Principles of Mixing in the Fatty Oil Industries

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LIQUID MIXING plays a part in almost all oil-industry processes. It is an operation whereby different fluids are made to interpenetrate one another to achieve homogeneity. With miscible liquids the result is blending; with immiscible liquids, dispersions or emulsions are formed; with gases and liquids, dispersions result; and with solids and liquids, suspensions are formed. If fluids are to be heated or cooled, mixing provides the mechanism for making the temperature uniform.

Mixing serves different purposes in the different processes. The blending of feed stocks and the blending of finished products are essential for economy of operation and quality control. Caustic or other alkalies are mixed with oil to refine it and to remove fatty acids as soaps. Steam and oil are contacted and mixed to remove odor bodies and fatty acids. Hydrogen and oils are contacted and mixed (and finely divided nickel catalyst is suspended at the same time) for hydrogenation. Solids are suspended in oil by mixing for such processes as clay treating.

All processes that use mixing involve transfer of matter, either to produce uniformity of composition or to move reactants to an interface. Blending of miscible liquids can take place slowly by molecular diffusion and natural convection, but a mixer forces convection so that homogeneity can be attained quickly. Hence the energy spent for mixing must be justified on the basis of the shorter time required and the greater uniformity of product.

Forced convection is achieved in two ways. One is typified by small currents such as are present in turbulent fluid motion. These eddies move material short distances in all directions and thus provide small-scale material transfer and mixing. This is the "agitation" mechanism of mixing. On the other hand, large scale motion results from a major current of mass flow traveling a long distance and transporting large quantities of material.

The proper combination of turbulence and mass flow is necessary for economical use of mixing energy. Optimum use of power is achieved by applying the proper ratio to each type of motion. The amount of each motion is a function of the physical properties of material, the manner in which they are fed to each other, and shape of the mixing vessel. The mixer itself produces mechanical effects only. Any chemical effect is a result of mass transfer to interfaces where reactions can occur.

Process Requirements

Different mechanical effects can be obtained with different types of mixers, thus the needs of the process determine the best type of mixer to be used.

Batch blending uses mixers to distribute miscible components uniformly: the mixer is operated as long as necessary to accomplish the purpose. Continuous blending requires that mixers distribute the components so rapidly that no holding time is needed to achieve uniformity of large volumes.

Treating, washing, and refining processes use mixers to distribute immiscible liquids uniformly in drop form. Small drops that settle easily are best. Turbulence in the continuous phase is also desired to promote mass transfer.

Gas-liquid contacting, such as steam-stripping, has the same process requirements as treating, washing, and extracting. The mixer flow forms small gas bubbles and distributes them uniformly through the turbulent liquid phase.

Where solid or liquid catalysts must be suspended in liquids, the mixer must supply sufficient velocity and momentum to lift the solid particles and distribute them uniformly.

In all these processes one requirement is common, uniformity of distribution. Differences arise from the types of material to be handled, the speed with which the materials must be mixed, the drop or bubble size to be formed, the flow velocity required, and the turbulence necessary.

In each of these processes except blending, material is transferred to reaction interfaces by molecular diffusion and forced convection. Diffusion rates are fixed by temperature, but convection rates may be raised to increase mass transfer. The rate equation for mass transfer is

$$W = K_L A \triangle C \qquad (1)$$

where W is is the amount of material transferred per unit time across an interface of area A. The size and number of drops, bubbles, or solid particles govern the area A. K_L, the coefficient of mass transfer is based on the continuous phase and is a function of fluid motion and turbulence. $\triangle C$, the concentration gradient, can be maximized by thorough distribution of components.

A mixer can thus be used to increase the rate of mass transfer in three ways: by increasing the interfacial area A, by distributing the components uniformly and rapidly, and by increasing the coefficient K_L in the continuous phase. Mass transfer through the drop or bubble is unaffected by a mixer; hence, if the major resistance to mass transfer is known to lie in one liquid, the mixer will have its maximum effect if that liquid is chosen as the continuous phase.

When heat is to be transferred either to or from a reaction, the mixer provides the turbulence and flow over the heat-transfer surfaces that give high rates of transfer. When close control of temperature is needed to maximize yield or minimize side reactions, the mixer serves by distributing reactants and heat rapidly and uniformly. The principle of controlling temperature by rapid dispersion of reactants into a large mass of liquid is highly important to mixing in continuous-flow equipment.

Theory Behind Mixing

Because mixing is a physical process involving fluid motion, it depends upon the mechanics of moving fluid streams and the means by which they are moved. Fluid is moved either by an impeller rotating in a tank or by a pump forcing it through a pipeline or into a large vessel. The amount and velocity of such flows are known for the major types of impellers (4) and can be determined easily for

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pumps. The formation, spread, and propagation of turbulence are functions of the size of the container, the velocity of the stream, and the viscosity and density of the fluid.

In flowing streams there are three principal causes for the initiation of turbulent currents. Rapid flow along a smooth or rough wall will result in "boundary-layer" turbulence. Turbulence in a pipeline is generated this way. Flow around a projection or a sharp change of direction will produce "form separation" and turbulence. An orifice or a screen in a pipeline produces this effect. A high-velocity flow moving past slower-moving fluid results in "velocity discontinuity" and turbulence. A jet of fluid or the discharge from an impeller causes turbulence by this mechanism. Regardless of the manner by which turbulence is initiated, the result is a three-dimensional eddy.

Turbulence is defined in terms of scale and intensity. Scale is the diameter of the eddy, and intensity is the instantaneous velocity of it. The product of scale (L) and velocity (u) is known as eddy viscosity. For a given amount of turbulence it may be made up of a large scale and low velocity or of a low scale and high velocity. To date, it has not been possible to evaluate turbulence other than as a product, yet the mixing effect of equal values of (Lu) may differ widely with the scale (L) value of the turbulence.

A basic property of turbulence is that it continually changes in both scale and intensity. Energy of eddy motion is dissipated to heat through viscous shear because of the velocity discontinuity between the eddy and the surroundings. Some eddies grow in size at the expense of others; thus, when turbulence is once generated, it spreads in volume but declines in energy to both smaller and larger eddies.

The viscosity of a fluid is a basic property affecting scale and propagation of turbulence. The ratio of turbulence (Lu) to kinematic viscosity (ν) is the Reynolds number (Lu/ν). Coefficients of mass transfer and heat transfer are often correlated with the Reynolds number because these mechanisms are functions of turbulent motion. The characteristics of mixing impellers and the results of their operation can also be related to the Reynolds number (3).

Velocity fluctuations in flowing streams can be measured and related to turbulence. If the instantaneous velocity of flow in an axial direction is designated as u and the average stream flow in the same direction is $\bar{u}$, then the instantaneous velocity fluctuation u' is defined as

$$u' = u - \bar{u} \qquad (2)$$

The average of the velocity fluctuations, computed as the root-mean-square $\sqrt{\bar{u}'^2}$, is proportional to the velocity of the eddies and thus to the turbulence Lu.

Power, in ft. lb./sec., is equal to the product of the rate of flow, Q, the fluid density, ρ, and the head, H, against which the flow takes place:

$$P = \rho Q H \qquad (3)$$

H is the total of all kinetic and potential heads. Kinetic heads are due to mass flow in the axial direction, to turbulence, and to rotary or non-axial flow. The kinetic head of mass flow is calculated from the average velocity $\bar{u}$, of turbulence from the fluctuation velocity u', and of non-axial flow from the corresponding velocity (4).

Equipment Used for Mixing in Oil Processing

Mixing is accomplished by six principal techniques: pipeline flow, turbulence generators in pipelines, mechanical mixers in pipelines, expanding jets, steam or air blowing, and rotating impellers. The first five depend almost entirely on turbulence whereas the rotating impellers supply both mass flow and turbulence. The best mixing technique for any particular application is that with the lowest operating cost consistent with process requirements, flexibility, control, and maintenance.

Pipeline Flow. The energy for mixing in a pipeline is applied by a pump or ejector that forces the fluid through the line at high enough velocity to produce turbulence. Some turbulence is produced by the rotating impeller of the pump, but most is produced by the boundary-layer at the pipe wall. Higher velocities and smaller pipe diameters produce more turbulence. Longer pipes allow more time for mixing and also develop more turbulence. The amount of energy expended is proportional to the turbulence formed; it is often measured by the pressure drop in the line.

There is a serious limitation to pipeline mixing. The turbulence generated results in good mixing perpendicular to the pipe axis but allows little mixing in an axial direction.

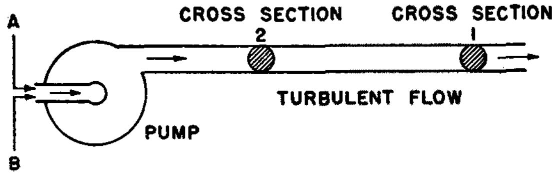


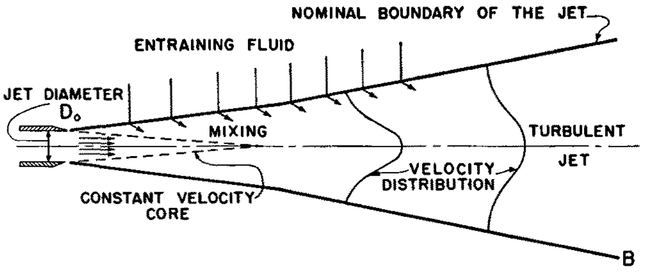
FIG. 1. Mixing of high velocity flow in a pipeline

Figure 1 illustrates the use of a pump and pipeline to mix components A and B. The material at cross-section 1 may be well mixed, and that at section 2 may also be well mixed. If the proportion of A and B entering the suction of the pump does not vary, the composition at section 1 will be exactly the same as at section 2, and the discharge from the line will be uniform. However if there is any fluctuation in either the A or B stream between the time the material at 1 and that at 2 entered the pump, the composition at 1 and 2 will not be the same. For uniform composition, material at 1 and 2 must be brought together. If precise proportioning devices were available so that the ratios of components could not vary, this method of mixing would be much more useful.

Pipeline mixing can be used efficiently in certain operations where proportioning is not critical. Water washing of finished products is an example. The proportioning device is adjusted so that the amount of water is always equal to or greater than the minimum required. If excess water is neither harmful nor costly and the washing requires relatively little turbulence, the energy consumption will be low and the operation will be economical. If however the treating agent is expensive, for example, caustic soda, then pipeline mixing is not well suited to the job.

Turbulence Generators. Many forms of "pipeline mixers," such as orifices, screens, valves, vanes, and tortuous-path devices, can be incorporated in a pipeline to act as turbulence generators. The energy is still supplied by the pump; turbulence is produced by form separation. The principal advantage of such devices is that they can be placed in short pipelines to produce more turbulence than could otherwise be generated. Because they usually cannot achieve mixing in an axial direction, they suffer the same limitation as pipeline flow. The energy spent for mixing is proportional to the pressure drop across the device.

Mechanical Pipeline Mixers. Machinery is available to create highly turbulent flow by means of high-speed rotating impellers encased in relatively close-fitting forms. Such "contactors" and "flowmix" devices provide the energy for turbulence and perform much like inefficient high-speed centrifugal pumps. They are used mostly to disperse immiscible liquids. Equivalent results can usually be obtained by applying the same amount of energy with an ordinary pump to a line containing a simple turbulence generator. If slugs of material are fed to these devices, they will persist and the discharge will contain non-uniform but well-mixed segments, as in the case of Figure 1.



AT B, TOTAL FLOW = 4 TIMES FLOW AT D_0

FIG. 2. Expansion of flow from a submerged circular jet.

Expanding Jets. When a stream of high-velocity fluid enters a fluid of low velocity, the high-velocity jet will expand and entrain and mix the surrounding fluid through the turbulence mechanism. Figure 2 is a schematic diagram of the spread of a circular jet flowing into a quiet fluid. At the nominal boundary of the jet the velocity discontinuity is sufficient to initiate turbulence, which then spreads toward the center of the stream. The material accelerated at the boundary of the flow is thus entrained and becomes a part of the turbulent flowing jet. The kinetic energy of mass flow is used for entrainment. The distance over which a jet will entrain is a function of its velocity. It is this phenomenon of the expanding jet that allows axial as well as non-axial mixing to be achieved by a flowing stream. In Figure 1, sections 1 and 2 can be brought together and mixed by an expanding jet. More mixing is accomplished by the expanding jet for the same energy cost than by any of the pipeline turbulence generators.

Fluid jets may be formed by flow from any size of pipe. Sometimes a constriction in the form of a nozzle is used. Sometimes the pipe is inclined to force the jet toward the surface of the liquid (Figure 3). The jet will give mass flow in addition to turbulent flow. The entire contents of a tank can be entrained by the jet, and the whole mass can thus be made homogeneous.

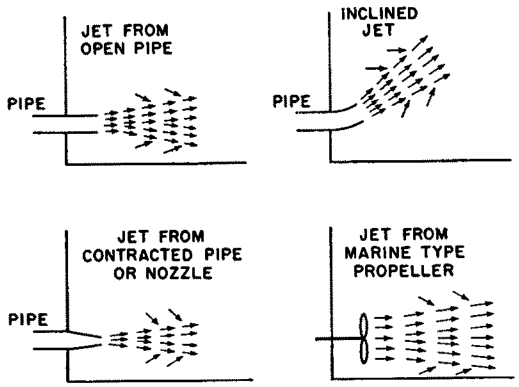


FIG. 3. Entraining mixing jets.

Two types of jets are recognized in mixing, the "pure" jet, which leaves a circular pipe or nozzle, and the "propeller" jet, which is produced by an uncased propeller (Figure 9). The kinetic energy in a pure jet is almost entirely axial-flow energy; the initial turbulent energy is small. A propeller jet initially has spiral flow and turbulence. Spiral flow can be resolved into axial and non-axial components. Thus the jet from a propeller has less energy in axial flow and more energy in non-axial flow and turbulence than the pure jet. This difference accounts for the superior mixing performance of the propeller jet over that of the pure jet (4).

Jets from pipes or nozzles are used for mixing during the filling of tanks, also for recirculation of the contents of a tank through an external pump. The jet must have enough velocity and momentum to penetrate to the most remote portion of the tank. A jet can be made to entrain for large distances, but there is an optimum jet diameter for a given distance per unit of power expended (1). For a pure jet the theoretical optimum diameter for maximum entrainment per unit of power is $\frac{1}{17}$th of the entraining distance. For example, if a jet is to be used in a tank 20 ft. in diameter and is to entrain for a distance of 17 ft., the optimum pipe opening would be 1 ft. For tanks 100 ft. in diameter and more, it is not feasible to use jets of optimum size. Accordingly the propeller is used to give the large diameter flow as required for best mechanical efficiency.

Steam and Air Blowing. One of the oldest methods of mixing, still used in many refineries for steam stripping and deodorizing and other finishing operations, is steam blowing. Steam is blown through small holes in sparge pipes into the bottom of a liquid to produce turbulence. The rate of mixing is low for the energy expended, partly because of the large energy loss in expansion of the steam and partly because of the lack of liquid circulation. Rates of steam stripping can always be increased by the use of a mechanical mixer to create smaller bubbles and to achieve higher mass transfer coefficients (5).

Air blowing can seldom be justified. Exceptions are in fully depreciated installations, where excess air-compressor capacity makes the cost for the operation insignificant, or in shallow tanks where other methods are unsuitable. In new installations, when air contacting is necessary, a combination of air blowing and mechanical mixing gives faster rates of reaction for the same energy input (5).

Rotating Impellers. The most versatile mixers available to the oil industry are rotating impellers. More is understood about the performance of this type than of others. They operate freely in tanks of relatively large size and can be used in batch or continuous processing.

Most mechanical mixers are axial-flow propellers (Figure 9). Radial-flow impellers however are used in increasing numbers because they are adaptable to a wide variety of requirements and their mixing characteristics are well known. Simple rotating paddles are used much less frequently than in the past.

The inherent advantage of mechanical mixers is that both mass flow and turbulence can be generated to any desired extent. Uniform distribution of components can be achieved rapidly. The interaction of the impeller, the fluid, and the container are of utmost importance. There have been many misconceptions about the behavior of impellers, but much research during the past decade has greatly increased our knowledge (4).

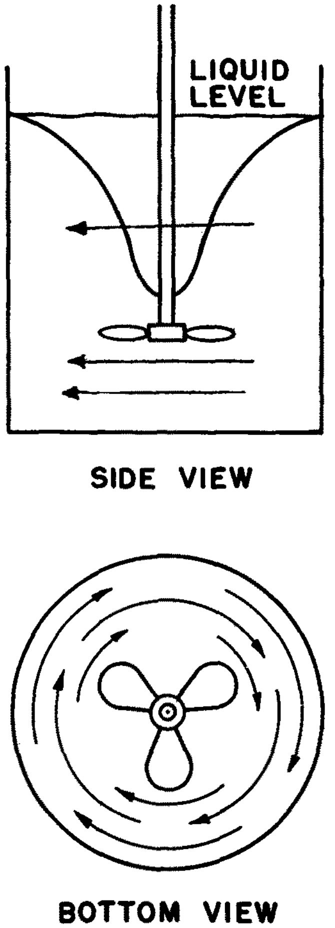


FIG. 4. Swirling flow pattern for impeller of any shape, without baffles.

Figure 4 illustrates the flow pattern for a single impeller of any shape, a marine propeller, a flat-blade turbine, or a flat paddle, rotating in a low-viscosity liquid in a cylindrical tank without baffles. A vortex forms, around which the liquid swirls. This motion often results in separation or stratification rather than mixing. The liquid moves in large circular paths with little vertical motion.

Mixing in a tank is best accomplished when there are vertical and lateral flow currents that distribute material rapidly to all areas. An effective and convenient way to obtain vertical as well as lateral flow is to prevent swirling by using four vertical baffles at or near the tank wall (Figures 5 and 6). These flow patterns are conducive to good mixing. Much more power can be exerted to produce mixing when swirling and vortex formation are avoided.

Baffles can be avoided and swirling eliminated with

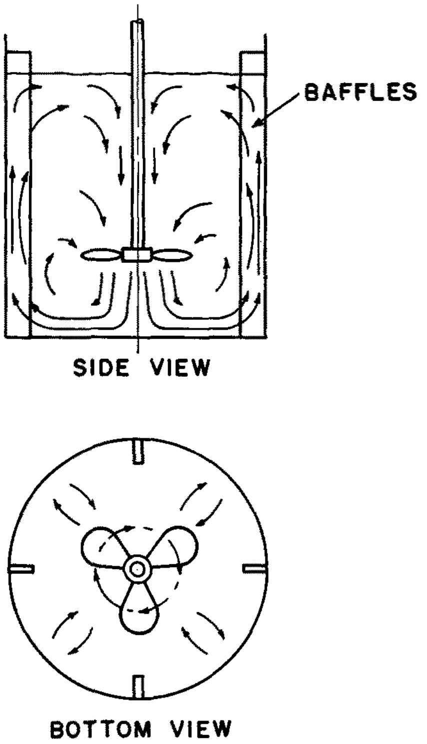


FIG. 5. Flow pattern for propeller with baffles at tank wall.

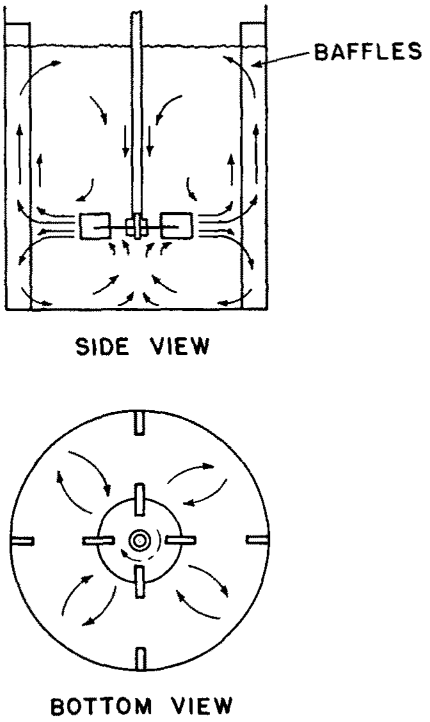


FIG. 6. Flow pattern for turbine with baffles at tank wall.

propellers located at certain "off-center" positions. Figure 7 shows a propeller shaft entering through the surface of the liquid. When the propeller turns counter-clockwise and the discharge is downward, the shaft is placed to the left of the center line and at an angle to the verticle. Many processes use propellers mounted this way. The exact mounting position is critical; and significant change will cause rotary flow.

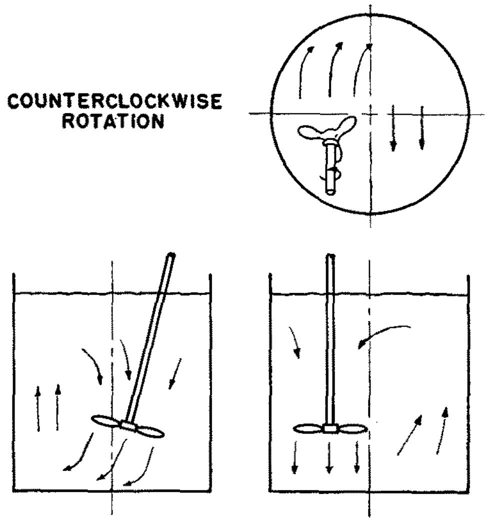


FIG. 7. Flow pattern for propeller top-entering, off-center, without baffles.

In large tanks for blending raw oils, propeller shafts are mounted through the side of the tank. To avoid the need for baffles the shaft is placed parallel to the bottom and to the left of a diameter when the rotation is clockwise. Again the angle off-center is critical. Figure 8 illustrates proper and improper placement of side entering propellers. Figure 9 shows a picture of a typical installation.

The interrelation of power, flow, and turbulence as produced by impellers must be understood for proper sizing of commercial equipment and for proper interpretation of pilot-plant results. Impeller performance must be compared on the basis of equal power input for if two impellers perform an operation equally well, the one using the lesser amount of power is the more efficient. Different amounts of mass flow and turbulence can be obtained from impellers of different size operating at the same power. The total power is proportional to the product of mass flow rate and turbulence. The ratio of Q/H from Equation 3 is a measure of the ratio of energy in mass flow and turbulence.

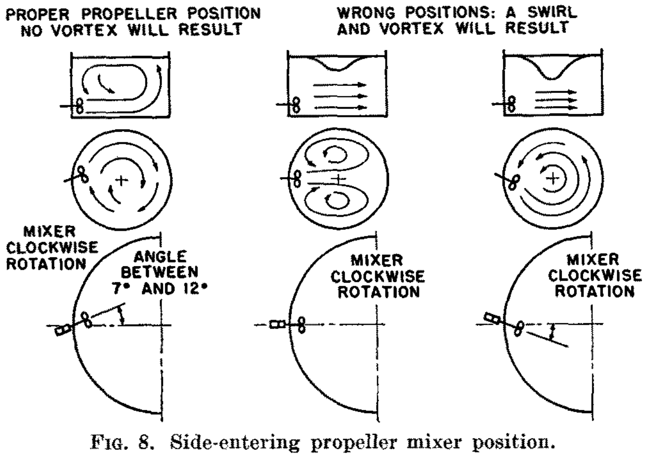


FIG. 8. Side-entering propeller mixer position.

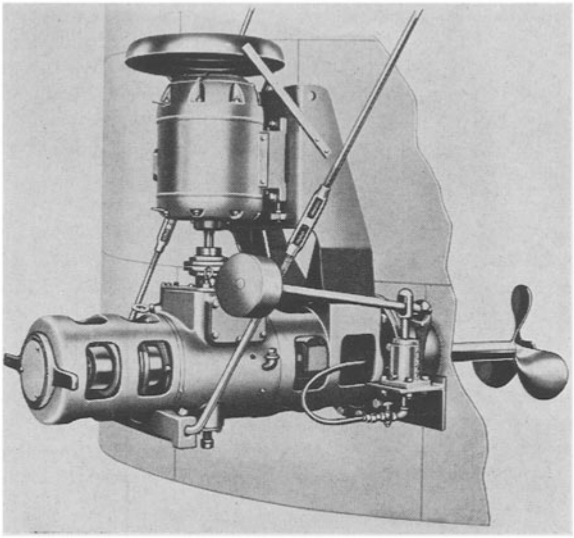


FIG. 9. Side-entering propeller mixer mounted on tank wall. *(Courtesy, Mixing Equipment Co.)*

The power necessary to rotate the most important types of impellers under various conditions is well known (3, 4). When swirling is eliminated and liquid viscosity is not high, the power, P, is proportional to the liquid density ρ, to the cube of speed of rotation N, and to the fifth power of the impeller diameter D. Or

$$P = \frac{K}{g} \rho N^3 D^5 \qquad (4)$$

where K is the proportionality constant and g is the gravity constant. Thus if liquid density is doubled, power must be doubled. If speed of rotation is doubled, power must be increased eight times. If impeller diameter is doubled, power must be increased 32 times.

The amount and velocity of flow from certain propellers and flat-blade turbines has been measured (4). The rate of discharge is proportional to the speed of rotation and to the cube of the diameter of the impeller. Thus if the speed of a propeller is doubled, the flow will double. If the diameter of a propeller is doubled, the flow will increase eight times.

Figure 10 illustrates the relations between diameter, speed, flow, and turbulence for dimensionally similar impellers at constant power and fully developed turbulence. The black bars represent kinetic energy in the principal flow; the shaded bars represent the energy of turbulence. The total energy in each stream is the same, but the ratio of flow to turbulence is different for each combination of diameter and speed.

To achieve equal power input to different size, geometrically similar impellers (and thus to have a basis for comparison of performance at equal expenditure of energy) equation 4 is used for two diferetnt impeller sizes. Thus if D_2 and D_1 identify the large and the small size impellers, respectively,

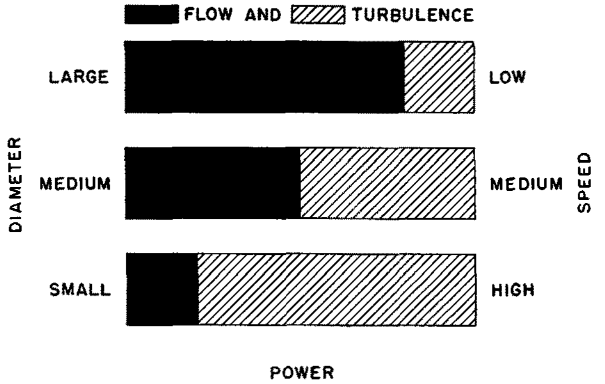


FIG. 10. Constant power. Effect of impeller size and speed on flow and turbulence.

and N_2 and N_1 the rotational speeds of the same impellers, then for equal power:

$$N_2/N_1 = \left(\frac{1}{D_2/D_1}\right)^{1.67} \qquad (5)$$

This shows, for example, that if an impeller D_2 is twice the size of an impeller D_1, then the larger impeller should run at a rotational speed of

$$N_2 = N_1\,(1/2)^{1.67}, \text{ or } N_2 = 0.316N_1.$$

In other words, the larger impeller, turning at 31.6% of the speed of the smaller impeller, will exert the same power on the system.

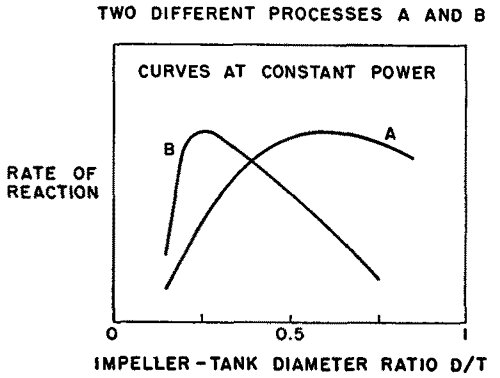


FIG. 11. Effect of impeller size on reaction rate at equal power input.

Although all mixing requires both flow and turbulence, some operations require more of one than the other. In Figure 11 reaction rate is plotted as a function of the ratio of the impeller and tank diameters (D/T) for dimensionally similar impellers in the same tank at constant power input. Curve A illustrates a process where the rate of reaction increased as impeller size was increased and reached a maximum with an impeller diameter equal to 0.6 of the tank diameter. Power was maintained constant by decreasing the speed for each increase in diameter. Curve B shows a process in which the maximum reaction rate was obtained with the impeller size equal to 0.25 of the tank diameter; larger impellers gave poorer results. Here are two processes to which the same energy was provided for mixing, yet one required a large impeller running at low speed and the other required a small impeller at high speed to use the energy best. The differences are based on the different flow and turbulence requirements of the processes. The large impeller at low speed gives more flow and less turbulence than the small impeller at high speed. Blending, solid suspension, and most extraction processes are of the type of curve A. Water washing is of this type also. Gas-liquid contacting, as in hydrogenation, is of type B. Caustic refining of oils is either of type B or intermediate between A and B.

The largest use of side-entering mixers is in blending. Off-centered propeller mixers, top-entering (Figure 7), are used for a wide variety of operations, such as, blending, dissolving, suspending of solids, and liquid-liquid contacting. These mixers may be of portable or of permanently mounted construction. Care must be taken that they are mounted in the proper position.

Turbine mixers are used for all types of process requirements. They are capable of producing wide ranges of flow to turbulence to take care of a wide variety of process requirements. They are used for blending, dissolving, suspending of solids, liquid-liquid contacting, and also for gas-liquid contacting. For hydrogenation, steam-stripping, or other gas-liquid operations where small bubbles and highly turbulent liquid are desired, the flat blade turbines are especially useful. The gas is distributed by a circular ring just below the impeller blade tips, or by a pipe directly below the center of the turbine. The disc of the turbine prevents gas by-pass up along the shaft and insures that all the gas is present in the highly turbulent discharge stream from the turbine.

Continuous cocurrent and countercurrent washing, extraction, and gas-liquid contacting are often performed with multiple impellers on a shaft in a vertical column. The column of Figure 12 is divided into sections by means of horizontal plates having large center openings. Here turbine impellers are located midway between the separating plates, and baffles run along the side wall. This combination gives the best flow for efficient mixing. Such columns have high through-put and can achieve equilibrium extraction efficiencies of 80% per section (2). The largest ones recently installed are 9 ft. in diameter and use three mixing stages. Some commercial columns have as many as 20 mixing stages with a single shaft holding the turbines.

Other extraction processes use mixer-settler combinations, in which the mixing is done by rotating turbines, propellers, or paddles.

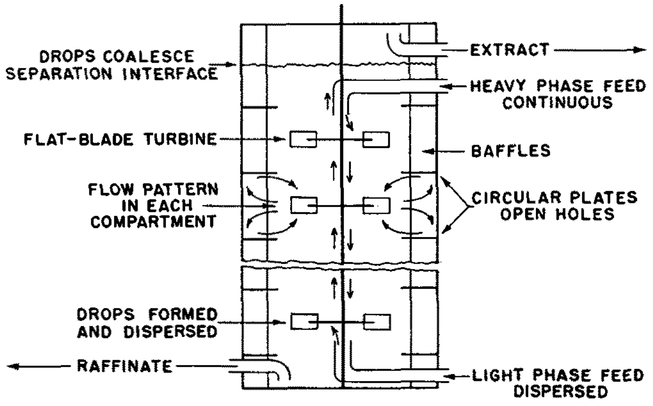


FIG. 12. Extraction column. Multiple mixer turbines.

In small tanks, turbine mixers can also be used in place of mechanical pipeline mixers for continuous treating. If the turbine is run to discharge a large flow compared to the rate of feed, rapid and uniform mixing will result and the product can be withdrawn continuously.

Conclusion

The principles of mixing are now so well understood that it is possible to determine the fluid motion best suited for any specific process. Equipment can be selected that will give the desired motion most economically. In some processes pipeline mixing is sufficient and convenient. Most operations require intermixing of materials on both large and small scales and can be done best with propellers and turbines operating in tanks.

At all stages of the development of a new process, exploratory-research, bench-scale, and pilot-plant, attention to the mixing impeller and tank arrangement is necessary so that equivalent results can be reproduced in commercial sizes. When scale models of propellers and turbines are used, with well-known flow, turbulence, and power characteristics, the mixers can be selected with assurance. Otherwise the sizing of large-scale equipment becomes mainly conjecture and improvisation.

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Automatic Control

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One of the most significant trends in the chemical industry has been the continuous development of more and more complex automatic control systems. The modern chemical processing plant depends to a large extent on automatic controls for much of its efficiency. Present indications are that this trend toward more automatic systems will continue and at an accelerated rate. This is due in large part to the contributions made to development of basic control theory and control equipment during the last 10 years. Much of this development has been directed specifically at military applications, but fortunately the problems involved in aiming a gun at an enemy target are much the same as those encountered in setting a valve in a process line. Before discussing future developments however, it is best to review briefly some of the progress made in chemical process control and to establish in a general way the characteristics of a typical chemical process control system. This system can then be used as a basis for discussion of future trends.

Process Control Problems

Before discussing control systems in detail, it will be best to spend a little time discussing some of the problems which are peculiar to chemical processes.

A characteristic feature of a chemical process is the large amount of work done with fluids—gas, liquid, and even solid. In the latter case the solids are finely divided and supported in a gas or liquid stream. Usually one or more fluid streams enter the process, pass through a number of processing units, and then flow out as finished products. The processing units probably do one or more of three basic steps: heat or cool the fluid, subject the fluid to conditions such that chemical changes occur, or mix the fluid with another material. The most characteristic chemical control problems are found in the handling of flowing fluids. The usual control device (in fact, practically the only control device) used in a chemical plant is the valve. By opening and closing valves, materials may be rerouted through the processing steps or the speed at which they are moving may be changed.

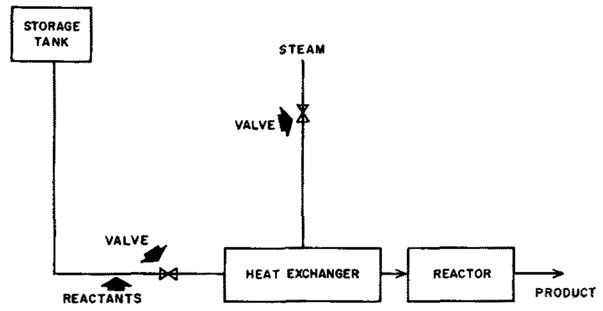

FIGURE 1

A typical chemical process is shown in Figure 1. The process is typical in that all the elements in it are common—not that such a process is often found in chemical plants. The process is described in some detail below because it will be used to illustrate the discussion of control systems given in the following sections.

The reactants are pumped from the storage tank, through the heat exchanger, and then through the reactor where a catalyst is used to increase the reaction rate. It will be assumed that the degree of reaction as measured by reactor effluent concentration is the critical product specification. The control agents which are available for changing the degree of reaction are the two valves, the one in the process flow stream and the other in the steam line to the heat exchanger. The factors which determine the settings of these valves can be listed as follows:

1. Changes in desired value of concentration in reactor effluent.

2. Changes in rate at which product is required. Short-term variations can be smoothed by providing a surge tank after the reactor. In the long run how-