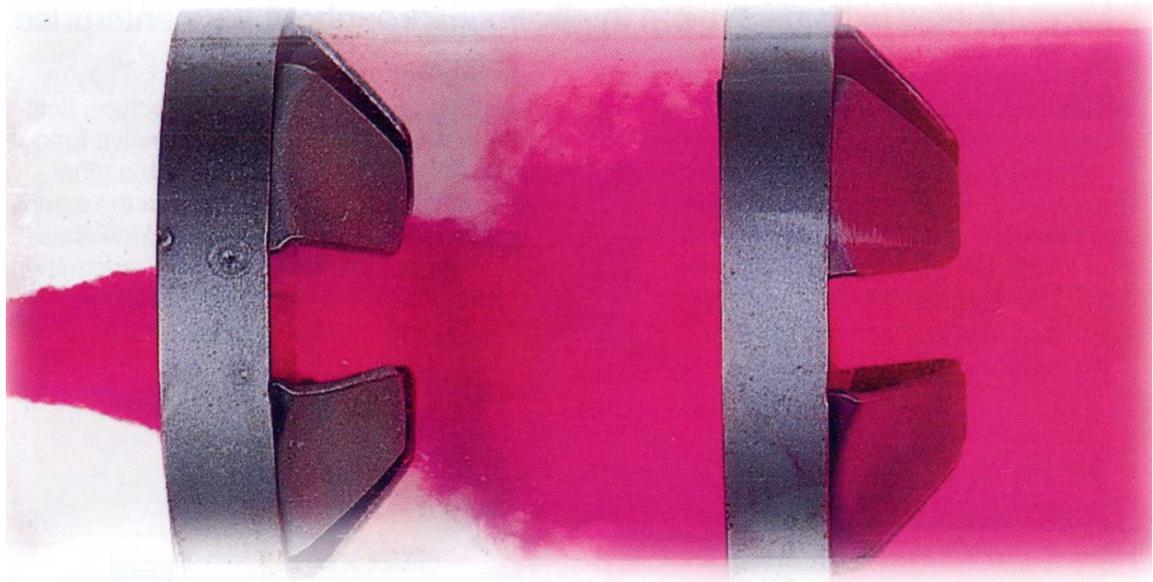


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STATIC MIXERS



Avoid Agitation By Selecting Static Mixers

Here's a guide on when to consider static mixers vs. agitators. Mixing mechanisms in static mixers are explored, as well as design formulations for the various types of operation.

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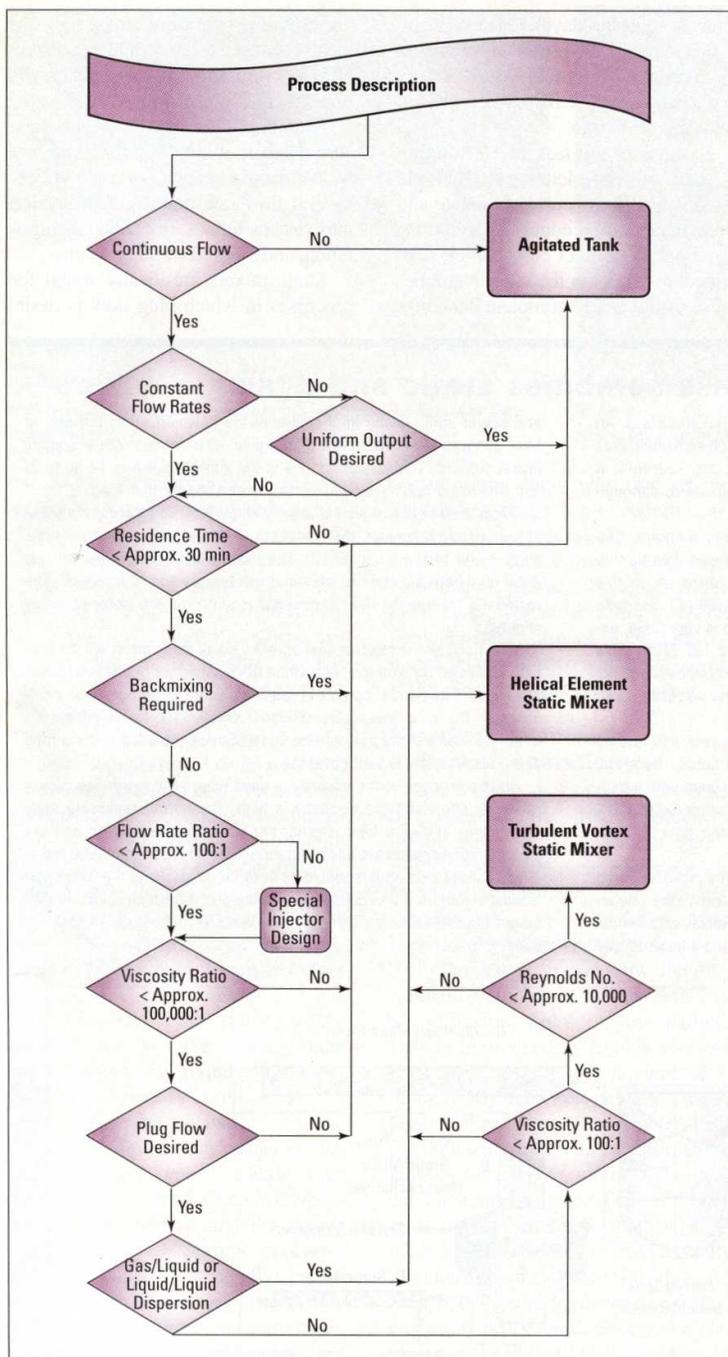
Over the past 35 years, static mixer technology has matured into an integral and essential unit operation in the chemical process industries (CPI). These mixers are marketed worldwide by several manufacturers and are found in a diverse assortment of applications (see Table 1). Static mixers are used for laminar, transitional, and tur-

bulent blending of miscible liquids, in laminar-flow heat exchangers, for laminar and turbulent homogenization, as tubular reactors, for dispersion of immiscible phases, and for interphase mass transfer between immiscible phases.

The principle of operation is straightforward: By placing elements in a pipe, the flow field is altered relative to that of an

Table 1. Static mixers meet a variety of CPI needs.

Industry	Applications
Chemicals	Chlorination and oxidation Steam injection Acid and base dilution Fast reactions
Food Processing	Acid washing of fats and oils Constituent blending Starch slurry cooking
Mineral Processing	Slurry dilution Metal recovery by solvent extraction
Paints and Resins	Coloring and tinting Solvent blending Color concentrate dilution
Petrochemicals and Refining	Gaseous reactant blending Gasoline blending Emissions monitoring and control
Pharmaceuticals	Nutrient blending Sterilization pH control
Polymers and Plastics	Reactant/catalyst blending Thermal homogenization Plug-flow finishing reactors
Pulp and Paper	Chemical and coatings preparation Stock dilution and consistency control Addition of bleaching chemicals
Water and Waste Treatment	Polymer dilution Disinfection, aeration, and dechlorination



■ Figure 1. Flow chart shows the main issues in deciding whether to use a static mixer or an agitated tank.

open pipe, yielding efficient mixing with no moving parts. The characteristics of static mixers are well-known and are listed in Table 2. This article discusses the fundamentals and applications of this technology including the basic mechanisms of mixing, design for blending miscible fluids, pressure-drop determination, and heat-transfer characteristics.

We will focus on the blending and dispersing of liquids, and the mixing of gases. Static mixers can also be used to mix pure solids, solids in liquids, and gases in liquids, but those applications are beyond the scope of this article. See Ref. 1 for information.

Static or dynamic mixing?

Before the performance and design of static mixers are considered, the question of whether to use static mixers or agitators (dynamic mixers) must be addressed. For reviews of dynamic mixing technology, refer to (2, 3). The choice is straightforward in many processes, although there can be processes where either a static mixer or an agitated tank can be used. The flowchart in Figure 1 illustrates the most important issues to consider when selecting the proper mixer.

Continuous flow is the primary requirement for the use of static mixers,

Table 2. Static mixer characteristics offer varied advantages.

- No moving parts
- Little or no maintenance requirements
- Small space requirements
- Available in many materials of construction
- No power requirements other than pumping
- Mixing achieved in short conduit lengths
- Minimal chance of material hangup or plugging
- Short residence times
- Narrow residence time distribution
- Enhanced heat transfer
- Cost effective

although they can also be incorporated into pump-around loops for use in batch and semibatch processes. Conversely, dynamic mixers are ideally suited to batch and semibatch processes, but present some difficulties for continuous use. Similarly, static mixers are often limited to processes that require short residence times (on the order of seconds to minutes) while dynamic mixers are most likely to be used in processes with longer residence

times (minutes to days). One exception to this involves the use of static mixers for continuous polymerization reactors that frequently have residence times on the order of 30 min.

Because of the lack of backmixing in static mixers, blending of multiple streams requires accurate flow rate and feed concentration control to minimize variations in product composition with respect to time. On the other hand, because of the nearly complete backmix-

ing provided by stirred tanks, they are ideally suited for providing controlled effluent composition when feed conditions fluctuate with time.

Static mixers are used in a wide variety of applications, but they are not well-suited for handling extreme viscosity and flow rate ratios, gas dispersion into viscous liquids, dry solids incorporation, and size reduction of solids.

Static mixers are ideally suited for processes in which plug flow is desir-

The polystyrene process combines static and dynamic mixers

Static mixers are now being employed in many industrial processes. An example is polystyrene. Less than 20 years ago, this polymerization was completely carried out using only stirred tank reactors. Currently, a combination of stirred tanks and static mixers is standard, although systems with only static mixers have been proposed.

The figure shows a typical polystyrene process diagram. The styrene monomer enters stirred tank reactor (A) equipped with turbine agitators. Initiator may be added to start the polymerization. In this stage the viscosity is fairly low, less than 50 Pa·s (50,000 cP). Because the reaction is exothermic and initially the conversion is very rapid, extensive cooling is required. Typical temperatures are 180–220°C. This step can be carried out in a multiple-tube static mixer heat exchanger, but because of the size required and the relatively low viscosity it can be more cost-efficient to use a stirred tank reactor.

As the polymerization progresses, viscosity increases and turbine agitators are not effective in agitating highly viscous fluids. Therefore, the second stage in the reaction is a stirred tank equipped with a helical ribbon impeller (B) (2). The viscosity now increases up to 500 Pa·s, and extensive cooling is still required. The residence time in each stirred vessel is typically 1–2 h.

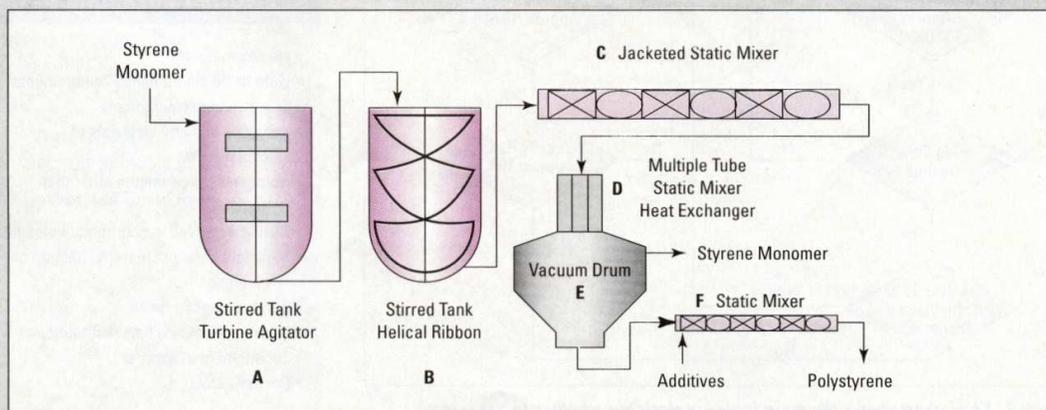
The last 10–20% of the conversion is carried out in a jacketed static mixer (C). The viscosity can increase to 2,000 Pa·s. Because the viscosity is so high, it is more cost-efficient to use a static mixer with helical elements rather than a helical ribbon impeller requiring a large torque

and power input. In the final stages of the polymerization, the rate of heat generation is low and a single-pipe static mixer with a cooling jacket suffices. The residence time in the static mixer may be up to 30 min. The mixer can have a dia. up to 1 m and can be 10 m long.

Total styrene conversion is usually about 90%. To strip out the unreacted styrene monomer, the mixture is first heated in a multiple-tube, static mixer heat exchanger (D). The mixture then enters the vacuum drum (E) where the styrene monomer evaporates and is drawn off. The residence time in the heat exchanger is short, on the order of a few minutes.

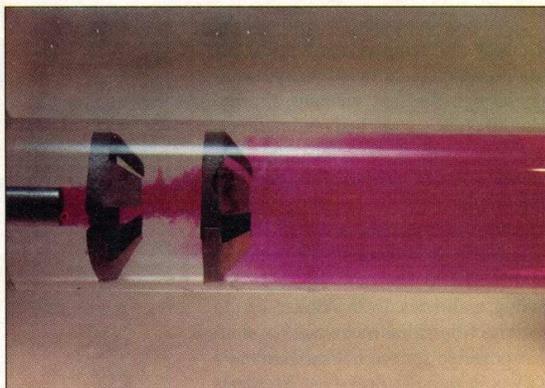
The polystyrene mixture next enters a small static mixer where specific additives, for example, ultraviolet (UV) stabilizers or fire retardants, are added. The residence time is relatively short, on the order of a few minutes. The plug-flow characteristics of the static mixer produce a uniform mixture of the polystyrene and additives, provided that the ratio of the feedstreams is kept constant.

In this process, static mixers are used where the residence time is relatively short and the viscosity is high. The stirred tanks are used where the residence time is long, the viscosities are lower, and the cooling requirements are such that otherwise possibly expensive multiple-tube heat exchangers would have to be used. Using the mixer that is most suited for the various stages in the process results in a more efficient plant than when only agitated tanks or only static mixers are used.





■ Figure 2. Helical element mixer is optimal for laminar flow in-line mixing.



■ Figure 3. The turbulent vortex mixer is selected for high Reynolds numbers.

able, *e.g.*, fast competitive reactions (4). Such processes can often be intensified by retrofitting batch and semi-batch reactors with static mixers.

The two main types of static mixers discussed in this article are the helical element mixer (Figure 2) and the turbulent vortex mixer (Figure 3). The former is used in laminar flow, systems with relatively large viscosity ratios (> 100:1) between the bulk fluid and the addition, and gas/liquid or liquid/liquid dispersions. The turbulent vortex mixer is selected for high Reynolds number flows (Reynolds number > 10,000) provided that the viscosity ratio is relatively small (< 100:1).

All quantitative information presented in this article is based on experiments with the Kenics Mixer (KM) for the helical element mixer and the High-Efficiency Vortab (HEV) as the turbulent vortex mixer. Other static mixer designs may require the use of different constants or correlations.

Some practical advantages of static mixers over agitated tanks include the ability to readily process a wide range of viscosities, limited space and maintenance requirements, and the almost complete lack of sealing concerns. However, agitators generally permit for greater flexibility in process flow rates and energy inputs per unit mass.

Most industrial processes are not completed in one step. Multiple stages are often required, and the product

composition along with mixing requirements can vary significantly throughout the process. To achieve optimum performance, many plants use a combination of static mixers and agitated tanks. The sidebar illustrates the complementary use of static and dynamic mixers in such a process, specifically the polymerization of styrene.

Mixing mechanisms in laminar operation

The mixing that must be provided by a static mixer is strongly influenced by the flow regime. The basic mixing mechanisms of laminar and turbulent flow are dramatically different, and, therefore, unique element designs have been developed for each regime.

In laminar open pipe flow, the only mechanism for radial mixing is molecular diffusion, which is slow, particularly in high-viscosity liquids. However, the use of static mixers can lead to dramatically enhanced radial mixing in laminar flow. Figure 2 shows the helical element mixer that is optimal for laminar flow in-line mixing. The helical elements split the flow into two semi-circular channels that twist as they flow through the mixer. Usually the elements are twisted 180 deg., although in special applications 90 deg. elements can be used. Successive elements are placed at 90 deg. relative to each other and provide alternating right- and lefthand rotation. The stan-

dard design length of the helical element is $1\frac{1}{2}$ times the pipe dia. for elements 0.30 m (12 in.) or less in dia. and equal to the pipe diameter for elements 0.36 m (14 in.) or greater in dia.

As early as 1894, Reynolds (5) identified stretching and folding of fluid elements as critical to the mixing process. Ottino and coworkers (6, 7) have recently been using these concepts to develop fundamental theories of mixing. Because of the inherent experimental difficulties associated with probing the flow field within a static mixer, the mixing mechanisms in these devices have never been critically examined in an experimental manner. However, growth in computational power has allowed computational fluid dynamics (CFD) simulations to become a valuable tool in studying the flow and mixing in static mixers.

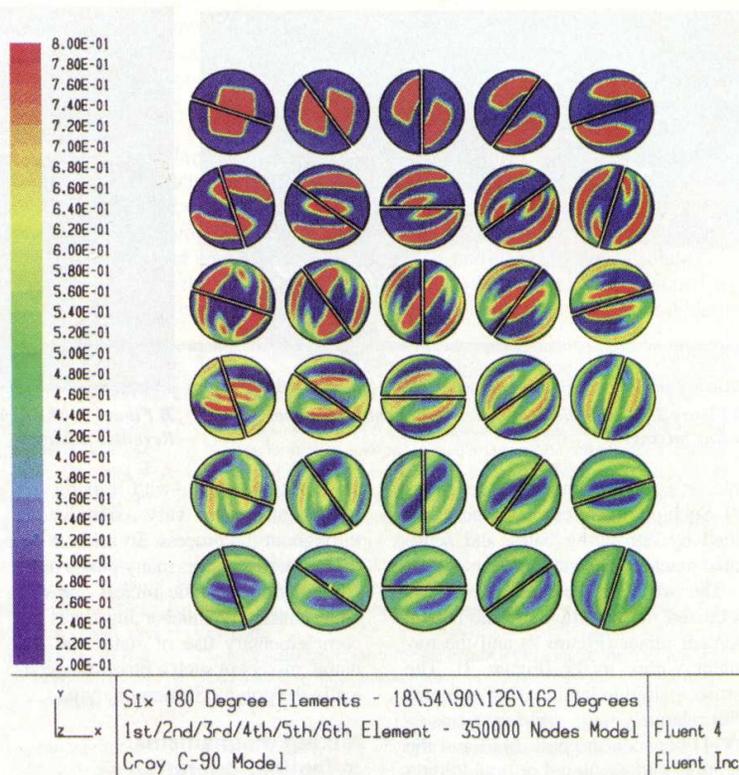
Figure 4 illustrates the blending of two distinct chemical species in a series of six helical elements (as determined by CFD) (8). The Reynolds number is 10. The horizontal rows show how the mixing proceeds in Elements 1 through 6. The vertical columns show concentration profiles at 18, 54, 90, 126, and 162 deg. twist of the element, respectively. The Schmidt number is high (> 10⁶), typical for the blending of viscous liquids, such that the effects of molecular diffusion are small. Initially, the two species are isolated with the red material forming a

core at the center of the conduit and the blue material being in the annular region near the conduit wall. While passing through the first element, the red material is split, stretched, and redirected to the wall. Conversely, the blue material moves inward forming two semicircular regions that surround the red material. As the material passes through the third element, the red material is moved from the region of the conduit wall back to the center of the conduit. This radial movement of fluid is responsible for the helical element's success in laminar flow heat exchangers and reactors. A continual exchange of material between the central and wall regions of the conduit leads to a uniform thermal history for all of the material being processed.

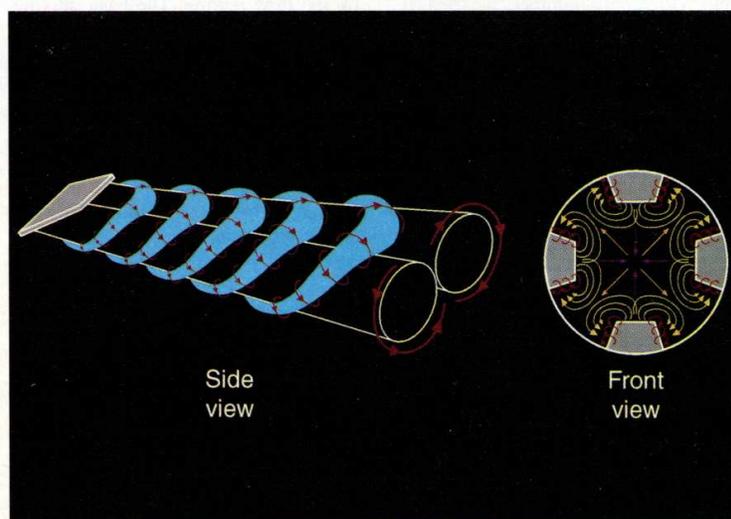
In addition to the gross movement of the red and blue fluids described in the previous paragraph, blending of the two materials can be seen to occur. By the time the material passes through the sixth element, blending is essentially complete. This blending is achieved through repeated splitting, stretching, and realignment of fluid elements (9). Consider the flow as it leaves the second element. The regions of red and blue are aligned such that as they enter the third element they are split, creating more interfacial area. While moving through the third element, this new interfacial area is stretched and realigned by the flow field in the helical element. By the end of the third element, the regions of red and blue have again been realigned such that as they enter the fourth element, they are split once more, generating even more interfacial area. As this process is continued, the length scales of the red and blue regions are further reduced. When the striations become sufficiently thin, molecular diffusion will eliminate the final concentration differences in the mixture.

Mixing mechanisms in turbulent operation

Mixing in turbulent open pipe flow is greatly enhanced over that of laminar flow. However, thorough blending may require pipe lengths in excess of



■ Figure 4. Blending of two distinct chemical species in a series of six helical ele-



■ Figure 5. Strong induced vortex motion is the primary mixing mechanism of the turbulent vortex mixer.

Table 3. Blending statistics relate COV to the distribution of concentrations.

Fraction of Fluid Within Specified Deviation	COV = 0.01	COV = 0.025	COV = 0.05	COV = 0.10
	Required Deviation from Mean Composition (expressed as ± percent of mean)			
0.500	0.7%	1.7%	3.3%	6.7%
0.683	1.0%	2.5%	5.0%	10.0%
0.750	1.2%	2.9%	5.8%	11.5%
0.900	1.7%	4.1%	8.2%	16.5%
0.950	2.0%	4.9%	9.8%	19.6%
0.990	2.6%	6.4%	12.3%	25.8%
0.999	3.3%	8.2%	16.5%	33.0%

100 pipe dia., a distance often not available in CPI operations. The helical elements provide efficient turbulent mixing, but their real strength is in laminar operation. Several manufacturers now sell special vortex generating devices for efficient blending in turbulent flow. One such device is the turbulent vortex mixer shown in Figure 3. A series of tab arrays, separated by one conduit dia., are placed along the conduit length. This design is the result of extensive testing to determine the optimal tab geometry (shape, length, width, and angle of attack) that will achieve enhanced mixing with minimal energy requirements. The design of the tabs also provides superior flexibility in that it can readily be adapted to any shape of conduit cross section (square or rectangular, for example) and for flow in open channels (prevalent in water treatment). The tab arrays are well suited to both liquid/liquid and gas/gas blending.

Strong induced vortex motion is the primary mixing mechanism of the turbulent vortex mixer, as illustrated in Figure 5 (10). Counterrotating longitudinal vortices that are attached to the conduit wall (not to the tabs) are formed in the wakes of the tabs. Near their point of generation, the axes of these vortices are nearly parallel with the tab, and they bend to longitudinal

vortices with centers near the tips of the tabs. Further, the tabs shed transient hairpin vortices that move downstream with the larger longitudinal vortices. This complicated vortex system provides efficient blending over the whole cross section of the pipe.

Design for blending

Early theories of laminar blending with helical element mixers were based on the striation thicknesses produced. Each element splits the flow (doubles the number of striations) such that after the flow has passed through n elements, the maximum striation thickness d would be expected to be:

$$\frac{d}{D} = \frac{1}{2^n} \quad (1)$$

Recently, more advanced theories such as Danckwerts' scale of mixing and intensity of mixing have been used to evaluate the performance of static mixers (11). However, a statistical analysis is most often used in practical static mixer design calculations, and the basis of this approach is presented here.

The accepted approach for determining composition uniformity in a flow field is to take simultaneous samples at various points over the conduit cross section at a fixed axial location. The most widely used measure of uniformity is the coefficient of variation

COV which is the ratio of the standard deviation in composition σ and the mean composition x_m :

$$COV = \frac{\sigma}{x_m} = \frac{\sqrt{\frac{\sum(x_i - x_m)^2}{N-1}}}{x_m} \quad (2)$$

As a rule-of-thumb, most industrial blending operations can be satisfied with a coefficient of variation of 5% ($COV = 0.05$). However, some applications, such as the blending of colors to visual uniformity, may require coefficients of variation of 1% or less ($COV \leq 0.01$) (12).

Note that a COV of 5% does not mean that all concentrations are within 5% of the mean concentration (that is, $x_{min} = 0.95x_m \leq x \leq 1.0x_m = x_{max}$). Rather, the standard deviation of the concentration is equal to 5% of the mean concentration ($\sigma = 0.05x_m$). Assuming that the point concentrations are distributed normally about the mean, the COV can readily be related to the distribution of concentrations as listed in Table 3. This table illustrates what fraction of the point concentrations are within a specified range of the mean (expressed as a plus/minus percentage of the mean concentration). Thus, for $COV = 0.05$, 68% of the point concentrations fall within $\pm 5.0\%$ of the mean concentration; 90% fall within $\pm 8.2\%$, 95% within $\pm 9.8\%$, and 99% within $\pm 12.3\%$.

COV design data for the helical element mixer and turbulent vortex mixers are presented in Figures 6 and 7 respectively (13). Note that this information has been presented in terms of the feed COV to the mixer which can be determined as follows:

$$COV_0 = \sqrt{\frac{1 - \phi_a}{\phi_a}} \quad (3)$$

ϕ_a represents the ratio of the volumetric flow rate of the added material and the total volumetric flow rate:

$$\phi_a = \frac{Q_a}{Q_t} \quad (4)$$

Since vortex structures continue to mix beyond the end of the mixer, the

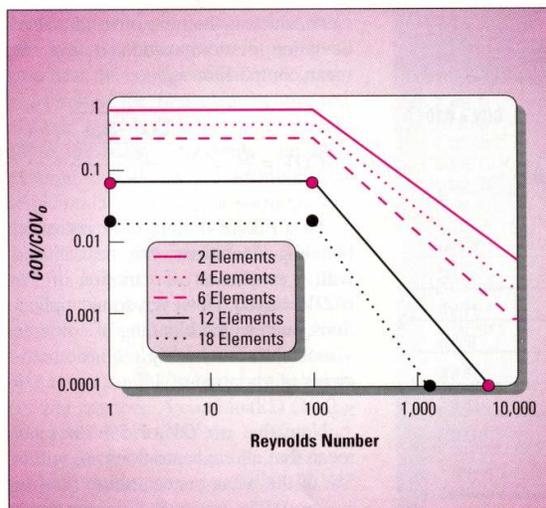


Figure 6. COV design data for the helical element mixer.

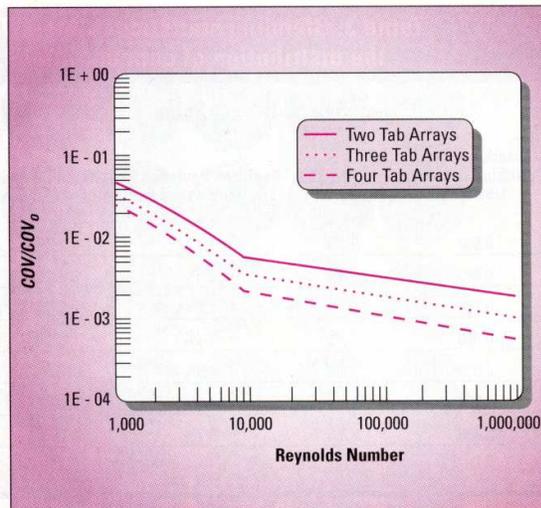


Figure 7. COV design data for the turbulent vortex mixer.

position of measurement downstream from the turbulent vortex mixer influences the COV. The data of Figure 7 are for a typical measurement location of 3 pipe dias. downstream from the end of the static mixer.

In addition to the rigorous design calculations provided by this statistical approach, extensive design experience leads to the selection guidelines presented in Table 4 for the helical element mixer (14).

Difficult blending operations can require special design considerations for both helical element and the turbulent vortex mixers. This includes operations with extreme viscosity ratios or with extreme flow rate ratios. Such applications can be handled with static mixers; however, these applications are typically handled on a case-by-case basis because they may require careful analysis and unique equipment designs. When the viscosity ratio exceeds 100,000:1, it is often more cost-effective to use an in-line dynamic mixer. Special injection systems may be required if the flow rate ratio exceeds 100:1. Parameters which affect the injector design include the Reynolds number, shear rate, surrounding piping configuration, and the required mixture homogeneity and its effect on downstream processes or

measurement and control equipment. Extreme density ratios are uncommon in liquid blending, and therefore do not usually cause design problems. However, in gas blending extreme density ratios can hinder mixing and modified design strategies may be required.

Few comparative studies of the blending performance of the various commercial static-mixer designs are available. This is partly due to the lack of a definitive performance criterion. One approach is to compare the pressure drop required to produce a desired COV. Godfrey (1) summarized the laminar-flow blending performance of a number of static mixers using this method with the results indicating significant variation in efficiency. No comparative studies of turbulent blending performance are available.

Pressure-drop calculations

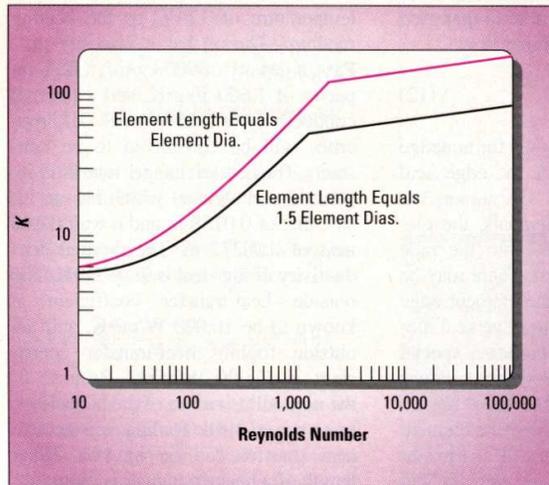
With no moving parts, the only energy requirement for blending in static mixers is that required to overcome pressure drop. The pressure drop in the helical element mixer Δp_{KM} is calculated relative to the pressure drop in an open pipe, Δp_{OP} :

$$\Delta p_{KM} = K \Delta p_{OP} \tag{5}$$

As shown in Figure 8, the multiplier K is dependent on the Reynolds number and pipe size (the multiplier is greater for the larger elements because the twist of the elements is greater; the larger elements have an L/D of 1, while the smaller elements have an L/D ratio of $1\frac{1}{2}$). For Reynolds numbers < 10 , K can be taken to be constant at 5.5 for smaller pipes and 6.0 for larger pipes (small is ≤ 0.3 m, and large is ≥ 0.35 m).

Table 4. Helical element selection guidelines.

Reynolds Number	Recommended Number of Helical Elements
<10	18
10-100	12
100-1,000	6
1,000-5,000	4
> 5,000	2



■ Figure 8. K depends upon the Reynolds number and pipe (element) size.

The pressure drop in an open pipe can be estimated using the Darcy friction factor f_{OP} :

$$\Delta p_{OP} = f_{OP} \left(\frac{L}{D} \right) \left(\frac{\rho v^2}{2} \right) \quad (6)$$

In laminar flow, the Darcy friction factor for open pipe flow of a Newtonian fluid only depends on the Reynolds number:

$$f_{OP} = \frac{64}{N_{Re}} \quad (7)$$

In turbulent flow, the Darcy friction factor is a more complex function of Reynolds number and conduit surface smoothness, and can be obtained from standard sources, such as Ref. 15.

Use of this pressure drop calculation procedure for the flow of non-Newtonian fluids in the helical element mixer requires two modifications. First, the pressure drop in the open pipe Δp_{OP} must be correctly determined for the non-Newtonian fluid properties of interest. Second, the multiplier K of Figure 8 must be determined correctly. This can be achieved by calculating the Reynolds number using the apparent fluid viscosity at the average shear rate in the helical elements which is 3 times the average

shear rate in open pipe flow. Further information concerning the pressure drop for non-Newtonian flow in helical element mixers is presented by Shah and Kale (16).

The pressure drop in the turbulent vortex mixer is determined directly from the Darcy friction factor:

$$\Delta p_{HEV} = f_{HEV} \left(\frac{L}{D} \right) \left(\frac{\rho v^2}{2} \right) \quad (8)$$

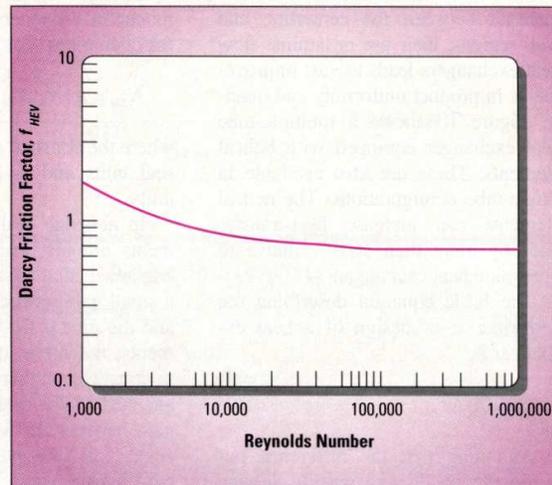
which is shown in Figure 9.

Once the pressure drop associated with a static mixer has been determined, the associated power require-

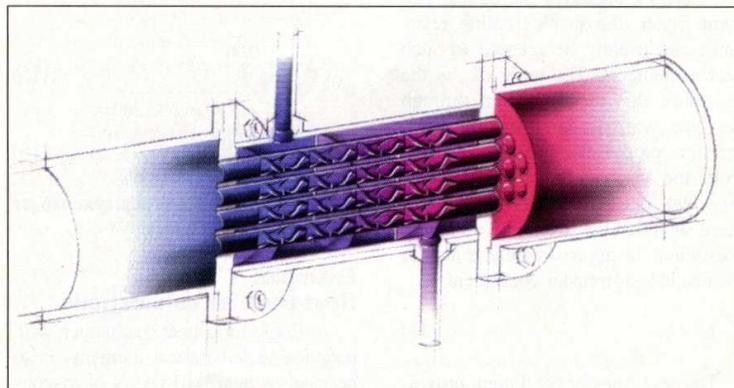
ment is the product of the pressure drop and the volumetric flow rate.

Heat transfer in static mixers

The processing of viscous materials often requires heat transfer. With no radial heat-transfer mechanism other than thermal conduction, which is typically extremely slow in viscous materials, large radial temperature gradients develop in conventional open-pipe heat exchangers. This results in products of nonuniform and often unacceptable quality. However, because of the enhanced radial mixing provided by static mixers, with continual exchange of



■ Figure 9. Pressure drop in the turbulent vortex mixer is determined directly from the Darcy friction factor.



■ Figure 10. Multiple-tube heat exchanger with helical elements.

material between the centerline and wall regions, their use in laminar flow heat exchangers leads to vast improvements in product uniformity and quality. Figure 10 shows a multiple-tube heat exchanger equipped with helical elements. These are also available in single-tube configurations. The helical elements can increase heat-transfer rates by more than 400% relative to open-pipe heat exchangers (17).

The basic equation describing the performance or design of a heat exchanger is:

$$Q = UA\Delta T_{LM} \quad (9)$$

Assuming that the difference between the inside and outside surface areas of the pipe is negligibly small, the overall heat-transfer coefficient U is comprised of a number of heat-transfer resistances:

$$U = \frac{1}{\frac{1}{h_i} + \frac{1}{h_o} + \frac{x}{k_w} + \frac{1}{h_{f_i}} + \frac{1}{h_{f_o}}} \quad (10)$$

The inside and outside heat-transfer coefficients h_i and h_o , respectively, are functions of operating conditions, fluid properties, and exchanger geometry. Fouling resistances, represented by $1/h_{f_i}$ and $1/h_{f_o}$, are most often due to scaling, crystallization, polymerization, or biological growth. These deposits are often of low thermal conductivity and thus represent significant resistance to heat transfer. Because of the self-cleaning nature of the helical element mixer, the inside fouling resistance can usually be ignored in such heat exchangers. The term x/k_w is the resistance due to conduction through the tube wall. In laminar flow heat-transfer processes, transfer of heat from the viscous fluid to the inside pipe wall is often the dominant resistance such that the overall heat-transfer coefficient is approximately equal to the inside heat-transfer coefficient:

$$U \approx h_i \quad (11)$$

The heat-transfer coefficient provided by the helical elements can be cor-

related in a manner similar to that used for open pipes. For laminar flow:

$$N_{Nu} = a (N_{Re} N_{Pr})^{1/3} \quad (12)$$

where the constant a is 1.5 for nonedge seal units and is 2.25 for edge seal units.

In nonedge seal elements, the elements are just inserted into the pipe and attached at the ends. There may be a small gap between the element edge and the pipe wall. With edge seal elements, the mixer undergoes a special treatment, such that the element edge is attached to the wall and there are no gaps between the wall and the element edge. This improves the heat transfer between the static mixer element and the pipe wall.

The heat-transfer rate is higher in edge seal units, because they provide an internal fin that conducts heat directly across the pipe cross section. For turbulent flow operation, the heat-transfer coefficient provided by a heat exchanger with helical elements can be calculated from the following correlation:

$$N_{Nu} = 0.078 N_{Re}^{4/5} N_{Pr}^{1/3} \quad (13)$$

This heat-transfer coefficient is 3 times that of turbulent flow in an open pipe. In these heat-transfer correlations, the Nusselt, Reynolds, and Prandtl numbers are defined as follows:

$$N_{Nu} = \frac{h_i D}{k} \quad (14)$$

$$N_{Re} = \frac{\rho D v}{\mu} \quad (15)$$

$$N_{Pr} = \frac{C_p \mu}{k} \quad (16)$$

An example of a heat exchanger calculation follows.

**Example:
Heat-transfer calculations**

A single-tube heat exchanger with nonedge-sealed helical elements is to be used to heat 0.015 kg/s of viscous oil from 15°C to 80°C using steam at a

temperature of 120°C as the heating medium. The oil has a viscosity of 1 Pa•s, a density of 900 kg/m³, a heat capacity of 1,600 J/kg•K, and a thermal conductivity of 0.15 W/m•K (all properties will be considered to be constant). The heat exchanger tube is 1/2 in. Sch. 40 carbon steel which has an inside dia. of 0.0158 m and a wall thickness of 0.00277 m. The thermal conductivity of the steel is 70 W/m•K. The outside heat-transfer coefficient is known to be 10,000 W/m²•K, and the outside fouling heat-transfer coefficient is 12,000 W/m²•K. Because of the nonfouling nature of the helical element mixer, inside fouling resistance to heat transfer can be ignored. What length of a heat exchanger is required?

Solution: The required heat-transfer rate is:

$$Q = m C_p (T_o - T_i) = (0.015)(1,600)(80 - 15) = 1,560 \text{ J/s}$$

Further, the log mean temperature difference can be calculated:

$$\Delta T_{LM} = \frac{\Delta T_i - \Delta T_o}{\ln \frac{\Delta T_i}{\Delta T_o}} = \frac{(120 - 15) - (120 - 80)}{\ln \frac{(120 - 15)}{(120 - 80)}} = 67.4 \text{ K}$$

For the given mass-flow rate and pipe dimensions, the superficial fluid velocity is 0.0850 m/s which leads to a Reynolds number of:

$$N_{Re} = \frac{\rho D v}{\mu} = \frac{(900)(0.0158)(0.0850)}{1} = 1.21$$

while the oil's Prandtl number is:

$$N_{Pr} = \frac{C_p \mu}{k} = \frac{(1,600)(1)}{0.15} = 10,700$$

Equation 12 can now be used to calculate the inside heat-transfer coefficient:

$$h_i = \frac{1.5k}{D} (N_{Re} N_{Pr})^{1/3} = \frac{(1.5)(0.15)}{(0.0158)}$$

$$[(1.21)(10,700)]^{1/3} = 334 \text{ W/m}^2\cdot\text{K}$$

Equation 10 (at right) can be used to calculate the overall heat-transfer coefficient:

Rearrangement of Eq. 9 allows the required heat-transfer area to be determined:

$$A = \frac{Q}{U\Delta T_{LM}} = \frac{1,560}{(311)(67.4)} = 0.0744 \text{ m}^2$$

Since the given conduit has an inside surface area of 0.0496 m² per m of length, the required heat exchanger length is 1.5 m.

If the same heat-transfer process is carried out in an open-pipe heat exchanger, a Graetz-type correlation can be used to calculate the inside heat-transfer coefficient:

$$N_{Nu} = 1.86 \left(N_{Re} N_{Pr} \frac{D}{L} \right)^{1/3} \quad (17)$$

If the design calculations are repeated, an open-pipe heat exchanger length of 9.6 m is found. This length is more than six times that of the heat exchanger with helical elements.

Thermal homogenization

A subject closely related to heat transfer is thermal homogenization. Because of their enhanced radial mixing characteristics relative to open pipe flow, both the helical and turbulent vortex mixers are often used to eliminate radial temperature gradients in process fluids. An example is using helical elements to deliver a thermally homogeneous melt stream to a mold or die. This represents a superior alternative to varying screw designs and adjusting die gaps when attempting to solve the problems associated with feed-stream temperature gradients. Helical elements have been shown to be capable of reducing radial temperature gradients by more than a factor of 10 (17). In turbulent flow, the turbulent vortex mixer has been found to have thermal homogenization abilities similar to those of the helical element mixer (13).

$$U = \frac{1}{\frac{1}{h_i} + \frac{1}{h_f} + \frac{x}{k_w} + \frac{1}{h_{fo}} + \frac{1}{h_o}} = \frac{1}{\frac{1}{334} + \frac{1}{\infty} + \frac{0.00277}{70} + \frac{1}{12,000} + \frac{1}{10,000}} = 311 \text{ W/m}^2\cdot\text{K}$$

Equation 10.

Nomenclature

<i>a</i>	= constant of Eq.12, dimensionless
<i>A</i>	= heat-transfer area, m ²
<i>C_p</i>	= fluid constant-pressure heat capacity, J/kg•K
<i>COV</i>	= coefficient of variation (defined in Eq. 2), dimensionless
<i>COV₀</i>	= coefficient of variation at inlet to the static mixer, dimensionless
<i>d</i>	= striation thickness, m
<i>D</i>	= conduit dia., m
<i>f_{HEV}</i>	= Darcy friction factor for a turbulent vortex static mixer (defined in Eq. 8), dimensionless
<i>f_{OP}</i>	= Darcy friction factor for open pipe flow (defined in Eq. 6), dimensionless
<i>h_f</i>	= inside fouling heat-transfer coefficient, W/m ² •K
<i>h_{fo}</i>	= outside fouling heat-transfer coefficient, W/m ² •K
<i>h_i</i>	= inside heat-transfer coefficient, W/m ² •K
<i>h_o</i>	= outside heat-transfer coefficient, W/m ² •K
<i>k</i>	= fluid thermal conductivity, W/m•K
<i>k_w</i>	= heat exchanger wall thermal conductivity, W/m•K
<i>K</i>	= helical-element pressure drop multiplier (defined in Eq. 5), dimensionless
<i>L</i>	= conduit length, m
<i>m</i>	= mass-flow rate, kg/s
<i>n</i>	= number of elements in a static mixer
<i>N</i>	= number of data points in a sample
<i>N_{Nu}</i>	= Nusselt number, dimensionless
<i>N_{Pr}</i>	= Prandtl number, dimensionless
<i>N_{Re}</i>	= Reynolds number, dimensionless
<i>ΔP_{HEV}</i>	= pressure drop in a turbulent vortex mixer, N/m ²
<i>ΔP_{KM}</i>	= pressure drop in a helical element mixer, N/m ²
<i>ΔP_{OP}</i>	= pressure drop in an open pipe, N/m ²
<i>Q</i>	= heat-transfer rate, W
<i>Q_a</i>	= volumetric flow rate of added material, m ³ /s
<i>Q_t</i>	= total volumetric flow rate, m ³ /s
<i>T_i</i>	= inlet temperature, K
<i>T_o</i>	= outlet temperature, K
<i>ΔT_i</i>	= inlet temperature difference, K
<i>ΔT_o</i>	= outlet temperature difference, K
<i>ΔT_{LM}</i>	= logarithmic mean temperature difference, K
<i>U</i>	= overall heat-transfer coefficient, W/m ² •K
<i>v</i>	= superficial velocity, m/s
<i>x</i>	= heat exchanger wall thickness, m
<i>x_i</i>	= point value composition
<i>x_m</i>	= mean composition
<i>x_{max}</i>	= maximum point composition
<i>x_{min}</i>	= minimum point composition

Greek letters

<i>μ</i>	= fluid viscosity, Pa•s
<i>ρ</i>	= fluid density, kg/m ³
<i>σ</i>	= standard deviation (defined in Eq. 2)
<i>φ_a</i>	= volumetric flow rate fraction of added fluid relative to total volumetric flow

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Other applications

Static mixers are also used in a number of other applications. Two of the most common are in tubular laminar flow reactors and for dispersion of immiscible phases. Laminar open-pipe chemical reactors suffer from a very broad residence time distribution. This residence time distribution can be substantially narrowed, approaching plug flow, through the addition of helical ele-

ments (18). Helical element mixers can also be used to generate narrow bubble or drop size distributions in gas-liquid and immiscible liquid-liquid dispersions (19). Although important, these applications are beyond the scope of this review.

Concluding remarks

Static mixer technology has been used to solve many process mixing problems. Static mixers have advanced

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to the stage where design data and calculations have been incorporated into knowledge-based computer programs that rapidly produce optimal, cost-effective designs for a wide variety of applications (for an introduction to knowledge-based computer design, refer to (20)). The information presented here should help you to evaluate the potential of static mixers for your process. **CEP**

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