Mixing

For our purposes, mixing is defined as a process that tends to result in a randomization of dissimilar particles within a system. This is to be

Fluids Mixing

Fundamentals

Flow Characteristics. Fluids may generally be classified as Newtonian or non-Newtonian, depending on the relationship between their

shear rates and the applied stress. Forces of shear are generated by interactions between moving fluids and the surfaces over which they flow during mixing. The rate of shear may be defined as the derivative of velocity with respect to distance measured normal to the direction of flow (dv/dx). The viscosity (dynamic) is the ratio of shear stress to the shear rate. For Newtonian fluids, the rate of shear is proportional to the applied stress, and such fluids have a dynamic viscosity that is independent of flow rate. In contrast, non-Newtonian fluids exhibit apparent dynamic viscosities that are a function of the shear stress.

The flow characteristics and mixing behavior of fluids are governed by three primary laws or principles: conservation of mass, conservation of energy, and the classic laws of motion. The

Mixing Mechanisms. Mixing mechanisms for fluids fall essentially into four categories: bulk transport, turbulent flow, laminar flow, and molecular diffusion. Usually, more than one of these processes is operative in practical mixing situations.

1. *Bulk transport.* The movement of a relatively large portion of the material being mixed from one location in the system to another con-

stitutes bulk transport. A simple circulation of material in a mixer, however, does not necessarily result in efficient mixing. For bulk transport to be effective it must result in a rearrangement or permutation of the various portions of the material to be mixed. This is usually accomplished by means of paddles, revolving blades, or other devices within the mixer arranged so as to move adjacent volumes of the fluid in different directions, thereby shuffling the system in three dimensions.

2. *Turbulent mixing.* The phenomenon of turbulent mixing is a direct result of turbulent fluid flow, which is characterized by a random fluctuation of the fluid velocity at any given point within the system. The fluid velocity at a given instant may be expressed as the vector sum of its components in the x, y, and z directions. With turbulence, these directional components fluctuate randomly about their individual mean values, as does the velocity itself.

In the case of turbulent flow in a pipe, the mean velocity in the direction of flow through the pipe is positive, of course, and varies somewhat depending on the distance from the pipe wall. In contrast, the mean velocity perpendicular to the wall is zero. The churning flow charac-

Turbulent flow can be conveniently visualized as a composite of eddies of various sizes. An eddy is defined as a portion of fluid moving as a unit in a direction often contrary to that of the general flow. Large eddies tend to break up, forming eddies of smaller and smaller size until they are no longer distinguishable. The size distribution of eddies within a turbulent region is referred to as the *scale* of turbulence.

3. *Laminar mixing*. Streamline or laminar flow is frequently encountered when highly viscous fluids are being processed. It can also occur if stirring is relatively gentle and may exist adjacent to stationary surfaces in vessels in which the flow is predominantly turbulent. When two dissimilar liquids are mixed through laminar flow, the shear that is generated stretches the interface between them. If the mixer employed folds the layers back upon themselves, the number of layers, and hence the interfacial area between them, increase exponentially with time. This relationship is observed because the rate of increase in interfacial area with time is proportional to the instantaneous interfacial area.

Example. Consider the case wherein the mixer produces a folding effect and generates a complete fold every 10 seconds. Given an initial fluid layer thickness of 10 cm, a thickness reduction by a factor of 10^{-8} is necessary to attain layers 1 nm thick, which approximate molecular dimensions. Since a single fold results in a layer thickness reduction of one half, n folds are required where:

$$(1/2)^n = 10^{-8}$$

or in logarithmic form, $\log[(½)^n] = n \log ½ = \log 10^{-8} = -8$. Therefore:

$$n = -8/\log ½ = 26.6$$

Thus, the time required for mixing is equal to n times 10 seconds (266 sec), or 4.43 min.

reach molecular dimensions. Therefore, good mixing at the molecular level requires a significant contribution by molecular diffusion after the layers have been reduced to a reasonable thickness (several hundred molecules) by laminar flow.

4. *Molecular diffusion.* The primary mechanism responsible for mixing at the molecular level is diffusion resulting from the thermal motion of the molecules. When it occurs in conjunction with laminar flow, molecular diffusion tends to reduce the sharp discontinuities at the interfaces between the fluid layers, and if allowed to proceed for sufficient time, results in complete mixing.

The process is described quantitatively in terms of Fick's first law of diffusion:

$$\frac{dm}{dt} = -DA\frac{dc}{dx} \qquad (1)$$

where the rate of transport of mass, dm/dt, across an interface of area A is proportional to the concentration gradient, dc/dx, across the interface. The rate of intermingling is governed also by the diffusion coefficient, D, which is a function of variables including fluid viscosity and the size of the diffusing molecules. The sharp interface between dissimilar fluids, which has been generated by laminar flow, may be rather quickly obliterated by the ensuing diffusion. Considerable time may be required, however, for the entire system to become homogeneous.

The concentration gradient at the original boundary is a decreasing function of time, approaching zero as mixing approaches completion. Since the amount of material passing a boundary plane in a given time depends on the concentration gradient, the time required to attain complete uniformity may be considerable unless the fluid layers are very thin.

5. *Scale and intensity of segregation.* The quality of mixtures must ultimately be judged upon the basis of some measure of the random distribution of their components. Such an evaluation depends on the selection of a quantitative method of expressing the quality of randomness or "goodness of mixing." Danckwerts has suggested two criteria that are statistically defined and may be applied to mixtures of mutually soluble liquids, fine powders, or gases. Perhaps the

tration gradients between adjacent lumps. On this basis, Danckwerts defined "two quantities to describe the degree of mixing—namely the *scale of segregation* and the *intensity of segregation*."

The scale of segregation is defined in a manner analogous to the scale of turbulence discussed earlier, and may be expressed in two ways: as a linear scale or as a volume scale. The linear scale may be considered to represent an average value of the diameter of the lumps present, whereas the volume scale roughly corresponds to the average lump volume.

The intensity of segregation is a measure of the variation in composition among the various portions of the mixture. When mixing is complete, the intentsity of segregation is zero.

6. *Time dependence.* In any given case, the

Equipment

Batch Mixing. When the material to be mixed is limited in volume to that which may be conveniently contained in a suitable mixer, batch mixing is usually most feasible. A system for batch mixing commonly consists of two primary components: (1) a tank or other container suitable to hold the material being mixed, and (2) a means of supplying energy to the system so as to bring about reasonably rapid mixing. Power may be supplied to the fluid mass by means of an impeller, air stream, or liquid jet. Besides

1. *Impellers.* The distinction between impeller types is often made on the basis of type of flow pattern they produce, or on the basis of the

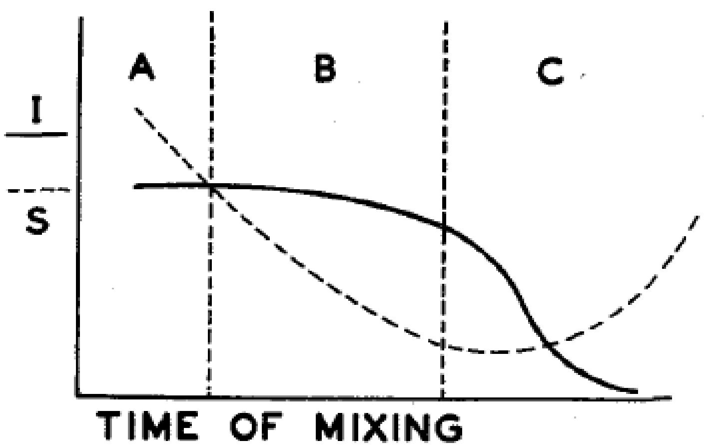

FIG. 1-1. *The intensity of segregation, I, and the scale of segregation, S, as a function of time. Bulk transport, turbulent mixing, and molecular diffusion are predominant over the time periods A, B, and C, respectively. The linear scale of segregation may be seen to increase at the end of the mixing operation. The final mixture will be uniform in composition and may be considered a single lump with a linear scale equal to the linear dimensions of the mixer.*

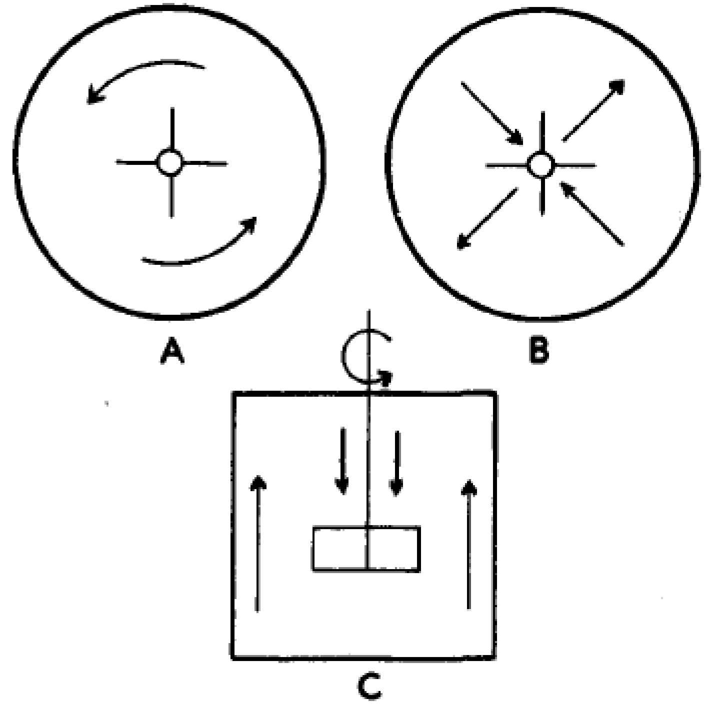

FIG. 1-2. A *and* B, *Diagrammatic representation of cylindric tanks in which tangential and radial flow occur, respectively.* C, *Side view of a similar tank in which axial flow occurs. These diagrams represent systems in which only one type of flow occurs, in contrast to the usual situation in which two or more of these flow patterns occur simultaneously.*

shape and pitch of the blades. Three basic types of flow may be produced: radial, axial, and tangential. These may occur singly or in various combinations. Figure 1-2 illustrates these patterns as they occur in vertical cylindric tanks. Propellers characteristically produce flow parallel to their axes of rotation, whereas turbines may produce either axial or tangential flow, or a combination of these.

Propellers of various types and form are used but all are essentially a segment of a multithreaded screw, that is, a screw with as many threads as the propeller has blades. Also, in common with machine screws, propellers may be either right-or left-handed depending on the direction of slant of their blades. As with screws, propeller pitch is defined as the distance of axial movement per revolution if no slippage occurs. Although any number of blades may be used, the three-blade design is most common for use with fluids. The blades may be set at any angle or pitch, but for most applications, the pitch is approximately equal to the propeller diameter. Propellers are most efficient when they can be run at high speed in liquids of relatively low viscosity.

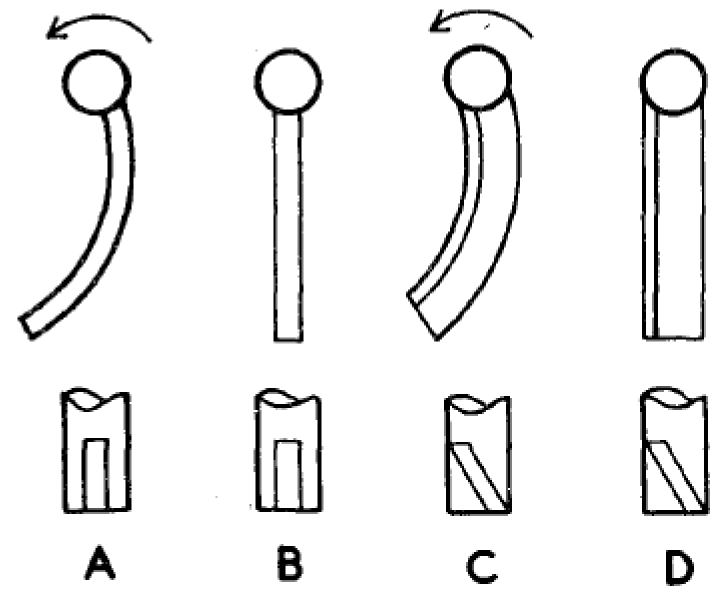

FIG. 1-3. *Impeller blade types (only one blade shown), top and side views. A and B, Radial flow design: C and D, mixed radial-axial flow design. For axial pumping, the blade must be set at an incline to the axis of the shaft.*

Turbines are usually distinguished from propellers in that the blades of the latter do not have a constant pitch throughout their length. When radial-tangential flow is desired, turbines with blades set at 90-degree angle to their shaft are employed (Fig. 1-3A,B). With this type of impeller, radial flow is induced by the centrifugal action of the revolving blades. The drag of the

Paddles also are employed as impellers and are normally operated at low speeds, 50 rpm or less. Their blades have a large surface area in relation to the tank in which they are employed, a feature that permits them to pass close to the tank walls and effectively mix viscous liquids or semisolids, which tend to cling to these surfaces. Circulation is primarily tangential, and consequently, concentration gradients in the axial and radial directions may persist in this type of mixer even after prolonged operation. Operating procedures should take these characteristics into account so as to minimize their

2. *Air jets*. Subsurface jets of air, or less commonly of some other gas, are effective mixing devices for certain liquids. Of necessity and for obvious reasons, the liquids must be of low viscosity, nonfoaming, unreactive with the gas employed, and reasonably nonvolatile. The jets are usually arranged so that the buoyancy of the bubbles lifts liquid from the bottom to the top of the mixing vessel. This is often accomplished with the aid of draft tubes (Fig. 1-4). These serve to confine the expanding bubbles and entrained liquid, resulting in a more efficient lifting action by the bubbles. The overall circulation in the mixing vessel brings fluid from all parts of the tank to the region of the jet itself. Here, the intense turbulence generated by the jet produces intimate mixing.

3. *Fluid jets*. When liquids are to be pumped into a tank for mixing, the power required for pumping often can be used to accomplish the mixing operation, either partially or completely. In such a case, the fluids are pumped through nozzles arranged to permit good circulation of material throughout the tank. In operation, fluid jets behave somewhat like propellers in that they generate turbulent flow in the direction of

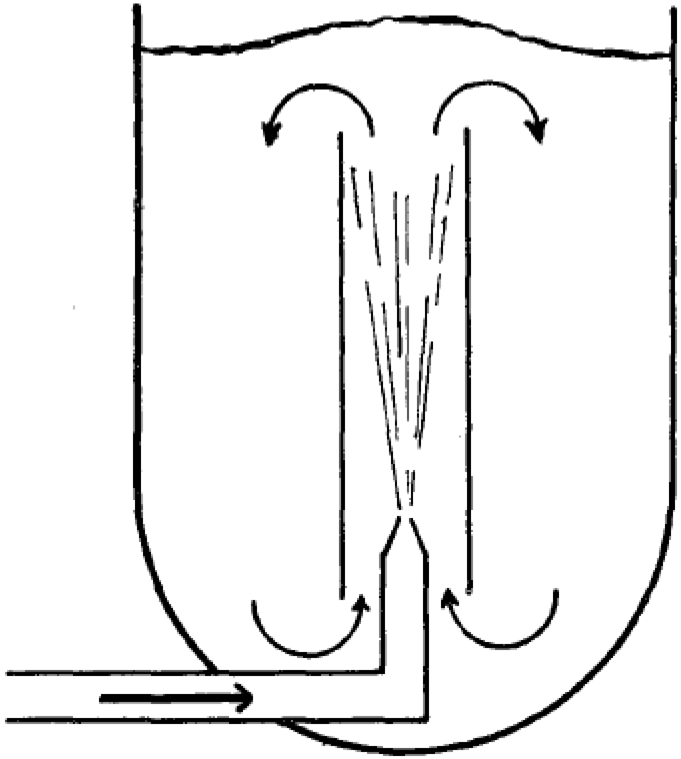

FIG. 1-4. *Vertical tank with centrally located air jet and draft tube. Bubbles confined within the draft tube rise, inducing an upward fluid flow in the tube. This flow tends to circulate fluid in the tank, bringing it into the turbulent region in the vicinity of the jet.*

4. *Baffles.* Bulk transport is important in mixing (see under previous section, "Mixing Mechanisms") and is particularly desirable in the initial stages, when segregation may be present on a large scale. For bulk fluid flow to be most effective, an intermingling must occur between material from remote regions in the mixer. To accomplish this, it is frequently necessary to install auxiliary devices for directing the flow of the fluid, usually baffle plates. Baffle placement depends largely on the type of agitator used.

Continuous Mixing. The process of continuous mixing produces an uninterrupted supply of freshly mixed material and is often desirable when very large volumes of material are to be handled. It can be accomplished essentially in two ways: in a tube or pipe through which the material flows and in which there is very little back flow or recirculation, or in a chamber in which a considerable amount of holdup and recirculation occur. (Fig. 1-5).

To ensure good mixing efficiency, such devices as vanes, baffles, screws, grids, or combinations of these are placed in the mixing tube. As illustrated in Figure 1-5A, mixing takes place mainly through mass transport in directions normal to that of the primary flow. Mixing in such systems requires the careful control of the feed rate of raw materials if a mixture of uniform composition is to be obtained. The requirement of exact metering in such a device results from the lack of recirculation, which would otherwise tend to average out concentration gradients along the pipe. Where suitable metering

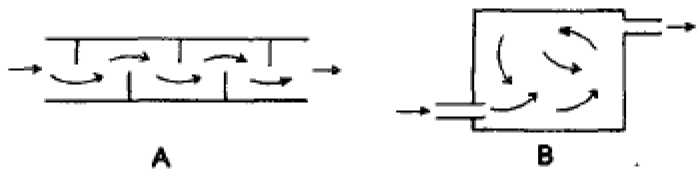

FIG. 1-5. *Continuous fluids mixing devices.* A, *Baffled pipe mixer;* B, *mixing chamber with flow induced recirculation. Both types induce turbulence in the fluid; however, recirculation is desirable when overall fluctuations occur in the material fed to the mixer, since these fluctuations will not be eliminated by simple transverse mixing in a pipe.*

Mixer Selection

Equipment Selection. One of the first and often most important considerations in any mixing problem is equipment selection. Factors that must be taken into consideration include (1) the physical properties of the materials to be mixed, such as density, viscosity, and miscibility, (2) economic considerations regarding processing, e.g., time required for mixing and the power expenditure necessary, and (3) cost of equipment and its maintenance. In any given case, a

1. *Monophase systems.* The viscous character and density of the fluid(s) to be mixed determine to a large extent the type of flow that can be produced and also, therefore, the nature of the mixing mechanisms involved. Fluids of relatively low viscosity are best mixed by methods that generate a high degree of turbulence and at the same time circulate the entire mass of material. These requirements are satisfied by air jets, fluid jets, and the various high-speed impellers discussed earlier. A viscosity of approximately 10 poise may be considered as a practical upper limit for the application of these devices.

Thick creams, ointments, and pastes are of such high viscosity that it is difficult if not impossible to generate turbulence within their bulk and laminar mixing, and molecular diffusion must be relied upon. Mixing of such fluids may be done with a turbine of flat blade design. A characteristic feature of such impellers is the relative insensitivity of their power consumption to density and/or viscosity. For this reason, they are particularly good choices when emulsification or added solids may change these quantities significantly during the mixing operation. This

2. *Polyphase systems.* The mixing of systems composed of several liquid or solid phases primarily involves the subdivision or deaggregation of one or more of the phases present, with subse-

The mixing of two immiscible liquids requires the subdivision of one of the phases into globules, which are then distributed throughout the bulk of the fluid. The process usually occurs by stages during which the large globules are successively broken down into smaller ones. Two primary forces come into play here: the interfacial tension of the globules in the surrounding liquid, and forces of shear within the fluid mass. The former tends to resist the distortion of globule shape necessary for fragmentation into smaller globules, whereas the forces of shear act to distort and ultimately disrupt the globules. The relationship between these forces largely determines the final size distribution in the mixture.

Highly viscous fluids, such as are encountered in the production of ointments, are efficiently dispersed by the shearing action of two surfaces in close proximity and moving at different velocities with respect to each other. This is achieved in paddle mixers, in which the blades clear the container walls by a small tolerance. Such mixers are relatively efficient since they not only generate sufficient shear to reduce globule size but if properly constructed, also induce sufficient circulation of material to ensure a uniform dispersion throughout the completed mixture.