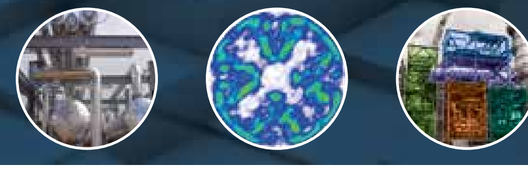

Employ Static Mixers for Process Intensification

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Static mixers can efficiently and effectively accomplish an increasing number of process objectives, expanding the opportunities to apply them for process intensification.

Mixing is a common operation in the chemical process industries (CPI), and is critical to the success of many processes. The cost of poor mixing — in the form of lower yields, difficulties in process development and scaleup, and lost opportunities to commercialize new products — has been estimated to be in the billions of dollars *(1)*. Improvements in mixing can enable the manufacture of new and better products, reduce the generation of unwanted byproducts, allow the use of smaller equipment, and reduce energy requirements.

In the 50 years since their commercial introduction, static mixers (also called motionless mixers) have become established throughout the CPI in numerous operations, including blending, phase contacting, chemical reaction, and heat transfer. Their low cost, small size, and lack of moving parts, as well as other performance characteristics, make their use advantageous in many instances. Over time, numerous designs have been developed to provide enhanced performance in a widening array of applications, such that static mixers should be routinely considered for process intensification of mixing-sensitive operations.

This article explains how static mixers work, describes the most common types of static mixing elements, and discusses how static mixers can be used in laminar- and turbulent-flow applications.

How static mixers work

The most common mixing apparatus is the agitated tank, which is used to accomplish a diverse array of process objectives. These dynamic agitators use rotating impellers to produce flow in the material to be mixed.

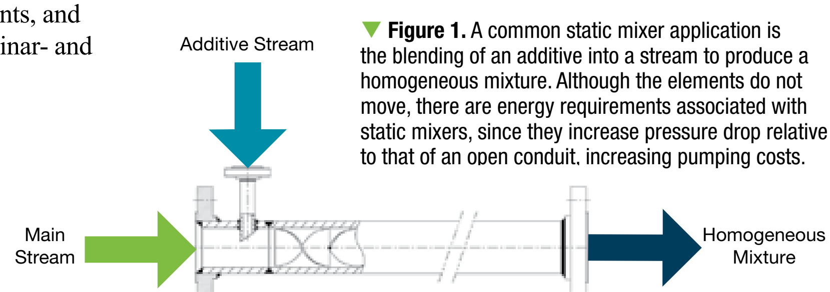
Conversely, static mixers (Figure 1) consist of stationary elements that are placed in a conduit to obstruct and direct the flow that is driven by another device, usually a pump. These stationary elements induce motion in the flowing fluid that is a function of element design and varies according to flow regime and process objectives.

In either case, the fluid motion caused by the mixing device, whether rotating impellers or static mixer elements, is responsible for achieving the desired mixing results.

When are static mixers the right choice?

Tank-mounted agitators are well-suited for use in batch and semibatch processes, while static mixers, because they are placed in conduits, are generally used in continuous processes. The advantages of static mixers can be realized in batch processing by connecting a static mixer pumparound loop to an agitated vessel.

While stirred tanks are a good option in many mixing operations, static mixers may often be a better choice. The large volumes of stirred tanks usually provide residence times on the order of hours, days, or even weeks. On the



▼ **Figure 1.** A common static mixer application is the blending of an additive into a stream to produce a homogeneous mixture. Although the elements do not move, there are energy requirements associated with static mixers, since they increase pressure drop relative to that of an open conduit, increasing pumping costs.

other hand, because most conduits have much smaller volumes, static mixers typically have residence times on the order of seconds or minutes. For products that degrade over time, long residence times should be avoided, making static mixers an attractive alternative to stirred tanks.

Additionally, the blending of material throughout a large stirred tank often requires minutes, making it difficult to achieve good performance when rapid mixing is required. This is the case when fast competitive reactions are being carried out, and in these applications static mixers that can achieve blending within seconds provide better performance.

In stirred tanks, energy is imparted to the agitated material via rotating impellers that typically occupy a small fraction of the vessel volume. This creates a broad distribution of energy dissipation rates throughout the vessel, with the dissipation rate in the impeller zone being orders of magnitude higher than the lowest energy dissipation rates. On the other hand, static mixers occupy a significant portion of the conduit volume and provide a significantly more uniform energy dissipation rate.

Similarly, stirred tanks have a wide range of residence times, and if poorly designed, stirred tanks are subject to the possibility of material bypassing the more-intense mixing in the impeller region or of material being trapped in sluggish or stagnant zones. Static mixers provide narrower residence time distributions that can create more-uniform product properties while also limiting the possibility of bypassing and stagnancy.

An open conduit with no mixing device is another alternative to static mixers. In laminar flow in open conduits, radial transport occurs solely by diffusive mechanisms, which translates to very slow rates of mixing and heat transfer, long conduit lengths, and broad residence time distributions. When flow is turbulent, some mixing processes can be accomplished in an open conduit; however, this may require an excessively long conduit, perhaps as long as hundreds of pipe diameters. In addition to extreme length, the slower mixing occurring in an open conduit can be detrimental when other processes (*e.g.,* fast competitive reactions) occur faster than mixing.

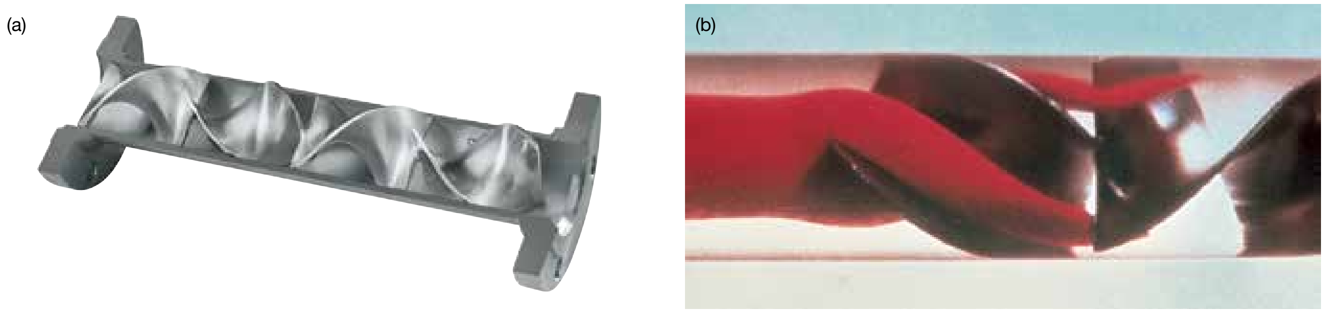
Numerous static mixer element designs are commercially available, and a complete review would be quite extensive. This article focuses on four of the most widely used element types. Motivation for these element designs stems from two basic factors: the flow regime (laminar or turbulent) and the difficulty of the mixing task.

Routine tasks in laminar flow

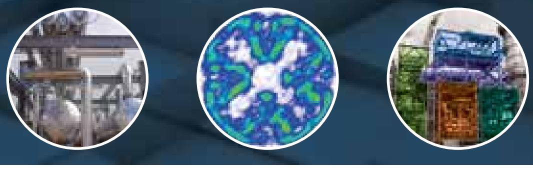
One of the earliest commercial applications of static mixers used the helical elements shown in Figure 2 for the laminar mixing of materials with similar properties (helical elements are also used in the blending operation of Figure 1). Each element divides the flowing fluid into semicircular regions that are rotated and then recombined at the end of the element, where the next element divides the flow again. Each flow division is perpendicular to the preceding division and each rotation is in the direction opposite the preceding rotation. Passing miscible fluids through a series of elements creates striations of continually decreasing thickness. In creeping flow (Reynolds numbers less than about one), this reduction in striation thickness is the primary blending mechanism, until the striations are thin enough that molecular diffusion can aid in the elimination of composition variations. At higher Reynolds numbers, secondary flows develop that also impact the blending process.

The rotation that the elements impart to the flowing fluid causes radial redistribution of material. As shown in Figure 2b, fluid at the conduit centerline moves to the wall and fluid at the wall moves to the centerline; this exchange is completed over approximately every two elements in laminar flow. This behavior makes helical elements effective for thermal homogenization and heat-transfer enhancement.

In laminar flow in an open conduit, fluid remains on a streamline at a fixed radial location, and molecular diffusion, a slow process in viscous fluids, is the only mechanism for radial transport of mass and energy. Thus, use of static mixers can substantially increase the heat-transfer rate and reduce the required heat-transfer area. Additionally, in laminar flow in an open conduit, fluid near the centerline has



▲ **Figure 2.** (a) Helical static mixer elements divide the flowing fluid into semicircular regions that are rotated and then recombined. (b) Fluid at the conduit centerline moves to the wall while fluid at the wall moves to the centerline.



significantly higher velocities than material near the conduit wall, creating a very broad distribution of residence times and thermal histories.

The radial redistribution provided by helical static mixer elements moves fluid back and forth between regions with higher and lower velocities, significantly narrowing the residence time distribution and providing a more uniform thermal history.

While helical static mixer elements promote blending and heat transfer in laminar flow, where accomplishing these operations is not easy, this performance comes with a price. Although designed to limit pressure drop, for Reynolds numbers less than ten, the pressure drop with helical static mixers is about six times that in an open conduit.

More-demanding tasks in laminar flow

Mixing tasks become progressively more difficult as differences in the physical properties, most notably viscosity and density, of the materials to be blended increase. Blending also becomes more difficult as the ratio of the materials' flowrates increases.

To minimize their impact on pressure drop in laminar flow, the helical elements discussed previously occupy a small fraction of a conduit's cross-sectional area. For difficult tasks such as uniformly blending a small amount of low-viscosity coloring agent into a high-viscosity polymer, low-pressure-drop elements such as helical elements allow the additive to snake through as a filament that is not blended into the primary flow. In these applications, the crossbar (or lattice) element design shown in Figure 3 provides better performance. While the angled bars of these elements cause radial interchange of material the way helical mixer elements do, much less of the conduit cross-section is open for flow. At the edges of the bars, axial flow through the open area of the mixer element stretches the adjacent fluid parcels that are slowed by the bars, and this elongation is effective at blending the fluid streams. This performance comes at the cost of increased pressure drop. At low Reynolds numbers, the pressure drop with crossbar elements is about 35 times that of an open pipe and six times that with helical elements.

Figure 4 compares laminar blending with helical (Figure 4a) and crossbar (Figure 4b) static mixers. The viscous Newtonian materials being blended have similar properties, the Reynolds number is five, and arrays of six mixer elements are used. Tracer fluid parcels (red) are injected into the flow near the conduit centerline, and the positions of these parcels are tracked as they move through

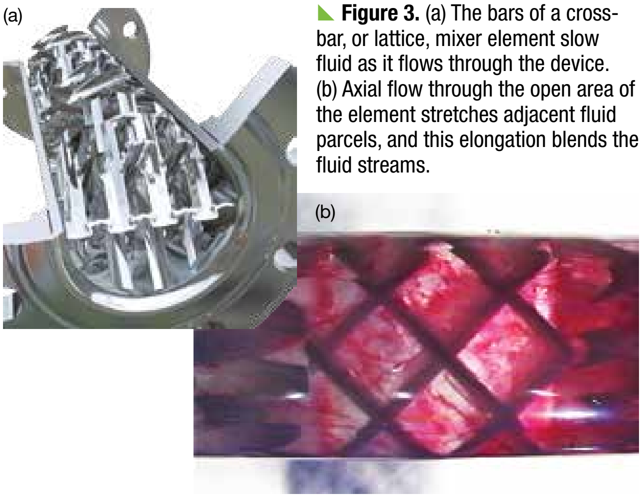


Figure 3. (a) The bars of a crossbar, or lattice, mixer element slow fluid as it flows through the device. (b) Axial flow through the open area of the element stretches adjacent fluid parcels, and this elongation blends the fluid streams.

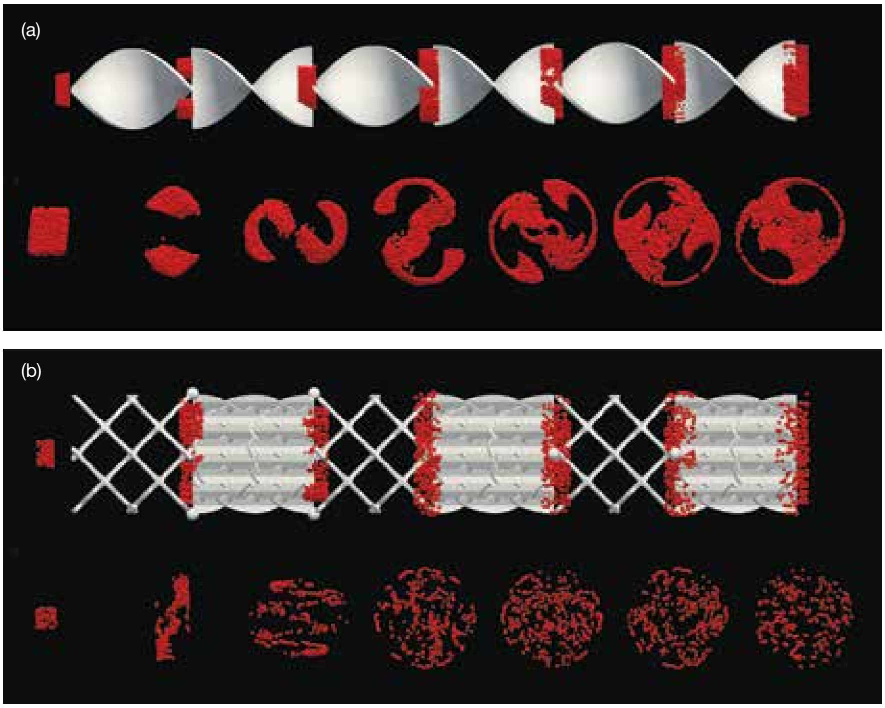


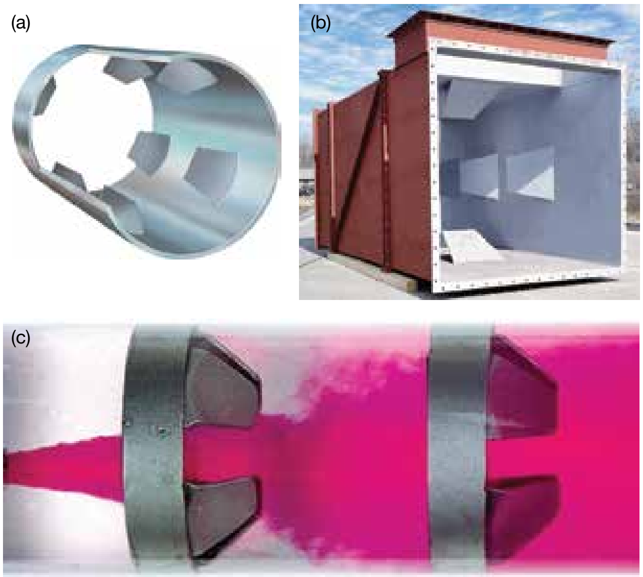
Figure 4. Laminar blending using (a) helical and (b) crossbar static mixers. Parcels of red tracer fluid are injected into a flow stream near the conduit centerline, and the positions of the parcels are tracked as they move through the mixers. At this low Reynolds number (Re = 5), 18 helical elements would be needed to achieve uniform blending, whereas four crossbar elements would be sufficient to distribute the tracer fluid parcels.

the mixers. The left-most images in Figure 4 show the tracer fluid parcel locations just before they enter the static mixer array. The other six images show the tracer parcels as they exit each subsequent mixer element.

In open-pipe laminar flow without a static mixer, molecular diffusion is the only mechanism for radial transport, a slow process in viscous materials. Tracer parcels would remain isolated and not mix radially to any significant extent as they flow through an open conduit.

In the helical element mixer (Figure 4a), the collection of tracer parcels that enters near the conduit centerline divides into two regions that move radially outward as they exit the first element. Subsequent elements continue to split and rotate the flow to distribute the tracer parcels over an increasing portion of the conduit cross-section. At this low Reynolds number, 18 helical elements would be required to achieve uniform blending.

The first element of the crossbar mixer array in Figure 4b is oriented such that the angled bars of the mixer primarily move the tracer vertically, and at the end of the first element the parcels are distributed along a relatively narrow line that stretches from the bottom to the top of the conduit. The second element is oriented perpendicular to the first element and distributes the tracer horizontally; subsequent elements alternate the crossbar orientation and the direction of fluid parcel movement. After the fourth element, the tracer parcels are distributed uniformly over the conduit cross-section and little change in the tracer distribution occurs as the fluid passes through additional elements.



▲ **Figure 5.** Low-profile tab vortex static mixers can be mounted on the walls of (a) a circular conduit or (b) a square conduit. (c) Blending occurs via vortex generation.

Routine tasks in turbulent flow

Figures 5a and 5b are two variations of a low-profile, wall-mounted tab vortex static mixer that is used in turbulent mixing applications. The tabs at the conduit wall disrupt the boundary layer and generate a complex vortex system that provides efficient mixing over the entire conduit cross-section.

Vortex mixers are used for both liquid/liquid and gas/gas mixing. They are particularly useful for blending samples to ensure uniformity when measuring composition and/or temperature. The tab geometry can readily be applied in conduits of any geometry (circular, square, or rectangular cross-sections), as well as in open channels (which are prevalent in water treatment).

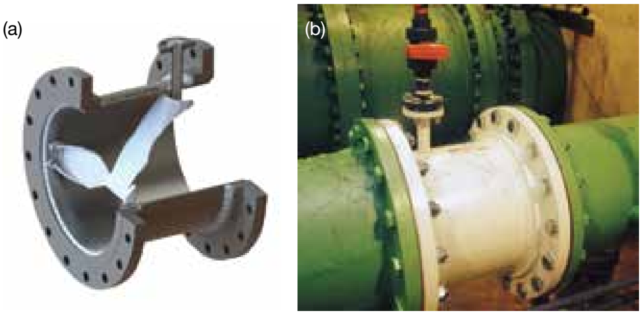
In addition to blending, tab mixers are used to condition, or straighten, turbulent flow in conduits by reducing swirl and asymmetry. Placed after elbows and/or before flowmeters, wall-mounted tab mixers reduce the length of straight pipe required to produce fully developed flow.

Specialized applications in turbulent flow

In some instances, mixing must be achieved very rapidly, in distances as short as three conduit diameters, with a single mixer element. Compact static mixers like the contoured-tab mixer shown in Figure 6 were developed to meet such stringent mixing requirements. Compact static mixers are a relatively recent advance in pipeline mixing *(2),* and to date have been used primarily in water treatment processes. While the literature contains significant information about other static mixer options, little has been published about compact static mixers.

When mixing must be accomplished quickly and/or the flowrates of the materials to be blended differ significantly, the mixing task becomes more difficult and a mixer that provides higher energy dissipation rates is required. Because the contoured-tab mixer occupies more of the conduit cross-section than the low-profile wall-mounted tab mixer, it is a higher-energy-dissipation device.

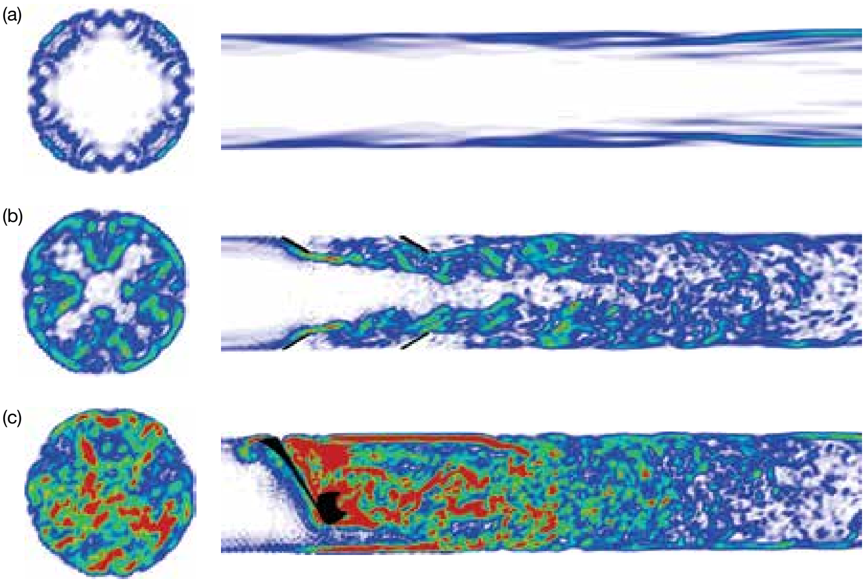
Figure 7 compares the energy dissipation rates of turbu-



▲ **Figure 6.** (a) A compact contoured-tab static mixer achieves fast mixing in a short distance. (b) A contoured-tab static mixer provides rapid mixing of alum coagulant as it is added to water.

lent flow in an open pipe (Figure 7a), a wall-mounted tab mixer (Figure 7b), and a contoured-tab mixer (Figure 7c). The left images show the conduit cross-sections and the right images are side views of the conduits (flow is from left to right).

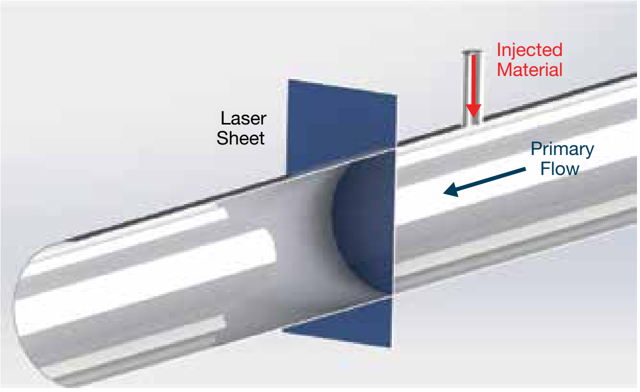
It is important to reiterate that while higher energy dissipation rates enhance the mixing capabilities of a device, this energy comes from the flowing fluid and does increase pumping requirements. When selecting a static mixer to meet a particular objective, a quantitative comparison of the overall pressure drop and associated energy requirements must be made. Although the contoured-tab mixer has a higher pressure drop per length of conduit, its ability to blend in very short distances often minimizes the overall pressure drop (relative to other element styles).



▲ **Figure 7.** Energy dissipation rates in turbulent flow (a) in an open pipe (white) are lower than those achieved by (b) a wall-mounted tab mixer (blue and green) or (c) a contoured-tab mixer (green and red).

The planar laser-induced fluorescence (PLIF) technique (Figure 8) is useful for studying static mixer performance. In this method, lenses convert a laser beam into a thin sheet, which is passed through a transparent conduit carrying the primary flow. A dye is added to the injected material, and the dye fluoresces as it passes through the laser sheet.

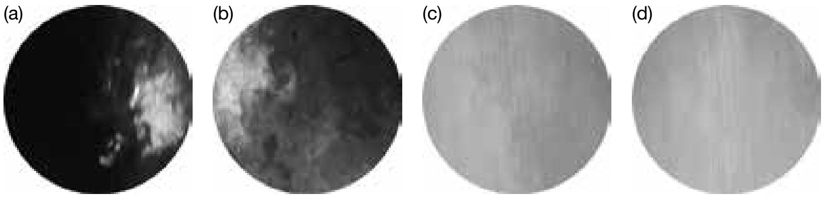
PLIF is an effective method for both qualitative and quantitative analysis of static mixer blending performance. The brightness of the fluorescing dye is related to the dye concentration, and the variation in dye concentration over the conduit cross-section can be measured. The non-uniformity of injectant concentration is typically quantified by the coefficient of variation (CoV), which is the standard deviation in concentration normalized by the average concentration. Although the criterion for good mixing varies by application, in many instances a CoV of 0.05 indicates that the system is sufficiently well-mixed.



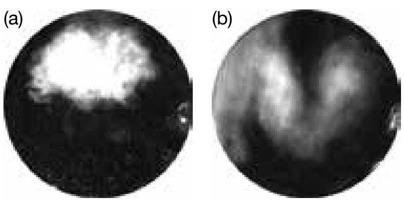
▲ **Figure 8.** The planar laser-induced fluorescence (PLIF) technique can be used for qualitative and quantitative analysis of static mixer performance. The brightness of the fluorescing dye is related to dye concentration, and the variation in dye concentration over the conduit cross-section can be measured.

To illustrate the range of mixing quality that might be encountered, Figure 9 presents PLIF images for various CoV values. The poorest mixing occurs in an open pipe (*i.e.,* without a static mixer), where the fluorescing injected material is present in less than half of the conduit cross-section and the CoV is 1.1 (Figure 9a). More mixing occurs downstream such that the injectant becomes distributed over the entire conduit cross-section and the CoV is 0.5, although there are obvious regions of significantly higher and lower injectant concentration (Figure 9b). The addition of a contoured-tab mixer significantly improves the mixing quality and reduces the spatial variation in injectant concentration, reducing the CoV to 0.1 (Figure 9c) and then to 0.05 (Figure 9d).

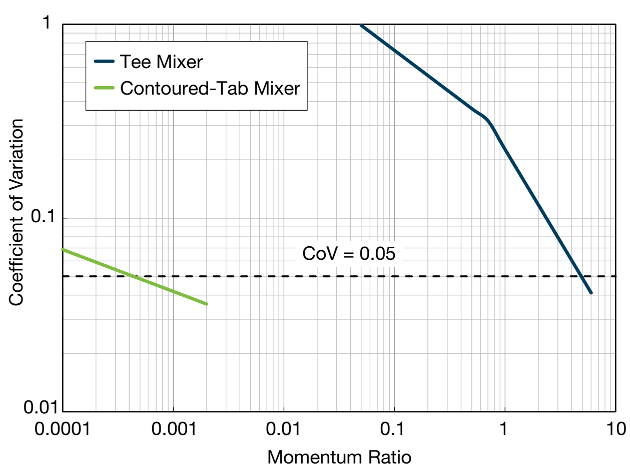
Although the method of injection is important in many static mixer operations, it is particularly important in those that require mixing in very short distances. Thus, to ensure optimal operation, the injector is often incorporated into compact static mixers (as shown in Figure 6). Figure 10 presents PLIF images immediately downstream of the introduction of injectant through the top of the conduit. In Figure 10a, the injectant momentum is too low relative to that of the primary flow, so the injectant does not penetrate very far into the primary flow and is isolated at the top of the conduit near the injection point. In Figure 10b, the injectant momentum is higher, so the injectant is distributed over a



▲ **Figure 9.** (a) Poor mixing in an open channel, where the fluorescing injected material is present in less than half of the conduit cross-section, is characterized by a coefficient of variation of 1.1. (b) As the injectant distributes throughout the entire conduit cross-section, the CoV drops to 0.5. (c and d) Adding a contoured-tab static mixer improves mixing quality and uniformity of injectant concentration, and reduces the CoV to 0.1 (c) and 0.05 (d).



◀ **Figure 10.** (a) When the injectant momentum is much lower than that of the primary flow, the injectant remains isolated at the top of the conduit near the injection point. (b) Higher momentum distributes the injectant over a larger portion of the conduit cross-section.



▲ **Figure 11.** A contoured-tab mixer with a built-in injector and vortex-generation capability operates effectively at low momentum ratios.

larger portion of the cross-section, before passing through the turbulent vortices generated by the tab mixer and then spreading uniformly over the entire conduit cross-section.

Figure 11 compares the blending capabilities of a contoured-tab mixer with those of a single-jet tee mixer *(3)*. A tee mixer is a very simple device that injects material at the conduit wall perpendicular to the primary flow, as shown in Figure 8, with mixing occurring in the open conduit downstream of the injection point. The comparison is made three conduit diameters downstream of injection, and the physical properties of the injectant and primary flow are similar so property differences do not increase the difficulty of the mixing task. The performance of both mixers is determined by the momentum ratio (injected flow momentum rate to primary flow momentum rate).

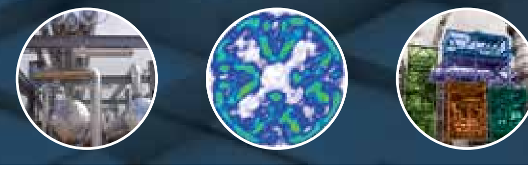
Tee mixers perform best at higher momentum ratios, which ensure that the injected flow penetrates a sufficient distance into the primary flow (refer to Figure 10) and that the injected flow provides sufficient energy to accomplish the mixing task. Conversely, the contoured-tab mixer, with its built-in injector and vortex-generation capability, is designed to operate effectively at the low momentum ratios encountered when the injectant and primary flowrates are substantially different. To achieve a CoV of 0.05, a tee mixer must operate at momentum ratios greater than five, whereas the contoured-tab mixer can be used at momentum ratios more than four orders of magnitude lower.

The high momentum ratios required for effective blending with tee mixers are accomplished by reducing the size of the injectant feed line, which in turn increases the feed line pressure drop (in turbulent flow, pressure drop is proportional to the square of the velocity). For a tee mixer to operate at a momentum ratio 10^4 times higher than that of the contoured-tab mixer, the diameter of the tee mixer's feed line would have to be a factor of one-hundred smaller than the feed line of the static mixer. In most operations adding small quantities of injectant, such as in water treatment, reaching the high momentum ratios required for acceptable tee mixer performance requires such high feed line pressure drops that tee mixers become economically unattractive relative to compact tab static mixers. The performance of tee mixers can be improved by using multipoint injection *(3)*. However, this complicates operation of what is intended to be a simple device.

The preceding discussion tacitly viewed mixing as a steady, invariant process. However, in turbulent pipe flow, conditions fluctuate with time. Figure 12 presents the temporal variation in the CoV based on 150 data points obtained over a 30-sec period. The average CoV for an open pipe with centerline injection (not wall injection, as with a tee mixer) is more than three times higher than the CoV for a contoured-tab mixer, and the variation with time is also substantially greater. Thus, the contoured-tab mixer not only provides significantly greater spatial uniformity in composition over the conduit cross-section, but temporal uniformity is better as well.

Comparing options in an example application

Consider the injection of a small amount of additive into a primary stream of water in turbulent flow. The pipe diameter is 0.1 m (approximately 4 in.) and the average velocity is 1 m/sec (3.3 ft/sec), corresponding to a Reynolds number of 100,000. The volumetric flowrate of the additive is only



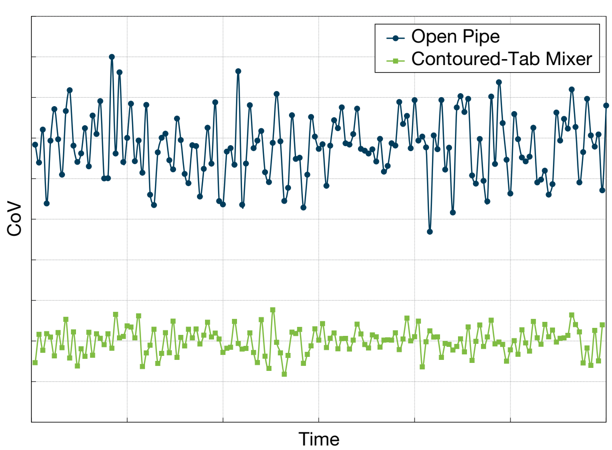
0.1% of the volumetric flowrate of the stream into which it is injected. The properties of the additive are not significantly different than those of water and thus do not affect the difficulty of the mixing process. Static mixers must reduce the CoV to 5% within three conduit diameters of the end of the static mixer array.

Various static mixer styles can be used to accomplish the mixing objective, and three will be considered here — helical elements (Figure 2), low-profile wall-mounted tab elements (Figure 5), and a compact contoured-tab mixer (Figure 6). Design requires first determining the number of elements that will provide the desired mixing, followed by calculation of the corresponding pressure drop. Table 1 compares the three design alternatives.

For the contoured-tab mixer, a 3-mm-dia. injector and an injectant velocity of 1.1 m/sec achieves a momentum ratio of 10^{-3}, a factor of two higher than that needed to provide the required CoV (refer to Figure 11). For a tee mixer to accomplish the mixing objective, a momentum ratio of five would be needed (Figure 11), which would require an unrealistic design of a 45-µm-dia. injector and an injectant velocity of 5,000 m/sec.

Mixing can also be achieved using a series of three helical or six wall-mounted tab elements. However, both of these options have a significantly higher pressure drop than the contoured-tab mixer. Additionally, both alternatives are longer than the contoured tab mixer. The mixing lengths listed in Table 1 are measured from the inlet of the static mixer to the point where the desired 5% CoV is achieved. These mixing lengths are expressed as multiples of the conduit diameter. The contoured-tab mixer is a very short mixer (approximately half a pipe diameter in length) that achieves mixing within three conduit diameters of the end of the mixer. The helical elements can achieve mixing within one conduit diameter of the end of the static mixer array, but each of the three elements has a length equal to 1.5 conduit diameters. The six wall-mounted tab arrays are separated by one conduit diameter and achieve mixing three conduit diameters downstream of the last element — the longest mixer option.

This design comparison is not intended to indicate that a contoured-tab mixer is always the best static mixer option. This application is the type for which contoured-tab mixers have been optimized, while the helical element and wall-mounted tab mixers are more generalized in their use. The takeaway of the example is that expanding static mixer options have led to improved performance over previous mixer options in some applications.



▲ **Figure 12**. The average CoV for a contoured-tab mixer is less than one-third the CoV for an open pipe with centerline injection, and it exhibits much less temporal variation as well.

Table 1. Static mixer design requires determining the number of elements that will provide the desired mixing and the corresponding pressure drop.

Element Style	Number of Elements	Mixing Length	Relative Pressure Drop
Helical	3	5.5 diameters	5.1
Wall-Mounted Tab	6	8 diameters	1.8
Contoured Tab	1	3.5 diameters	1

The Power of CFD

The impact of computational fluid dynamics (CFD) on mixing, as on many areas of chemical engineering, has grown steadily over the past 25 years. CFD allows engineers to quickly, accurately, and relatively inexpensively investigate the behavior of mixing systems without the need to build a physical model of the system. CFD can be used to evaluate numerous design alternatives and to identify and correct weaknesses, enabling the selection of the best design.

The laminar blending illustrated in Figure 4 and the turbulent energy dissipation fields of Figure 7 were identified using the Lattice Boltzmann approach, a relatively new development in the field of CFD. The computational efficiency of the Lattice Boltzmann approach permits more-accurate and less-costly simulation of most complex flows, particularly those that are turbulent. Rather than time-averaging the Navier-Stokes equations and approximating the turbulence in the flow using models, the lattice Boltzmann approach typically employs large eddy simulation in which a transient simulation determines the behavior of the large-scale turbulence, leaving only the smaller-scale turbulence to be modeled. Since this small-scale turbulence is nearly isotropic, it can be modeled accurately, making the simulations more physically realistic.

Article continues on next page

In closing

The array of static mixer options currently available makes it possible to use them to successfully meet process objectives in numerous applications. The various designs are intended for specific situations, with flow regime (laminar or turbulent) and difficulty of the mixing task being important factors in element selection. The recent development of compact static mixers to rapidly blend a small amount of an additive into a much larger flow is an example of static mixers continuing to evolve to meet the needs of the CPI and provide opportunities for process intensification. CEP

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Additional Resources

A previous article *(4)* provided a detailed review of static mixer applications and the choice between static and dynamic mixers, and presented more extensive design information for helical element and wall-mounted tab mixers, including friction factor, blending, and heat-transfer correlations. Thakur *et al. (5)* prepared a very thorough review of static mixers that covered fundamentals, applications, and key design parameters such as pressure drop, homogenization of miscible fluids, contacting immiscible fluids, thermal homogenization, and heat-transfer enhancement.

More recently, Ghanem *et al. (6)* reviewed static mixers with an emphasis on their application in process intensification. That work also includes extensive information on qualitative and quantitative experimental methods that can be used to characterize static mixer performance in both nonreactive and reactive applications.

An excellent source of information for all areas of mixing is the *Handbook of Industrial Mixing (7),* sponsored by AIChE's North American Mixing Forum (NAMF). Chapter 7 of this compilation, "Mixing in Pipelines" *(8),* provides an extensive treatment of mixing in open conduits as well as with static mixers, while Chapter 3, "Laminar Mixing: A Dynamical Systems Approach" *(9),* reviews a rigorous, fundamental method of examining laminar mixing with application to a helical-element static mixer.

Another subject of interest for process intensification that is detailed in the mixing handbook is rotor-stator devices capable of generating shear rates as high as 100,000 s^{-1} and local energy dissipation rates orders of magnitude higher than those found in conventional stirred tanks *(10)*; Ref. 11 also provides an overview of high-shear mixing.

The recently published *Advances in Industrial Mixing (12),* a companion to the handbook, provides valuable updates to the earlier material. Chapter 7b focuses on mixing in pipelines *(2),* and new chapters covering several areas pertinent to process intensification have been added. One such chapter details mixing for water treatment *(13),* a well-established industry that is now in need of better processing capabilities to deal with the growing demand for high-quality drinking water, tighter regulation, and the desire to reduce energy, equipment, and land usage. This chapter includes an interesting coagulant injection design example demonstrating that a static mixer can achieve better mixing at a lower power input than a stirred-tank flash mixer (Section 26-2.3). Another new chapter focuses on microreactors *(14),* a recent advance ushered in by microfabrication methods capable of producing conduits with diameters of 100–1,000 μm. The large surface-area-to-volume ratios of these microchannels are advantageous for processes that require very high heat- and mass-transfer rates and precise control of operating conditions.