously till an equilibrium is reached. Several other physical processes are also involved in making the situation extremely complex. The suggestion is, therefore, that one should always carry out a pilot plant trial, while physics could be used for scaling up. Further, it should be noted that the empirical equations should be used with extreme caution.

### Suspension

Keeping particles or emulsion droplets in suspension is another important job of an agitated system. Generally, the suspension is required for an efficient mass transfer operation. The type of physics that leads to the relevant equation is outlined in Table 4.

### Heat and mass transfer

Heat and mass transfer rates could be expressed by  
(rate of transfer) = (transfer coefficients)

**Table 4**  
Particles in suspension

(a) Theoretical equation

Criterion: Force needed to keep particles in suspension is provided by the turbulent eddies

$$\frac{\pi}{6} d_p^3 \Delta \rho g \propto \rho u_r^2$$

$$\frac{\pi}{4} d_p^2 u_r \propto (\sum d_p) \frac{1}{3}$$

and

$$\therefore d_p \Delta \rho g \propto \rho (\sum d) \frac{2}{3}$$

For turbine with four baffles and  $500 < Re < 10,000$

$$\Sigma = \frac{P}{V} \propto d^2 N^3 (Re)^{0.13}$$

$$N_{critical} \propto \frac{d_p^{0.17} \Delta \rho^{0.52} \mu^{0.05}}{d^{0.78} \rho^{0.91}}$$

(b) Empirical equation (Zwietering)

$$N_{critical} \propto \frac{d_p^{0.2} (\Delta \rho)^{0.45} (\mu)^{0.1}}{d^{0.85} \rho^{0.55}}$$

Where : N - rotational speed  
 $d_p$  - particle diameter  
 d - turbine diameter  
 $\rho$  - density  
 $\mu$  - viscosity  
 $\Delta \rho$  - density difference

x (contact area)  
 x (driving force)

Our requirement obviously is of higher transfer rates. This will be achieved by higher transfer coefficients or/and higher contact area.

**Contact area**

Heat transfer is either from the

vessel walls by means of a jacket or from the walls of coils and pipes inserted in the vessel. In both cases, the contact area can be easily computed. In the mass transfer operations, such as gas absorption from bubbles, liquid extraction from/to the immiscible drops or extraction from solid particles, the contact area is not easily known. Generally, the smaller the

particle (drops or bubbles) size, the higher is the contact area per unit volume. The average contact area is  $6 \phi$  per unit volume;  $\phi$  being the volume fraction of the particles and  $d_p$  their mean diameter. The calculation in Table 3 and the previous discussion on dispersion become very much relevant here.

**Transfer coefficients**

Together with such quantities as thermal and molecular diffusivities, transfer coefficients will also be dependent on hydrodynamics in the agitated vessel. Especially as the flow around the particles will determine the coefficients.

**Reaction**

For any reaction, the molecules have to come in contact with each other and at that point in space the temperature (and pressure) should have a given value. Obviously, both heat and mass transfer are the important factors in any and every reaction. It is through these processes that the hydrodynamics in an agitated vessel assumes enormous importance.

Reactor systems are generally characterised as homogeneous and heterogeneous. The former involves single phase reactions whereas the latter are with more than two phases. Reactions with a catalyst again bring in some added complexities.

"Product yield" and "conversions" are the two quantities one is finally interested in. "Yield" refers to the product recovered as a percentage of that expected. "Conversion" of a given reaction is the percentage of reactants that have reacted. Higher "yield" is generally our goal. An agitated system is thus to be designed in order to achieve this. Special attention is required because often one has to promote one reaction and damp another at the same time. Proper controls and generally complete command over the happenings in the reactor are of vital importance.

Operation and design of reactor systems should be backed up by thorough mathematical modelling. For several known reactions in given agitation systems such modelling has already been done. It is often based on a proper framework of physical chemistry.

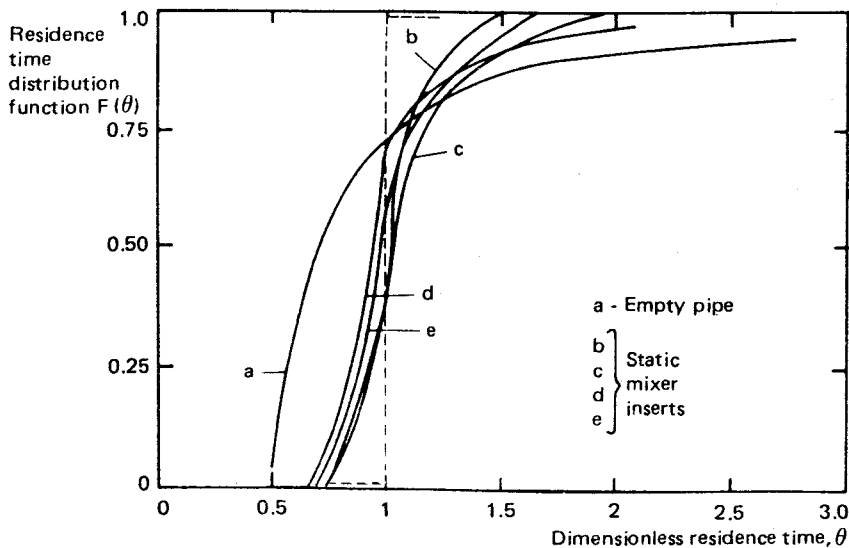


Fig. 4. Residence time distribution (RTD) function for laminar pipe flow.

### Continuous operations

Most of the discussion in the foregoing is relevant for continuous operations as well. Understanding and also the mathematical modelling (especially required in the design of control systems) are made possible by some rather elegant concepts in chemical engineering; these being:

- residence time distribution (RTD)
- dispersion coefficient, and
- micromixing.

RTD, as the name suggests, is the distribution of time spent by fluid elements in the reactor. A typical curve is shown in Fig.4. As it can be visualised, RTD is directly related to fluid flow and velocity patterns. Dispersion coefficient incorporates RTD (i.e. also the velocity distribution) and molecular or thermal diffusivities. These two concepts are only partially helpful especially in a reacting system. The importance of mixing at micro level has also been realised, especially in continuous reactors where the residence time is rather short. Here, mixing at the levels of small eddies (larger than

**If considerations are restricted only to conversion of reactants (and not to the details of product yield) then the maximum mixedness gives the lowest possible conversion of reactants for reaction orders greater than one and highest conversion for reaction orders less than one.**

molecular level) needs to be quantified. The upper limit on micromixing has been termed as the state of maximum mixedness, where the mixing occurs immediately at the entrance. If considerations are restricted only to conversion of reactants (and not to the details of product yield) then the maximum mixedness gives the lowest possible conversion of reactants for reaction orders greater than one and highest

conversion for reaction orders less than one. Complete segregation gives 'the highest possible' conversion for orders greater than one and the lowest conversion for orders less than one. The conversion for a first-order reaction is entirely determined by RTD and it is independent of the level of micromixing.

On various reactor systems mathematical modelling involving both fluid dynamics as well as physical chemistry is often done using the above noted concepts. There are several books written on this topic, which should be looked into for more details.

### Concluding remarks

"Keyjobs", that are to be done by agitated systems, were outlined in the foregoing. A precise knowledge of the keyjob is a most important prerequisite before one goes to design, select or operate such a system. Criteria of the selection of design and operating condition should always follow from the physics of a situation, as has been emphasised in the foregoing. □