EUROPEAN ROADMAP OF PROCESS INTENSIFICATION

- TECHNOLOGY REPORT -

TECHNOLOGY: Static mixers

TECHNOLOGY CODE: 1.1.4

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1. Technology

1.1 Description of technology / working principle

(Feel free to modify/extend the short technology description below)

Static (motionless) mixers are devices containing a series of precisely configured motionless elements (inserts) that impose splitting the fluid stream, reorientation and recombination of the sub-streams. In this way the elements generate mixing of fluid(s) flowing through the mixer, impose intense movement across the pipe, produce good conditions for heat and mass transfer, and increase interfacial surface area for immiscible fluids. At turbulent flow mixing, heat and mass transfer are enhanced by formation of eddies. Configurations of the elements are designed to suit different applications. The inserts are stacked one after another thereby forming modules. The elements are inserted into pipes, usually of circular cross-section although channels of different shapes, e.g., rectangular for large flows, are also used. Static mixers can be equipped with heating/cooling jacket or can be heated electrically. The mixing elements can be made from tubes, through which heat transfer media flow.

The energy for mixing is taken from the flow of fluid(s). Energy dissipation rates are high, with typical values between 10 and 1000 W/kg compared to an upper value of around 5 W/kg in conventional stirred tanks. Mass transfer coefficients (k_La) can be 10-100 times higher than in stirred tanks. An intensive radial mixing results in leveling of fluid velocity profile over the mixer cross-section. Consequently, residence time distribution (RTD) is narrow, i.e., nearly plug flow (axial dispersion is negligible) is reached. Pressure drop is very low due to the very high void fraction.

Static mixers were introduced in the middle of 1970s. Since then they have found thousands applications. They can be installed in existing systems without reducing the capacity of existing pumps. Due to small size of static mixers they can be easily placed in the existing plant without the need to rebuilding it. Diameter of standard mixers ranges typically from 3 to 300 cm but larger sizes are also available upon request. Disposable static mixers of smaller diameter (volume 2-600 mL) are also on the market. Typically, 12 to 24 elements are sufficient to provide a complete (macro)mix of miscible fluids. A length of 5 diameters is generally enough to produce sufficient interface surface area for immiscible fluids. Exemplary length of mixers that are offered by Ch. Ross & Son Co. for different applications is given below:

Application	Type and length of the mixer	Flow conditions
Organic liquid/liquid dispersions	LPD, 2-six elements modules	Highly turbulent
Gas-liquid contacting	LPD, 1-six elements module	Turbulent
Pipeline reactor for gas or liquid phase reactions	LPD, 1- or 2-six elements modules	Turbulent
Pipeline reactions in viscous media	ISG, 10 elements	Laminar
Neutralization of wastewater streams	LPD,1- or 4-six elements modules	Turbulent
Blend one grade of oil or gasoline into another	LPD, 2-six elements modules	Turbulent
Liquid/Liquid blending of viscous fluids	ISG, 4-6 elements	Laminar
Mixing two viscous resins	LPD, 4-six elements modules	Laminar
Thermal and color blending in injection molding applications	ISG, 4-6 elements	Laminar
Thermal and color blending in extrusion applications	ISG, 4-6 elements	Laminar
Admixing catalyst, dye or additive to a viscous fluid	ISG, 10-14 elements	Laminar
Solvent dilution	LPD, 1- six elements module	Turbulent
Multi-component reactive mixes using dispensing equipment	ISG, 10-14 elements	Laminar

Static mixers for carrying chemical reactions are usually longer and flow velocity is higher than for typical mixing operations. The above data show only approximately lengths of the static mixers. The length (or the number of mixing elements, *N*) depends on mixing requirements, properties of fluids, design of mixing elements and flow conditions. Hereunder, the data illustrating these dependencies are shown.

	Number of elements, N			
	$\mu_1/\mu_2 \approx 1$	$\mu_1/\mu_2 \approx 1$	$\mu_1/\mu_2 < 10^3$	$\mu_1/\mu_2 > 10^3$
Mixer type	Re<10	$10 < Re < 10^3$	$10^3 < Re < 2 \cdot 10^3$	$Re > 2 \cdot 10^3$
Kenics, L_e/D_e = 1.7	10	20	31	41
Sulzer SMV, L_e/D_e = 1	2	-	-	-
Sulzer SMX, L_e/D_e = 1.5	-	8	11	14
N-form, L_e/D_e = 1.2	7	13-19	19-25	25

Both pipe and mixing elements can be made from different materials of construction. A great variety of materials is used: carbon steel, stainless steels (304SS, 304LSS, 316SS, 316LSS), Alloy 20 Cb-3, Monel 400, Nickel 200, Inconel, Hastelloy B-2, Hastelloy C-276, titanium, tantalum, zirconium and other high alloys, PVC, CPVC, PTFE, Kynar, PVDF, FRP, polyacetals, and lined mixers. End configurations include flanged, threaded, welded, and plain connects.

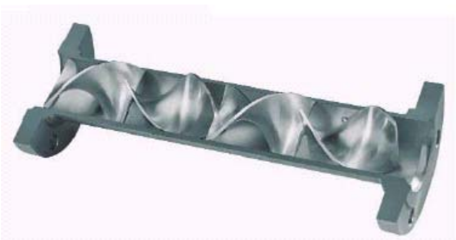
Static mixers are also discussed to some extent in Technology Reports Nos. 1.1.1.1 (Advanced heat exchangers – plate), 1.1.2 (Structured internals for mass transfer operations), 1.1.5 (Micro mixers), and 1.2.5 (Static mixers – reactors).

1.2 Types and "versions"

(Describe the most important forms/versions of technology under consideration, including their characteristic features, differences and similarities)

There are many types of static mixers that differ in small details from each other. In general, the following groups of static mixers can be distinguished: (i) open designs with twisted plates or ribbons, (ii) open designs with blades and baffles of high aspect ratio, (iii) open designs with blades of low aspect ratio, (iv) channels formed by corrugated or folded plates, (v) multilayer designs such as those formed by crossing bars or tubes, and (vi) closed designs with channels or holes that change significantly a cross-section for flow along the mixer. Hereunder, exemplary designs that are the most representative and/or the most widely used worldwide or seem to be the most efficient are briefly discussed.

(i) **Open designs with twisted strips or ribbons**



The KM Kenics mixer is probably one of the first static mixers that appeared on the market (mid 1970s). The KM is the most used and studied static mixer. It consists of rectangular plates that are twisted 180^0 to either the right direction or the left direction. The right- and left-hand helical elements are connected alternately with a connecting angle of 90^0. A fluid introduced to the mixer is divided at the front of the mixing element (flow division). When the flow passes the element, the fluid is mixed by a radial rotation of the flow within the mixing element (radial mixing). The flow direction is reversed at the connection point between the elements (flow reversal). The element aspect ratio does not contribute significantly to mixing efficiency at low Re numbers regime (Re < 100). The efficiency is affected, however, by the twist angle per mixer element over the whole Re region (Szalai and Munzio, 2003). The team of Technical University of Eindhoven (Galaktionov et al., 2003) found that that the KM mixer achieves the best macroscopic homogenization efficiency with the blade twist 140^0. This configuration provides also reasonably uniform interface distribution for immiscible liquids. The KM mixer is used mostly for blending or dispersion involving liquids and gases, as well as for enhancement of heat transfer. It is suitable for operations in both laminar and turbulent flow.

The design of the Koflo helical static mixers, series 246 has, like the KM Kenics mixer, two fluid divisions per element. Its mixing efficiency is almost independent of fluid viscosity or velocity. These static mixers are used primarily for low and high viscosity blending or the folding of two or more ingredients.

The JDMIX static mixer contains twisted ribbons that are arranged as shown in figure. Suitable for laminar and turbulent flow for low and high viscosities.

The CBMiM (Centre for Molecular and Macromolecular Studies of the Polish Academy of Sciences) mixer (on the right) consists of left- and right-twisted ribbons that are placed alternately to form the most dense packing. The minimum number of ribbons in the pipe is six but any even number of twisted ribbons may be packed into the tube. Here, a photo of the CBMiM mixer consisting of six ribbons placed in a tube of a round cross-section is shown, A better mixing efficiency is reached if ribbons are located in a tube of the cross-section that is adjusted to the contour of ribbons. The mixer is suitable for laminar and turbulent flow for low and high viscosities.

A MST mixer (on the left) that was worked out in the Institute of Industrial Chemistry, Warsaw, Poland consists of modules of left- and right-hand twisted plates with grids between the modules (not shown on the photo). It is suitable for laminar and turbulent flow for low and high viscosities.

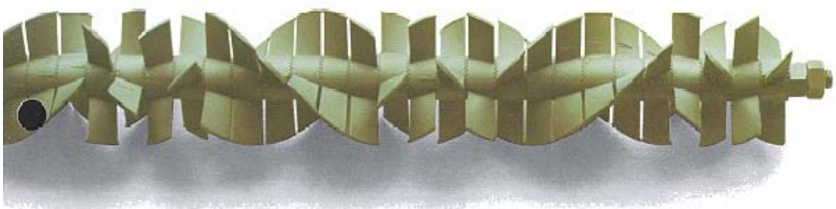
(ii) **Open designs with straight or bend blades and baffles of high aspect ratio**

The Ross LPD (low pressure drop) mixer (on the right) became a market product in mid of 1970s, like the Kenics mixers. It consists of a series of semi-elliptical plates, which are discriminately positioned in a tubular housing. A single element consists of two plates perpendicular to each other. The mixing operation is based on splitting and then diverting input streams. The LLPD (low-low pressure drop) mixer also consists of a series of semi-elliptical plates. The angle of the elements is less than the LPD, thus pressure drop consumed per element is lower. Most LPD mixers are constructed with 4 support rods to provide maximum rigidity. The LPD and LLPD are used in laminar and turbulent flow regimes and for fluids of different viscosities.

Koflo static mixer series 275 (on the left) is similar in design to Kenics mixers. So, the mixer characteristics and applications are similar.

Lightnin Inliner Mixer Series 45 (on the left) consists of semi-elliptical elements that create a distinct pattern of flow splitting and rotating vortices. Similarly to the Ross LPD and LLPD mixers, Inliner Mixers Series 45 are used in laminar and (mostly) turbulent flow regimes and for different viscosities, densities and fluids with unusual properties such as polymers.

A Bran and Lübbe N-form mixer (on the right) is the static mixer using forced flow separation and geometrically offset stream recombination. The N-form consists of the mixing elements that produce four separate flows (two times more than the Kenics and Koflo mixers), which are mixed simultaneously. It ensures an excellent radial mixing. The N-form static mixers are used for blending in both laminar and turbulent flow, also for highly viscous liquids.

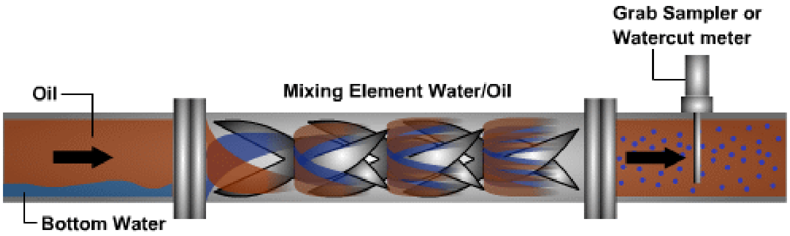


The Lightnin Inliner Static Mixer Series 50 consists of right- and left-handed helices. Configuration comprising 3 right-hand and 3 left-hand helixes is arranged so that the first element of a left-hand helix straddles the final element of the right-hand helix. This is obtained by indexing the adjacent blade edges 60^0 from each other. As the flow hits the leading edge of the first element it is divided into three streams and rotated 180^0. The stream then enters the turbulent section, a series of staggered segments. Here, it is instantaneously dispersed in radial direction. Subsequent sections alternately rotate the flow alternately 180^0 right and left. Segments can be individually aligned within each element so that the mixing action can be customized and tuned to process requirements. The mixer is excellent for widely differing viscosities, densities, and fluids with unusual properties, such as polymers. The mixer is suitable for laminar and turbulent flows.

The Komax static mixer SM series A is built right to eliminate any downstream centrifugal effects. The Komax static mixer achieves high efficiency through triple action mixing. They are designed for use where additives to the main pipeline flow have already been introduced upstream of the mixer. The SM-A mixers are used over the whole Reynolds regime for low and high viscosity fluids.

Kam Controls Inc. KPL static mixer is a fixed arrangement of positive and negative elements fixed in a pipe or tube. This static mixer achieves a high mixing action by dividing and recombining the phases of the fluid four times per element. Like the other mixers of this group, the KPL mixers are used over the whole Reynolds regime for low and high viscosity fluids.

Essiflo static mixers for additive mixing in both pipe and in-channel installations handle very small and large flow rates for liquids of both low and high viscosities.



BMX mixer BMF mixer

Bartlett Engineering static mixers: The BMX is typically used for high viscosity applications or applications, in which the fluid velocity is so low that turbulent flow cannot be achieved. In these applications, the BMX element produces the most mixing with the relatively low pressure drop. The BMF element was designed for applications with stringy or fibrous material in the flow stream. Its design utilizes no touching surfaces in the flow stream. The side blades have no places to snag fibrous material, and the center blades are cantilevered so that any fibrous material just slides off the end.

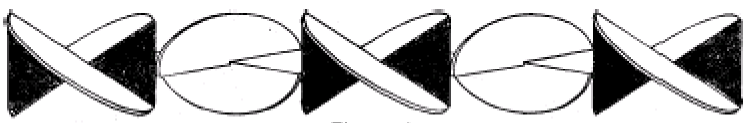
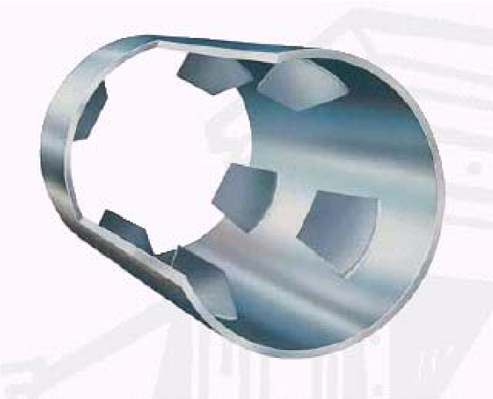


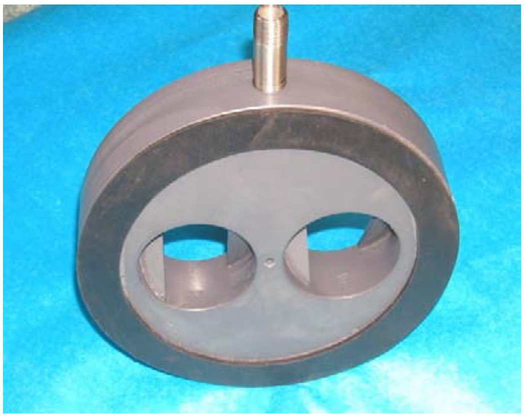
Figure 1

Cleveland mixer is similar in design to the Ross LPD mixer. The elements are made in two patterns. The left-handed inclined ellipse (LH) provides clockwise rotational flow. The right-handed inclined ellipse (RH) provides counter-clockwise rotational flow. The elements are connected at 90° angles to each other, and furthermore, the two element patterns are alternated in series (i.e., RH, LH, RH, LH.). The Cleveland mixers are suitable for liquids of different viscosities over a broad range of Re numbers.

(iii) **Open designs with blades and baffles of low aspect ratio**

This group of static mixers has been designed for fluids of low viscosity (gases) and turbulent flow where mixing is effected by vortices. Due to their small length, these static mixers are particularly suitable for applications in places where short space is available, i.e., for plant retrofitting. Large passages in static mixers of this category prevent clogging of the mixer. The Chemineer HEV mixer, Komax wafer-style mixer, and Sulzer CompaX and SMI series mixers are typical for this group.





The Chemineer HEV mixer Wafer type Komax mixer

Mixing in the Chemineer HEV mixer is accomplished by controlled vortex structures generated by the low-profile geometry. Complete mixing is reached with pressure drop 75 % less than in conventional static mixers. The HEV mixer is typically used for low-viscosity liquid-liquid blending processes, as well as gas-gas mixing. Mixing in a wafer type Komax mixer is accomplished by narrowing and subsequent expanding streams flowing through the holes of cross-section that is much smaller than that of the tube.

The CompaX™ of Sulzer The SMI™ mixer of Sulzer

The CompaX design consists of a highly efficient device integrated with dosing inlet point. The additive is fed into the zone where strong turbulent flow prevails. The CompaX mixer is used for mixing of gases, liquids and suspensions in the turbulent flow regime. Similarly, the SMI static mixer is designed for handling low viscosity fluids (gases, low viscosity liquids) in the turbulent flow regime where an efficient blending/mixing action is required. The SMI mixing baffles generate larger counter rotating eddy currents in the main fluid flow, which ensures a very effective cross flow pattern over the entire pipe cross-section of the mixer including flow regions close to the pipe walls. The above mixers have an open structure which eliminates the risk of clogging. In combination with appropriate dosing arrangements, simple construction, low pressure drops and efficient mixing within a short distance are particular features of this mixer design.

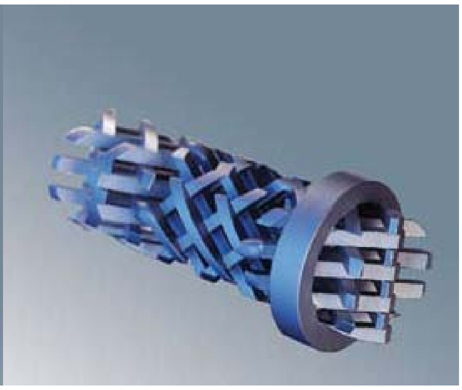
(iv) **Channels formed by corrugated or folded plates**

A typical representative of such mixers are Sulzer mixers of SMV™ series. The SMV mixing elements consist of intersecting inclined corrugated plates and channels, which encourage a rapid mixing action in combination with plug flow progression through the mixer. Elements of the mixer are rotated by each other. Any number of additives can be mixed at the same time within the mixing zone. The SMV mixers are characterized by a high mixing efficiency combined with large turn-down processing capabilities and short mixing lengths as well as relatively low energy requirements. This static mixer is suitable for applications requiring a distributive and homogeneous mixing and blending action in the turbulent flow regime. It is also efficient in dispersive mixing action or mass transfer in the turbulent flow regime. Higher shear forces are necessary for this dispersion duty. Mass transfer in the SMV mixer is very effective. The SMV mixers are recommended for the use in turbulent regime to handle with liquids of low viscosity, dispersing immiscible liquids and contacting liquids with gases.

(v) **Multilayer designs such as those formed by crossing bars**

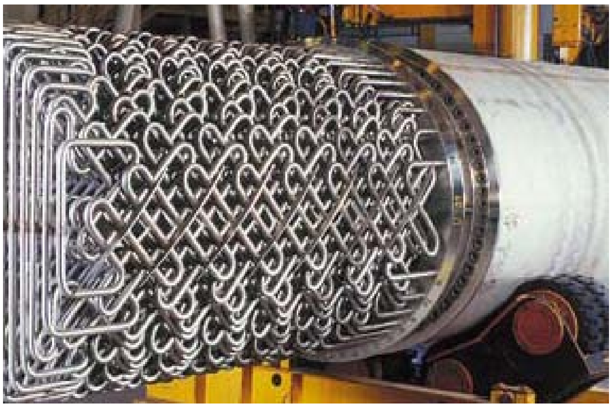
The Sulzer SMX™ static mixers consist of an array of similar, stationary mixing elements, placed one behind the other in a pipe. The mixing elements are complex networks of angled guide blades, positioned at an angle between 30° and 45° to the pipe axis. Mixing occurs through the continuous redirecting, splitting, stretching, and diffusion of the fluids as they pass through the available openings. The SMX static mixers are mainly used for difficult homogenization and mixing of highly viscous fluids (polymerizations and polymer processing), admixing low viscous media to the highly viscous liquids, and dispersing in laminar flow. A modified SMX mixer, designated as SMXL™ is typically used for enhancing heat transfer in viscous fluids. Heat transfer is enhanced by a special design of the elements near the tube wall. SMXS™ is also based upon SMX design that is adapted for processing highly viscous liquids by imparting extreme mechanical strength. Both SMX modifications have been designed for the use in the laminar flow regime.

The Sulzer SMXL mixer



The Sulzer SMXS mixer

The Sulzer SMR™ class of static mixers belong also to multilayer designs. The elements are made in a complex tubular form with heating/cooling medium flowing through the tubes whose heat exchange surface area per mixer volume is high. Due to the shape of the elements the SMR mixer levels the flow velocity over the cross-section and ensures nearly plug flow of the liquids. These features make the SMR static mixer to be an effective reactor-heat exchanger even for highly viscous liquids in laminar flow regime.



(v) **Closed designs with channels or holes**

The ISG (Interfacial Surface Generator) mixer is a typical representative for this class of mixers. It consists of mixing elements enclosed in a pipe housing. The ends of the elements are shaped so that adjacent elements form a tetrahedral chamber. Four holes bored through each element provide the flow paths. If two input streams enter an ISG mixer, the number of layers emerging from the first, second and third elements are 8, 32, 128. This exponential progression generates over two million layers in just 10 elements. This high theoretical efficiency comes at the price of higher pressure drop. The ISG mixer is used mostly for viscous fluids and in the laminar flow regime.

Recently microstructured mixers have become a subject of scientists and practitioners interest. Most of the currently investigated micromixers create lamellae of the order of 50 to 200 μm. Mixing times of a few 100 μs can be reached with so-called super focus mixers. Isothermal operation of micromixers for highly exothermic reactions is possible because of extremely high surface-to-volume ratio of about 30,000 m^2/m^3 compared to about 4 m^2/m^3 in the production scale stirred tank reactors. A temperature gradient of 1,000,000 K/s is possible. Fast mixing of reactants makes micromixers promising for chemical reactions, which are mixing-sensitive. For all above reasons, micromixers are promising for organic chemistry to manufacture mixing- and temperature-sensitive products. Microtechnology is intensively developed in Germany and Japan. The Forschungszentrum Karlsruhe and the Institut für Mikrotechnik Mainz are leaders in developments of microstructured components such as micromixers and micro heat exchangers in Germany. Japanese universities and industries established, with the help of Japanese Ministry of Economy, Trade and Industry, the Research Association of Micro Chemical Process Technology in Kyoto wit a budget of about 60 millions EUR over five years (Bayer and Himmler, 2005).

Differences in design of static mixers result in differences in mixing efficiency and intensity of transport phenomena that are decisive in the choice of the mixer for a particular application and are the basis for comparisons between mixers and their families.

Pressure drop

Energy that is needed to force flow through a mixer is proportional to pressure drop in the mixer. Pressure drop is a function of the mixer geometry, properties of fluids to be mixed and flow conditions. Three factors are commonly used to characterize pressure drop in static mixers: friction factor, f, pressure drop factor, Z, and power constant, K_p, the two latter being functions of friction factor. The dependence of friction factor on flow conditions for empty pipes and static mixers is generally given in a form:

$$f = A + \frac{B}{\mathrm{Re}^C}$$

where A, B, and C are adjustable coefficients whose values can be found in the literature (for empty circular tubes A=0, B=64 and C=1 at laminar flow regime and A=0, B=0.3164 and C=0.25 at turbulent regime, see Blasius equation with friction factor approaching the value of 0.02 for very high Re numbers). The friction factors for static mixers scatter significantly and show discontinuities at the borders of regions of validity of the equations for f. Similarly to flow in empty tubes, friction factors go to the constant values at very high Re numbers amounting to the values of 3, 11, 12, and 6-15 for Kenics mixers, Komax mixers, and Sulzer mixers SMX and SMV, respectively. The pressure drop factor, Z, is defined as the ratio of pressure drop in a static mixer to pressure drop in the empty tube:

$$Z = \frac{f_{SM}}{f_{ET}} = \frac{\Delta P_{SM}}{\Delta P_{ET}}$$

Since the coefficient A is usually small compared to the second component of the equation for friction factor, f, Z-factor can be considered approximately constant for static mixers in the laminar regime. The power constant, K_p, is a product of Newton number and Reynolds number:

$$K_p = Ne \cdot \mathrm{Re}$$

and is also approximately constant at laminar regime. Hereunder, Z-factors and power constants, K_p, are set for some commercial and developmental static mixers.

Static mixer (group)	Z	K_p		
		Vendor	Literature	CFD
Kenics (i)	8.1±1.7	170	195	255
CBMiM (i)	11	-	-	-
Ross LPD (ii)	7.4±1.4	195	220	225
N-form (ii)	16±1	-	450-510	-
Lightnin, 50 series (ii)	9	240	270	300
Komax (ii)	25	-	750	-
Cleveland (ii)	-	190	-	190
SMV (iv)	81±19	-	-	-
SMX (v)	55±45	1200	1140	1120
Ross ISG (vi)	275±25	7210	8140	8460

There are discrepancies in the literature data on pressure drop in static mixers. Moreover, please notice that friction factor in Sulzer mixers vary with pitch, thickness, crimp depth, angle between channels etc. Therefore, no exact conclusions can be drawn from the above figures for different groups of static mixers. Tendencies can be only observed. As expected pressure drop is the lowest for mixers containing helical elements and rises with growing complexity of configuration. Clearly, pressure drop is higher for mixers with elements that force more rapid changes in flow direction. A relatively good agreement exists between power constants determined from vendors data, CFD results and the literature data.

Mixing efficiency

Performance of static mixers in formation and recombination of sub-streams depends roughly on the number of passages that are formed at the edge of (modules of) mixing elements. A simple measure of (macro)mixing efficiency in laminar flow is the number of layers into which the stream of miscible fluids is broken up, n. It is a function of number of channels in the mixing element, K, number of elements or pitches in a twisted ribbon, N, number of spirals in a tube (CBMiM), n_s, and number of plates in a multilayer design, n_p (SMV) Theoretical number of layers generated by commercial mixers are tabulated below.

Mixer type	Kenics Ross LPD Cleveland Komax	Bran and Lübbe Ross ISG KAM	Lightnin Inliner 50	CBMiM	SMV
Number of layers, n	2^N (K=2)	4^N (K=4)	$K\cdot(2)^{N-1}$ (K=3)	$>n_s\cdot 6^{3N}$ (K>6)	$n_p\cdot(2n_p)^{N-1}$

The *n*-criterion for mixing efficiency is, however, less useful for assessment of mixing efficiency at turbulent flow where an influence of eddies on mixing becomes even greater than flow division and recombination. A more sophisticated measure of (macro)mixing performance is coefficient of variation, *CoV*, defined as:

$$CoV = \frac{\sqrt{\frac{1}{k-1}\sum_{i=1}^{k}(c_i - c_{mean})^2}}{c_{mean}}$$

where k is the number of measurements over cross-section of the pipe (usually $k \geq 9$), c_i is the time averaged concentration of *i*-th probe. The lower *CoV*, the better is mixing of streams. *CoV* of 0.01 or 0.05 are considered standards. The *CoV* is a function of the following variables:

$$CoV = f\left(\frac{\mu_1}{\mu_2}; c_{mean}; Q\right)$$

For $\mu_1 \approx \mu_2$, *CoV* is a function of L_{SM}/D_{SM} of the following form:

$$CoV = b \cdot \exp\left(-c\frac{L_{SM}}{D_{SM}}\right)$$

where b and c are adjustable coefficients. The coefficient c represents the rate of decrease of *CoV* per unit of the mixer length. Approximately, b depends only on c_{mean} at laminar flow and also on flow velocity at turbulent flow, while c depends mainly on the mixer geometry.

Below, approximate data on mixer characteristics and on energy consumption for some commercial mixers is given (Green, 2004) for constant flow, constant diameter, and similar *CoV* at laminar flow.

Static mixer	Ratio in respect to			
	Length	Pressure drop	Power input	Energy consumed
SMX	1	2	2	1
SMXL	2	1	1	1
Kenics KSM	3	1	1	1.3
Ross ISG	0.6	13	13	6

If flow and pressure drop are to be constant and *CoV* similar at laminar flow the geometry of those commercial mixers would be as follows:

Static mixer	Ratio in respect to	
	Length	Diameter
SMX	1	1
Kenics KSM	2.25	0.75
Ross ISG	1.5	1.65

The ratio of L_{SM}/D_{SM} at which *CoV* achieves the standard value, e.g. 0.05, is considered to be a measure of mixer performance in (macro)mixing. Hereunder, $(L_{SM}/D_{SM})_{CoV=0.05}$ for $c_{mean} = 0.1$ and laminar flow are tabulated. Generally, the above ratio decreases (i.e., mixing performance increases) with the complexity of the mixer design and flow path. The mixing performance is the highest for the Sulzer mixers of the most complex geometry. This is, however, achieved at the expense of energy that is required to force flow through the mixer. Mixing efficiency number, *ME*, is proposed to combine both mixing performance and pressure drop factor, *Z*. It is defined as the product of the mixing performance required by the pressure drop or energy used for achieving the required performance:

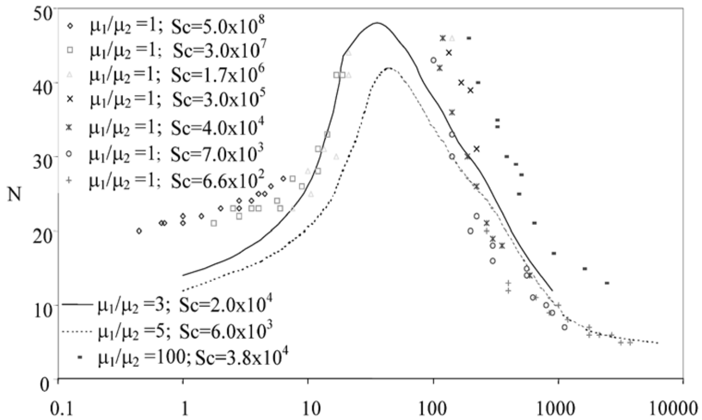
$$ME = Z \cdot \left(\frac{L_{SM}}{D_{SM}} \right)_{CoV=0.05}$$

The *ME* number is a measure of the mixer ability to produce the standard mix per expenditures for pumping fluids through the mixer. The lower mixing efficiency number, the less becomes energy that is required for standard mixing. The *ME* numbers for some commercial and developmental mixers are tabulated below.

Mixer type (group)	$(L_{SM}/D_{SM})_{CoV=0.05}$	*ME*
Kenics (i)	24.0	194
CBMiM (i)	17.0	187
Lightnin Inliner 50 (ii)	71.0	1136
Komax (ii)	29.2	730
SMV (iv)	3.1	251
SMX (v)	8.6	473

Mixing efficiency number passes through a maximum for mixers of open design with blades and baffles being the lowest for mixers of group (i). This conclusion contradicts slightly with the above tabulated data of Green, who claims that cost of energy would be the lowest for SMX mixer. All conclusions regarding mixing in static mixers must be taken cautiously having in mind discrepancies in the literature data on both pressure drop and homogeneity in static mixers.

The length of the static mixer, L_e, and the number of mixing elements, $N = L_{SM}/L_e$ increase with flow velocity at laminar regime to reach the desired homogeneity. At transition region the relationships is reversed and the number of mixing elements decreases with flow velocity approaching constant values for high *Re* numbers, see the figure (on the right) for the Kenics mixer. Molecular diffusion that is represented by Schmidt number, *Sc*, appeared to be negligible in the transition and turbulent regimes.



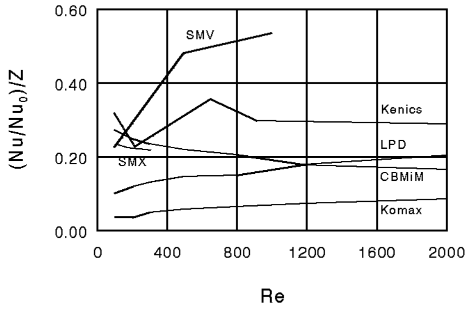
Backmixing in static mixers is negligible. The literature data on residence time distribution (RTD) show that static mixers behave as if they were nearly plug flow devices regardless the mixer design. Werner et al. (1987) studied RTDs for Komax, MST, CBMiM and Ross LPD using radioactive tracers technique. Peclet number, *Pe*, for all mixers studied exceeded 100, i.e., the value that is considered to be the limit for pseudo-plug flow.

Dispersion

In most papers dispersion whose measure is the ratio of Sauter-mean diameter to the mixer diameter depends on Reynolds and Weber numbers. The ratio is dependent on the Weber number with an exponent ranging from -0.74 to -0.4. This means that smaller drops are favored with increasing the flow rate or decreasing the surface tension. An exponent at Reynolds number is slightly positive indicating that increasing liquid viscosity leads to formation of smaller drops. Water was used as a continuous phase in all investigations of dispersion phenomena, so extrapolation on the other media must be done cautiously. Literature data on interfacial area and mass transfer indicate that mixers of group (iv) perform the best in respect to dispersion. The SMV mixer appears to be very flexible because of its flexibility in design of the hydraulic diameter. Unexpectedly, the CBMiM mixer turned out to be very efficient in dispersion of non-miscible polymer melts (Cybulski and Werner, 1986).

Heat transfer

A mechanism of heat transfer in terms of thermal homogenization is similar to that for mixing of miscible fluids. Heat exchange with the surroundings is usually described in terms of Nusselt numbers, *Nu*. Literature data on heat transfer scatter much. Thereby, comparisons between static mixers in this respect are difficult. Clearly, the greatest enhancement of heat transfer to the surroundings is for the most complex structures such as Sulzer mixers. As a first approximation, heat transfer coefficients can be increased by a factor of 2-3 for helical inserts and by a factor of 5 using SMX elements. The enhancement is reached, however, at the higher cost of pumping. Therefore, more reasonable comparisons must account also for pressure drop. Heat enhancement factor, *HEF*, is proposed for assessment of thermal efficiency of static mixers in this respect:

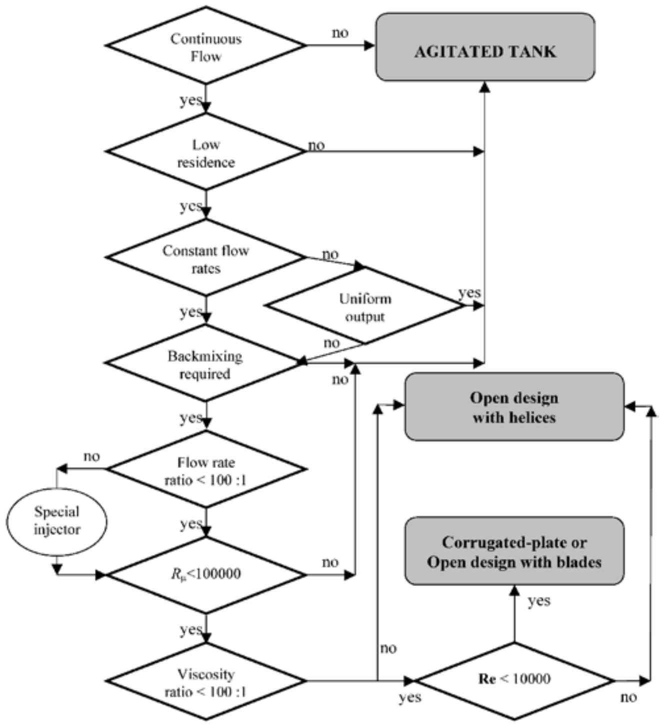


$$HEF = \frac{1}{Z} \cdot \left(\frac{Nu_{SM}}{Nu_{ET}} \right)$$

The HEF for laminar flow of water-like liquids and $L_{SM}/D_{SM} = 10$ is plotted vs. Re numbers in figure above. Here, static mixers of groups (i) and (v) perform the best. Again, this statement must be taken cautiously considering discrepancies in the literature data on heat transfer and pressure drop.

Mixer selection

The above discussed data are the basis for mixer choice. General guidelines for the mixer selection are shown (on the right) in the form of a logic diagram. Please, notice that static mixers are often used as complimentary in (semi)batch operations. The more detailed guidelines can be formulated as follows:



• Static mixers of group (i) are suitable and almost optimal for operations in laminar regime for mixing, thermal homogenization and heat exchange to the surroundings. The more mixing elements per cross-section area, the more efficient becomes the mixer also in respect to dispersion. The CBMiM mixer is particularly suitable for these purposes.

• Static mixers of groups (ii) and (iii) are good for turbulent flow applications such as mixing, heat transfer and thermal homogenization. The mixers of family (iii) are suitable for blending of solids (also with liquids), mixing and dispersion for low viscous fluids. Static mixers of families (i)-(iii) are less prone to plugging and fouling that mixers from groups (iv)-(vi).

• Static mixers of group (iv) are excellent for producing very homogeneous mixes and for developments of interfacial surfaces (gas-liquid, immiscible liquids) and enhancement of interfacial mass transfer. Enhancement of heat transfer with the surroundings by those mixers is significant.

• Static mixers of group (v) are suitable for operations with highly viscous liquids in laminar flow regime. They can also be used for multiphase operations when the continuous phase is viscous or viscoelastic. The SMR Sulzer mixer has been designed for polymerizations with the intensive heat transfer.

• Static mixers of group (vi) are suitable for homogenization of highly viscous liquids at laminar flow regime.

Mixer scale-up

Hereunder, the following approximate rules are recommended for scaling-up (Green, 2003; Thakur et al., 2003). The scale-up factor is generally defined as

$$S = \frac{capacity\ of\ \ full\ scale\ plant}{capacity\ of\ \ pilot\ plant}$$

Scale-up in parallel means the same process conditions in one tube and many tubes of the industrial scale device. The scale-up factor, *S*, is given by the following ratio:

$$S = \frac{number\ of\ tubes\ in\ a\ \ full\ scale\ plant}{number\ of\ tubes\ in\ a\ \ pilot\ plant}$$

or by multiplication by a number of tubes in a full-scale unit if the one-tube pilot plant was used. When scaling-up in series with constant tube diameter in both scales the scale-up factor is equal to:

$$S = \frac{Q_{full\ scale\ plant}}{Q_{pilot\ plant}} = \frac{\mathrm{Re}_{full\ scale\ plant}}{\mathrm{Re}_{pilot\ plant}}$$

Pressure drop will then increase significantly as S^2 in the laminar regime and as $S^{2.75}$ at fully turbulent flow (see literature correlations for friction factor). Mostly, diameter of the mixer is changed at scale-up. In such cases, for fast reactions: (a) mixing rate of the limiting step (characteristic time scale) should be kept constant, (b) residence time in the mixer should remain unchanged, and (c) the limiting mixing mechanism should not change. Process conditions (concentrations, flow rate ratio, mixer type, feed position) should remain unchanged. Then, for macromixing or mesomixing limitations

$$D_{FSP} = S^{1/3} \cdot D_{PP}$$

$$L_{FSP} = L_{PP} \cdot \frac{D_{FSP}}{D_{PP}}$$

and for micromixing limitations

$$D_{FSP} = S^{3/7} \cdot D_{PP}$$

If residence time is kept constant, fewer mixing elements will be required, and

$$L_{FSP} = L_{PP} \cdot \left(\frac{D_{FSP}}{D_{PP}}\right)^{1/3}$$

For immiscible liquid/liquid process at turbulent flow the energy dissipation needs to be kept constant, and consequently:

$$D_{FSP} = S^{3/7} \cdot D_{PP}$$

As a minimum, residence time should be then maintained

$$L_{FSP} = L_{PP} \cdot \left(\frac{D_{FSP}}{D_{PP}}\right)^{1/3}$$

Fewer elements will be usually required at a larger scale. However, for a conservative design and scale-up, the same number of elements should be maintained.

1.3 Potency for Process Intensification: possible benefits

(In Table 1 describe the most important documented and expected benefits offered by the technology under consideration, focusing primarily on energy; CO_2 emission and costs, providing quantitative data, wherever possible. Add other benefits, if needed).

Table 1: Documented and expected benefits resulting from technology application

Benefit	Magnitude	Remarks
Energy saving for mixing	According to team of JDMIX energy savings exceed even 90% compared with conventional system. Example: For mixing 6 m^3 of a viscous liquids in a batch operated stirred tank reactor, approximately one hour and 36 MJ of energy are required. In a small static mixer a homogeneous mixture of those liquids is achieved after only 0.25 seconds of residence time and a total energy consumption of only 2 MJ (Bayer and Himmler, 2005)	Conventional stirred tanks that are used for both mixing and carrying chemical reactions are highly inefficient in respect to energy utilization. A part of energy is consumed for friction between a mixer shaft and sealing. Moreover, energy dispersion in the tank volume is non-uniform: In more than 50 % of the tank volume energy input is ca. 20 % of the average input, while only in ca. 3 % the input is 15 times greater than the average (the above data are for a typical stirred baffled tank equipped with an open Rushton turbine agitator).
Capital cost saving	Savings of 10-90 %. Examples: (a) Glass-lined agitated reactor 6 m^3 in volume costs more than 20,000 EUR and the static mixer that is equivalent in function (see above) has volume of only 0.6 dm^3 and costs a few hundred EUR. (b) Replacement of the high shear mechanical mixer in the chlorine dioxide high substitution bleaching system in Mead Paper in Ohio and Michigan would cost $ 450,000 for a titanium high shear mechanical mixer and only $ 22,000 for a titanium Komax Systems static mixer.	Capital cost for a static mixer is very low compared to mechanical mixers. Moreover, installation costs for tanks equipped with mechanical mixers often are more expensive than the unit itself, while a static mixer is simply placed in the pipeline, and expensive installation costs are avoided. The engineering cost of designing a static mixer in the plant is extremely low. Requirements on homogeneity, flow rates, properties of the products to be blended, along with pressure drop restrictions and space constraints is in principle all the detail required to approximate design of the mixing unit with the static mixer with a sufficient margin of technical safety (overcapacity).
Easy retrofitting the existing plants	Difficult to evaluate	The surplus of power of pumps installed in existing plants is usually sufficient to force flow through additional mixing device such as a static mixer. A small size of the static mixer allows usually for mounting it without the need to change in plant construction.
Small size of static mixers	Difficult to evaluate	*CoV* indicating a very good homogenization at macroscale can be achieved at short length of vast majority of static mixers in both laminar and turbulent regimes. Accordingly, high efficiency of mixing can be reached for mixers of very small size, especially compared with conventional tank mixers.
Increased reactor capacity in the fine chemicals and pharmaceuticals manufacture	Up to 30-40 %. Examples: (a) Batch time of about 4 h on a 1 m^3 scale for reaction between amine and Boc-anhydride, while only 13 min was sufficient in a small static mixer-reactor (Brechtelsbauer and Ricard, 2001). (b) According to Zhou et al. (1993) productivity of the	Fine chemicals are mostly manufactured in multi-product plans that are equipped with semi-batch operated stirred tank reactors with a large proportion of charging and discharging times over a whole process time. Moreover, organic reactions are often fast and highly exothermic. Heat generated from the reaction can alter the reaction pathway or destroy the structure of products and, accordingly, extended dosing of reactants in the course of the batch is

	airlift column loop reactor with static mixer in Cephalosporin C synthesis was higher by ca. 15 % and power input reduced by ca. 30 % compared to stirred tank reactor.	the only way to keep temperature within the predetermined range. Replacing a batch reactor with a continuous plug-flow reactor equipped with a static mixer results in reduction of process time (elimination of charging and discharging times, shorter reaction time) and improved heat transfer (due to the increased surface-to-volume ratio and better heat transfer coefficients) that decreases a risk of excessive temperatures. However, replacement must give considerable advantages since stirred tanks already exist in the plants and are not utilized in 100 %. Therefore, only replacing of old tank reactors with static mixers systems is rather recommended.
Better quality of dispersions and emulsions (more uniform droplet size distribution)	Difficult to evaluate. Quality of products (dispersions, emulsions) improved	The distribution in stirred tanks is not uniform and therefore droplets of broad spectrum of size are produced. The distribution of energy dissipation in the mixer volume is a function of local variations of velocity. Points of higher and lower energy dissipation are regularly distributed in the mixer volume. Thus, the drop size distribution is more uniform in a static mixer. Emulsions produced by static mixers must be often stabilized by surfactants.
Improved yields and selectivities of mixing-sensitive reactions	Difficult to evaluate. Yields and selectivities increased by several percent	Yield and selectivity for the desired products in the case of competitive reactions of different reaction orders depends strongly on local concentrations. Often a high concentration of reactant(s) favors the formation of side products. Dosing reactants to conventional stirred tank reactors results in high concentrations that influence negatively selectivity. The fast and intensive mixing in static mixers brings to lowering concentrations and, consequently, improvement of selectivity and yield.
Improved yields and selectivities of reactions that are sensitive to non-uniform RTD and temperature	Difficult to evaluate. Yields and selectivities increased by several ten percent possible, product quality can be better.	Conventional tubular reactors, particularly for reactions in highly viscous media, are characterized by non-uniform flow distribution over the tube cross-section. This effect is enhanced if reactions proceed with a high thermal effect. A good radial mixing and improved heat transfer to cooling medium outside the tube level both concentration and temperature profiles over the tube cross-section. Accordingly, the static mixer-reactor behaves like a plug flow reactor. This is particularly important for polymerization reactions. The molecular weight distribution of polymers manufactured in static mixer-reactors is usually narrower than that from tower or tubular reactors.
Increased safety	Difficult to evaluate	Volumes of static mixers is much lower than that of tank mixers. Accordingly, inventory of dangerous materials present in the mixer is much lower for static mixers and this makes the operation with static mixers safer.
Low shear stresses	Difficult to evaluate	Shear stresses near conventional rotating agitators are usually high. This can damage materials that are shear-sensitive. Static mixers outperform conventional mixers when gentle treatment of the materials is required.

1.4 Stage of development

Static mixers appeared on the market of chemical equipment in 1970s. Since then intensive R&D works have been performed to find solutions to industrial mixing problems. That resulted in many configurations of static mixers and thousands applications of static mixers in industries. Static mixers as chemical reactors is a rather new area of their applications although also this field is developing fast.

2. Applications

2.1 Existing technology (currently used)

(Describe technology (-ies) that are conventionally used to perform the same or similar operations as the PI-technology under consideration)

Conventional mixing operations are carried out in vessels of various shapes. Energy required for mixing is mostly supplied via a moveable stirrer (usually rotating), whose shape is adapted to physical properties of the mixture and its components. In some cases the vessel is moved in a specific manner (rotation, oscillations etc.) to provide energy for mixing. Chemical reactions that require mixing for both contacting reactants and improving heat transfer conditions are done usually in stirred tank reactors and column reactors. In the former reactors energy is supplied via mechanical rotating stirrer, while in the latter ones energy is supplied via pumps for feeding reactants and for recirculating the reaction mixture. Static mixers are a relatively new technique of mixing. However, first industrial applications of static mixers were reported in 1970s so this technology can be considered matured although research and development in this field is continued, in particular in applications for chemical reactions.

2.2 Known commercial applications

(Is the technology broadly applied on commercial scale? In which process industry sectors is the technology most often applied: large volume chemicals – specialty chemicals & pharma – consumer products – ingredients based on agro feedstocks? What is the estimated number of existing applications? In Table 2 provide the most prominent examples of realized applications and provide their short characteristics)

In general, static mixers are used for performing the following groups of processes and operations:

- Homogenization of flowing streams in respect to concentrations and/or temperature
- Mixing of miscible fluids (in-line dilution, dosing, and mixing of various additives) of viscosities differing even by orders of magnitude
- Gas-liquid and immiscible liquids contacting to improve dispersion and interface mass transfer
- Dispersion of solids into liquid streams
- Enhancement of heat transfer in heat exchanger tubes for viscous fluids and for carrying homogeneous reactions with a high thermal effect
- Carrying out reactions in tubular reactors to reach narrow residence time distribution (plug flow), better control of exothermic or endothermic reactions (improved heat transfer between the reaction zone and the surroundings)
- Carrying out fast competitive homogeneous reactions (e.g., acid-base neutralization, pH control)

There are **hundred thousand static mixers** installed and operated in process industries worldwide to perform the above processes and operations (www.lenntech.com). First applications were reported in late 1970s. One of the world leaders in technology, manufacturing and sales of static mixers, Sulzer CHEMTECH (see Sulzer CHEMTECH brochures), claims that they have more than **70,000 references for their mixers** installed and operated whereby over

15,000 references regards chemical process industry, over 15,000 – plastic processing, over 6,000 – disposable mixers and cartridges, over 4,500 – water and wastewater treatment, over 4,000 – food processing industry, over 3,000 – oils, gas and refinery, over 2,200 – fiber production, over 1,800 - environmental plants (deNOxification), and over 300 – polymer production (Sulzer CHEMECH brochures, 2006) . The Komax System Inc. has applied Komax technology to solve mixing problems for the process industries and established a technical base of over **one hundred thousand installations worldwide** (www.komax.com) with ca. 350 companies cooperating in this field. Accounting for the above, the author has made up his mind to give up citing numerous individual examples of static mixers applications. Instead, applications grouped in branches of industries and specific operations within the branch are set in Table 2.

Table 2. Industrial-scale applications of the Technology (existing and under realization)

Industry	Application
Municipal water and wastewater treatment	Coagulation processes, e.g. for phosphorous removal from waste water In-line dilution of flocculants (e.g., alginates) Diluting flocculants and mixing with water, wastewater or sludge Dosing of chemicals pH control Iron and manganese removal Admixing of water softeners Admixing of disinfectants Admixing of additives for the sea water treatment Aeration of drinking water Disinfection (Cl_2, O_2, O_3) of drinking water Water dechlorination Neutralization of wastewater streams Sludge conditioning (dewatering) BOD treatment of water
Oil, gas and petrochemical industries	Oil and gas wells, preliminary cleaning LPG sweetening Crude oil sampling Desalting crude oil with water Extraction of crude oil with acids and bases Caustic soda washing of hydrocarbon streams Dehydratation of gases with glycols Blending reactants and catalysts Adjusting the viscosity of heavy fuel oil with gas oil Blending of gasoline, diesel, lubricants, etc. Blend one grade of oil or gasoline into another Mixing additives into gasoline or fuel oil Removal of mercaptans for gasoline with base Gas scrubbing for removal of sulphur compounds Emission monitoring and control
Polymer production and processing	Polymerization post-reactors (polyamide, polystyrene, styrenic copolymers, polymethylmathacrylate, silicon polymers, polyethylene, terpene resins, polyoxymethylene) Polymer devolatilization Blending pre-polymers and activators Blending latex compounds Processing of viscous materials (u p to 1 million cps) Liquid/liquid blending of viscous fluids Blending of nearly immiscible polymers (e.g. polyamide 6 and LDPE) Mixing catalyst, dye or additive into a viscous fluid Admixing of low viscosity ingredients to polymer melts Melt homogenization Reaction injection moulding of polyurethanes Color blending extrusion and injection molding Plastic extrusion, injection mouldings

	Thermal homogenization, extrusion and injection molding Thermal and color blending in injection molding applications Thermal and color blending in extrusion applications Cooling of polyester melt in direct spinning plants Gentle heat-up of spinning solutions Homogenizing fibers Fiber spinning
Cosmetics and pharma-ceuticals	Blending of multicomponent drugs Additive blending Nutrient blending Dispersion of oils Mud dilution Sterilizations
Food	Food mixing and blending Continuous production and conversion of starch Starch slurry cooking Diluting molasses with water Heating and cooling of sugar solutions Admixing of additives such as vitamins or flavours to the milk line Acidification of milk during protein production Mixing of lean milk with fats Blending of fruits and adding flavors to yogurt and kefir Mixing of cream butter components Pasteurization of curds and cream products Adding air to cream butter or beer wort Washing fats and oils with acid Desliming vegetable oils with phosphoric acid Sterilization of vegetable oil or fruit concentrates Mixing of margarine Blending cheese and whey Deodorization of cacao butter Addition of lecithin, hazel nut paste and flavorings to chocolate masses Cooling chocolate and marzipan masses Sterilization of chocolate, creams or sweet masses Crystallization of caramel Heating of dough or coffee extract Mixing of dough with yeasts Carbonization of beer, fruit juices, wine or coffee extract Diluting concentrates and mixing flavourings Mixing of tomato pastes
Pulp and paper manufac-turing	pH control Acid and caustic dilution Pulp blending Low consistency bleaching Bleaching of suspensions and slurries
Paints and resins	Dye blending Coloring and tinting Mixing of colours, hardeners, detergents, paints Mixing of components of resins, adhesives, epoxies Mix two viscous resins Blending of two resins to form a homogeneous mixture Processing glues
Continuous processes and operations	Solvent dilution Evaporation of liquids into gas streams Liquid-liquid extraction (also in counter-current mode) Liquid-liquid reactions Metals recovery by solvent extraction Oil-water dispersions Co-current extractions with supercritical carbon dioxide (e.g., caffeine) Emulsifications (e.g., epoxy resins) Bitumen emulsification (for road surfacing)

	Mixing of sealant components Preparing silicon foams-in-place Fertilizer and pesticide formulations preparation Electrolysis Catalyst additions Dissolving of gases in organic liquids for oxidation, chlorination, nitration, and hydrogenation Dispersing air into detergent slurry upstream of spray driers Absorption of gases in liquids Scrubbing (e.g., ammonium, hydrogen chloride or cyanides with water, NO_x scrubbers, noxious organic compounds with various solvents) Gas mixing (e.g., injecting ammonia into flue gas for NO_x removal)

2.3 Known demonstration projects

(Are there any demonstration projects known related to the technology under consideration? In which process industry sectors are those projects carried out: large volume chemicals – specialty chemicals & pharma – consumer products – ingredients based on agro feedstocks? In Table 3 provide the short characteristics of those projects.)

As mentioned, technology of static mixers has been matured. Therefore, only a few demonstration projects have been found. The projects are related to a relatively new field of SMs applications, namely microstructured static mixers.

Table 3. Demonstration projects related to the technology (existing and under realization) (after Bayer and Himmler, 2005)

Sector	**Who is carrying out the project**	**Short characteristic of application investigated, including product name/type**	**Aimed year of application**	**Reported effects**
Heat exchange	Siemens Axiva (today Siemens Solution Process Industries, Frankfurt, Germany)	Two electrically heated microstructured heat exchangers in series were operated.	2002	Preheating took about 5 ms, i.e. 15 times faster than in the conventional process
Radical polymerization of acrylates	Siemens Axiva	Capacity of micromixers reaction system is about 8 kg/h, corresponding to a theoretical annual capacity of about 60 tons	2000	Fouling by insoluble high-molecular weight polymers has been avoided – no plugging problems have appeared during operation
Fine chemicals	Merck, Darmstadt, Germany	Synthesis of mixing-sensitive metallo-organic compounds, industrial scale production started. Home-made micromixers	2000	Yield of reaction improved by 23 % compared to batch stirred tank reactor
Fine chemicals	Clariant, Frankfurt, Germany	Pigment production on pilot scale	2002	Azo pigments showeg better coloring strength, while having the same transparency and brightness, compared to those produced by batch processing.

2.4 Potential applications discussed in literature

(Provide a short review, including, wherever possible, the types/examples of products that can be manufactured with this technology)

Applications of static mixers for homogenization of liquid streams, blending miscible and immiscible fluids, dispersing in liquids, heat exchange and some chemical reactions are numerous and well documented. There is, however, a room for new designs of static mixers that would be suitable to handle with solids themselves (with limitations originating from adhesion of wet solids to walls of devices) and with liquids. Some of the known mixers have been used for such purposes but the whole area of continuous mixing of solids (also with liquids) using static mixers has not been covered yet. The use of static mixers as chemical reactors will also certainly expand with the priority given to the following fields: (i) recycle loop reactors with static mixers inserted into the loop pipe, (ii) mechanically agitated tank reactor with recycle loop, (iii) CSTRs with feed streams mixed with static mixer, (iv) polymerization reactors, (v) reactors for fast competitive reactions in the manufacture of fine chemicals and pharmaceuticals, (vi) biochemistry and food processing, and (vii) stagewise fed (reactants and/or catalysts) continuous reactors[1] in all branches of chemical industry. Numerous research papers on such applications of static mixers have been published in recent years.

3. What are the development and application issues?

3.1 Technology development issues

(In Table 4 list and characterize the essential development issues, both technical and non-technical, of the technology under consideration. Pay also attention to "boundary" issues, such as instrumentation and control equipment, models, etc.) Also, provide your opinion on how and by whom these issues should be addressed)

Table 4. Technology development issues

Issue	**Description**	**How and by whom should be addressed?**
Microstructured static mixers	Static micromixers offer unique possibility of carrying out exothermic processes at isothermal conditions if advantageous for selectivity, or close to optimal temperature-time profile using micromixers in series.	R&D projects for departments of chemical engineering at universities in cooperation with manufactures of static mixers (novel structures and applications).
Modeling of static mixers for chemical applications	Design and choice of a static mixer from the existing mixer families is relatively easy for materials of non-"exothic" physical properties. In case of applications of static mixers as chemical reactors, the modeling techniques are not always effective and require improvements.	R&D projects for departments of chemical engineering at universities (specialists in the field of fast competitive reactions and polymerizations) in cooperation with manufactures of static mixers
Design and scale-up mixers for fast chemical reactions	Fast chemical reactions require high flow velocity thus entering the turbulent flow region. The total energy dissipation for an empty pipe is about 5 W kg^{-1}, while Sulzer SMV and SMXL mixers can	R&D projects for departments of chemical engineering at universities in cooperation with manufactures of static

[1] Static mixers in tubes and between them to admix reactants and/or the catalyst in continuous process for the manufacture of polyester resins is an exemplary process of this type, see Cybulski, A. *et al.*, A continuous process for the manufacture of unsaturated polyesters (Polish), Przemysł Chemiczny, 60 (5), 261-263 (1981). Mixing of polyester with styrene (see Cybulski *et al*., Mixing of components of the polyester resins using the static mixer (Polish), Polimery, 12, 376-378 (1977)) was also encompassed by the invention (PL 127634, 1986),

	generate, respectively, ca. 800 and 500 W kg^{-1} for fluid velocity 2 m s^{-1}. However, the resulting turbulence is less homogeneous than in an empty tube. The Kolmogoroff scale depends on the local rate of turbulent energy dissipation and thus varies from point to point within the bulk fluid, leading to localized regions where the reaction occurs preferentially. Design and scale-up of mixer-reactors for turbulent flow is hence a difficult task. CFD modeling combined with detailed kinetic studies will help in search for the best configuration of inserts and flow conditions for any specific reaction.	mixers.
Modeling of static mixers for liquid-liquid systems	Energy dissipation in static mixers is high and relatively uniform over the mixing space. Therefore, static mixers can be used in liquid-liquid systems to decrease dispersed phase droplet sizes for uniform dispersion and to increase interfacial mass transfer. However, prediction power of methods for scale-up dispersion processes is relatively weak. By now, predictions have been based upon empirical formulae. More fundamental approach (CFD + surface phenomena) is needed to improve predictions. Measurements of local energy distribution in static mixers by laser-Doppler anemometery is difficult due to internals. Therefore, calculations using CFD techniques are recommended to analyze mixer performance in this respect and to improve their configuration. However, system performance is very case-specific and difficult to generalize.	R&D projects for departments of chemical engineering at universities in cooperation with manufactures of static mixers.

3.2 Challenges in developing processes based on the technology

(In Table 5 list and characterize the essential challenges, both technical and non-technical, in developing commercial processes based on the technology under consideration. Also, provide your opinion on how and by whom these challenges should be addressed)

Table 5. Challenges in developing processes based on the technology

Challenge	**Description**	**How and by whom should the challenge be addressed?**
Selection of mixer type, comparisons between mixers	There are discrepancies and inconsistencies in the literature data on transport phenomena and mixing in static mixers. Critical assessment and experimental verification of those data is necessary to make comparisons between mixers and the engineering procedures more reliable.	R&D projects on critical assessment of the literature and vendor's data for an expert, group of experts and departments of chemical engineering at universities in cooperation with manufactures of structured catalysts and reactors and end users. CFD techniques will be very helpful in this task. It is suggested to establish experimental station for investigations of transport phenomena and mixing in one of the departments of chemical engineering.
Optimization of mixer design	Sir and Lejacks (1982) recommended the use of the following formula to estimate the optimal number of mixing elements in the Kenics mixer:	R&D projects for departments of chemical engineering at universities in cooperation with manu-

	$$N_{opt} = a_1 \cdot \mathrm{Re}^{a_2} \cdot Sc^{a_3} \cdot \left(\frac{Q_1}{Q_2}\right)^{a_4} \cdot \left(\frac{\mu_1}{\mu_2}\right)^{a_5}$$ where a_i are adjustable coefficients. The formula of this type is also recommended for the other static mixers. However, such equations are applicable for standard geometries and are useless in search for improvements of static mixers geometry. Experimental search for the best configuration over the whole flow region is time- and money consuming effort. Therefore, computer techniques (CFD) should be used to find optimal solutions. CFD will also help in identification of behavior of static mixers.	factures of static mixers (CFD techniques).
Polymerization reactors	Polymerizations occur with heat evolution that changes significantly viscosity of the reaction mixture. This is the reason of thermal instability (temperature runaway) and hydrodynamic instability. Recycling of partially polymerized monomer is one of way for elimination of instabilities. The other methods should be searched to solve the problem.	R&D projects carried out at universities in cooperation with manufactures of structured catalysts and reactors and end users.
Static mixers as the basis of heterogeneous catalysts	Good radial mixing, nearly plug flow and excellent heat transfer to the surroundings make static mixers interesting as the basis of heterogeneous catalysts for carrying (also gas-phase) reactions of high thermal effect. The CBMiM mixer is a very promising candidate due to its high external surface area (ca. 300 m^2 m^{-3}), which is commensurable with that of commercial particulate catalysts for partial oxidations of hydrocarbons, high heat transfer coefficients to the surroundings, and excellent mixing characteristics. Methods for transformation of metal structures into catalysts are known.	Configuration of the CBMiM mixer should be optimized from the viewpoint of its new application. Methods for the manufacture of rigid bundles of mixers should be worked out. Methods for simultaneous insertion and removal of the bundles from multitubular reactor should be developed. R&D projects for departments of chemical engineering at universities in cooperation with end users of the catalyst.

4. Where can information be found?

Hundreds of papers have been published on static mixers: on transport phenomena in mixers and their applications. Below, some reviews are quoted and those research papers that are cited here.

4.1 Key publications

(Provide the list of key publications in Table 6)

Table 6. Key publications on the technology

Publication	**Publication type (research paper/review/book/report)**	**Remarks**
Bayer, Th. and Himmler, K., Mixing and Organic Chemistry, *Chem. Eng. Technol.*, **28** (3), 285289 (2005)	Review	Considerations on applications of static mixers in organic chemistry
Brechtelsbauer, C. and Ricard, F., Reaction engineering evaluation and utilization of static mixer technology for the synthesis of pharmaceuticals, *Org. Process Res. & Develop.*, **5**, 646-651 (2001).	Research paper	Application of static mixers in synthesis of pharmaceuticals

Couvert, A., Sanchez, C., Charron, I., Laplanche, A., and Renner, C., Static mixers woth a gas continuous phase, *Chem. Eng. Sci*., **61**, 3429-3434 (2006)	Review	Results of own investigations also presented
Cybulski, A. and Werner, K., Static mixers – criteria for applications and selection, *Intern. Chem. Eng.*, **26** (1), 171-180 (1986); original in Polish: *Inżynieria i Aparatura Chemiczna*, **21** (4), 13 (1982)	Review	Results of own investigations also presented
Etchells, A.W. and Meyer, Ch.F., Mixing in pipelines, in Hanbook of Industrial Mixing, Paul, E.L., Atiemi-Obeng, V.A., and Kresta, S.M., eds, J. Wiley, New York 2004.	Review, Chapter in the book	
Galaktionov, O.S., Anderson, P.D., Peters, G.W.M., and Meijer, H.E.M., Optimization of Kenics static mixers, *Intern. Polymer Process.*, **18** (2), 138-150 (2003)	Research paper	CFD studies on Kenics mixers
Green, A., Inline and high-intensity mixers, Chapter 7 in Re-engineering the chemical processing plants. *Process intensification*, A. Stankiewicz and J.A. Moulijn, eds, M. Dekker, New York, 2004	Review in a book	
Mutsakis, M., Streiff, F.A. and Schneider, G., , Advances in static mixing technology, *Chem. Eng. Progr.*, 42-48, July 1986	Review	
Pahl, M.H. and Muschelknautz, E., Einsatz und Auslegung statischer Mischer, *Chem.-Ing.-Tech.*, **51** (5), 347-364 (1979); Statische Mischer und ihre Anwendung, *ibid.*, **52** (4), 285 –291 (1980)	Reviews	
Rauline, D., Tanguy, P.A., Le Blévec, J.-M. and Bousquet, J., Numerical investigation of the performance of several static mixers, *Can. J. Chem. Eng.*, **76**, 527-535 (1998)	Research paper	Comparative study by CFD
Schulz, N., Mischen und Wärmeaustauschen in hochkonsistenzen Medien, *Chem.-Ing.-Techn.*, **51** (7), 693-697 (1979)	Review	On the use of static mixer for operations with highly viscous liquids
Sir, J. and Lejacks, Z., Pressure drop and homogenization efficiency of a motionless mixer, *Chem. Eng. Commun.*, **16**, 325-334 (1982)	Research paper	
Song, H.-S. and Han S.P., A general correlation for pressure drop in a Kenics static mixer, *Chem. Eng. Sci.*, **60**, 5696-5704	Review	An attempt to generalize data on pressure drop in a Kenics mixer
Streiff, F.A., Mathys, P. and Fischer, T.U., New fundamentals for liquid-liquid dispersion using static mixers, *Récents Progrès en Génie des Procédés*, **11** (51), 307-314 (1997)	Review	Results of own investigations also presented
Szalai, E.S. and Muzzio, F.J., Fundamental Approach to the Design and Optimization of Static Mixers, *AIChE Journal*, **49** (11) 2687-2699 (2003)	Research paper	An extensive CFD analysis of flow in Kenics mixers
Thakur, R.K., Ch. Vial, Ch., Nigam, K.D.P., Nauman, E.B., and Djelveh, G., Static mixers in the process industries-A review, *Trans IChemE*, **Vol 81**, Part A, August issue, 787-827 (2003)	Review	The most extensive overview in recent years
Werner, K. and Cybulski, A., Static mixers (review of designs and applications) (Polish), Inżynieria i Aparatura Chemiczna, **17** (6), 1 (1978)	Review	Results of own investigations also presented
Werner, K., Cybulski, A., Dukielski, M. and Grzelewski, L., A comparative analysis of static mixers. II. Residence time distribution (Polish), Inżynieria i Aparatura Chemiczna, **26** (3), 11 (1987)	Research paper	A comparative study of some static mixers in respect to RTD
Zhou, W., Holzhauer-Rieger, K., Bayer, Th., and Schügerl, K., Cephalosporin C production by a highly	Research paper	

productive *Cephalosporinum acremonium* strain in an airlift tower loop reactor with static mixers, *J. Biotechnol.*, **28**, 165-177 (1993)		

4.2 Relevant patents and patent holders

(Provide the list of relevant patents in Table 7. Under "remarks" provide, where applicable, the names/types of products targeted by the given patent.)

Approximately **2780** results were found in the worldwide database of the European Patent Office for: **static mixer** in the title or abstract. Even considering that many findings concern the same invention that has been patented in many countries (4-5 in average) the number of patented static mixers is 500-700. More patents should be added because some static mixers have been patented under another name (e.g., mixing device, inline mixers, interfacial surface generator, interactive surface mixer etc.). In Table 7, the author's selection of patents and patent application is given considering current mixer applications and features that make a mixer promising. Exemplary applications of static mixers patented are also set in the last rows of the table. Some designs of the patented static mixers are similar to each other and it is difficult to find the superior over the others. The author's impression is that several companies worked out their own structures with only one target: To omit patent claims of competitors.

Table 7. Relevant patents

Patent	Patent holder	Remarks, including names/types of products targeted by the patent
US 3286992, 1966	Little Inc.	Probably the first patent for static mixer[2], (i)-type[3]
US 3652061, 1972	Dow Chemical Co.	LPD mixer, now manufactured by Ch. Ross & Son Co., (ii)-type
US 3583678, 1971	Dow Badische Co.	ISG mixer, now manufactured by Ch. Ross & Son Co., (vi)-type
US 3917811, 1975	Kenics Corp.	KM mixer, (i)-type
US 3775063, 1973	Kenics Corp.	Static mixer, (i)-type
US 3923288, 1975	Komax Systems, Inc.	SM-mixer, A-series, (ii)-type
US4753535, 1988	Komax Systems, Inc.	Arrangement for the inlet to static mixer
EP 0861684, 1997	Komax Systems, Inc.	Static mixer, (vi)-type
US 5605399, 1997	Komax Systems, Inc.	SM-mixer, M-series, (iii)-type
US 5947597, 1998	Komax Systems, Inc.	Static mixer, (ii)-type
EP 0884549, 1998	Komax Systems, Inc.	Mixer-heat exchanger, (v)-type
EP 0927573, 1999	Komax Systems, Inc.	Static mixer-reactor
US 2005077034, 2005	Komax Systems, Inc.,	A tube-in-tube static mixer-heat exchanger
GB 2061746, 1981	Sulzer AG	Pre-SMX mixer
JP 6087120, 1994	Sulzer AG	Static mixer, (v)-type
EP 0766996, 1995	Sulzer Chemtech AG	Static mixer arrangement in a plant

[2] Motionless devices for mixing were patented even earlier, in the second half of XIX century, but design patented a century later became a "father" of contemporary static mixers.

[3] Classification of mixer types according to Section 1.2.

EP 0727249, 1995 US 5851067, 1998	Sulzer Chemtech AG	Static mixer, (v)-type
EP 0815929, 1996 US 6769801, 2004	Sulzer Chemtech AG	Static mixer, (ii)-type
EP 0800857, 1996	Sulzer Chemtech AG	Static mixer, (ii)-type
CN 1140098, 1997	Sulzer Chemtech AG	SMXS-like mixer
EP 0993864, 1998	Sulzer Chemtech AG	The inlet arrangement
WO 0062915, 1999	Sulzer Chemtech AG	Static mixer, (iii)-type
EP 1206962, 2000	Sulzer Chemtech AG	An element of the static mixer, (ii)-type
EP 1210985, 2000	Sulzer Chemtech AG	Adapter for the static mixer
US 2001038576, 2001	Sulzer Chemtech AG	Static mixer, (iv)-type
EP 1125626, 2001	Sulzer Chemtech AG	Static mixer, (ii)-type
WO 2004007063, 2002	Sulzer Chemtech AG	SMX-like mixer, (v)-type
US 2004114461, 2002	Sulzer Chemtech AG	Static mixer, (v)-type
EP 1510247, 2003	Sulzer Chemtech AG	Static mixer, (v)-type
WO 2004091760, 2003	Sulzer Markets & Technology AG	SMV mixer modified
US 2004223408,2003 EP 1493485, 2005	Sulzer Chemtech AG	CompaX
EP 1437173, 2004	Sulzer Chemtech AG	SMXS-mixer
EP 1510247, 2005	Sulzer Chemtech AG	Static mixer, (v)-type
U S5967658, 1998	Kam Controls Inc.	Static mixer, (iii)-type
WO 0067887, 1999	Statiflo Int. Ltd.	Static mixer, (ii)-type
DE 19623051, 1996	BASF AG	Static mixer, (iv)-type
DE 19623105, 1996	BASF AG	Static mixer, (ii)-type
DE 10103425, 2001	BASF AG	Static mixer, (iv)-type
DE 10162124, 2001	Plamex Maschinenbau GmbH	Static mixer, (vi)-type
DE 10324886, 2003	Framatome Anp GmbH	Mixing element, (iii)-type
DE 19813600, 1998	Bayer Technology Services GmbH	Static mixer, (ii)-type
EP 0967004, 1998	Bayer Technology Services GmbH	Static mixer, (ii)-type
DE 10005457, 2000	Bayer Technology Services GmbH	Static mixers, (v)-type
EP 1216747, 2000	Bayer Technology Services GmbH	Static mixer, (ii)-type
WO 9635506, 1995	Labatt Brewing Co. Ltd.	Static mixer, (iii)-type
US 2004156763, 2001	Wood M D	Reactor for facilitating reaction process for use in chemical and pharmaceut-ical industries
WO 9904892, 1997	Siemens Axiva GmbH & Co. KG	Serpentine pipe configu-ration for use as chaotic static mixer, (v)-type
DE 10019759, 2000	Tracto-Tech GmbH	Element of a static mixer, (vi)-type
DE 10046013, 1999	Madison Group Polymer Processing Res.	Static mixer, (vi)-type
DE 20310555U, 2003	Hunschede J.	Static mixer, (i)-type
DE 29922044U, 1999	Tuchenhagen GmbH	Static mixer, (ii)-type
EP 1566211, 2004	Hilti AG	Static mixer, (ii)-type
DE 10158651, 2001	Ritter GmbH,	Static mixer insert, (ii)-type
EP 1426099, 2002	Mixpac Systems AG	Static mixer, (ii)-type
PL 106155, 1980	Institute of Industrial Chemi-stry, Warsaw, Poland	MST mixer, (i)-type
FR 2807336, 2000	Soc. Ind. Dev. Antipollution & Chim. Sarl.	Static mixer, (ii)-type

JP 2001038182, 1999	NABCO Corp.	Static mixer, (vi)-type
JP 2001113148, 1999	NABCO Corp.	Static mixer, (vi)-type
JP 2001120973, 1999	Fuyo Sangyo KK	Static mixer, (i)-type
JP 2001334136, 2000	NDC KK	Static mixer ,(vi)-tpye
JP 2003260344, 2002	Osaka Gas Co. Ltd.	Static mixer, (ii)-type
JP 2004255320, 2003	Fujikin KK	Static mixer, (vi)-type
JP 2006102724, 2004	Fujikin KK	Static mixer, (vi)-type
JP 2005034750, 2003	Noritake Co. Ltd.	Static mixer, (i)-type
JP 8206480, 1995	Noritake Co. Ltd.	Element of the static mixer, (i)-type
JP 8196884, 1995	Nissin Jabara Ind. Co. Ltd.	Static mixer, (ii)-type
JP 9234354, 1996	Nissin Jabara Ind. Co. Ltd.	Static mixer, (ii)-type
JP 9299776, 1996	Shinyou Technologies Inc.	Static mixer, (vi)-type
KR 20040055889, 2002	Park K. W.	Static mixer, (vi)-type
RU 2079352, 1995	Bulgakov B. B.	Static mixer, (vi)-type
RU 2092236, 1995	Conserve & Fruit Drying Ind . Inst.	Static mixer, (vi)-type
RU 2133143, 1998	Tuma Educational	Static mixer, (ii)-type
RU 2237511, 2002	Slavneft-Yaroslav-Nefteorg-Sintez Stock Co.	Static mixer, (iii)-type
US 2003048694, 2001	TAH Ind. Inc.	Static mixer, (ii)-type
US 2004100861, 2001	UOP LLC.	Static mixer, (vi)-type
US 5826981, 1996	NOVA Biomedical Corp.	Static mixer, (vi)-type
US 5839828, 1996	Glanville R. W.	Static mixer, (iii)-type
US 5938327, 1997	Ingalls P.	Static mixer, (vi)-type
US 6135632, 1999	Flint T. R.	Static mixer, (ii)-type
WO 0209858, 2000	Chemineer Inc.	Element of static mixer (ii) - type
WO 0226368, 2000	Mercatel Group BV	Static mixer, (vi)-type
WO 0232561, 2000	Krauss-Maffei Kunst. GmbH	Static mixer, (ii)-type
WO 03055581, 2001	Tetra LAVAL Holdings & Finance SA	Static mixer, (vi)-type
WO 9736675, 1996	Flo Trend Systems Inc.	Static mixer, (vi)-type
WO 9900180, 1997	Robbins & Myers Inc.	Static mixer, (ii)-type
US 4590030, 1986	Saint Gobain Vitrage	Static mixer applied for producing an optically uniform, transparent coating, layer, film
DE19539923, 1995	ESG GmbH	Application of a static mixer ((ii)-type) for preparation of ammonia-air mixtures
WO 0032513, 1998	Johnson Matthey PLC,	Catalytic selective oxidation reactor
WO 1999048845	Mobil Oil Corp.	Sulfuric acid alkylation reactor system with static mixers (ii)-type
US2002097634, 2001	Labatt Brewing Co. Ltd.	Static mixer in the mixing conduit of a gas-lift bioreactor, e.g., fermenter useful in the production of beer
US6369190, 2002	General Electric Co.	Extraction of triethylamine in polycarbonate by the use of static mixers
DE102004052827, 2004	Lurgi AB	Application of a static mixer for preparation of *o*-xylol-air mixtures
EP 1595596, 2004	Oxeno Olefinchemie GmbH	Reactor for carrying out a three-phase reaction, es-

		pecially selective hydrogenation of butadiene to linear butenes.

4.3 Institutes/companies working on the technology

(Provide the list of most important research centers and companies in Table 8)

Table 8. Institutes and companies working on the technology

Institute/Company	**Country**	**Remarks**
Sulzer Chemtech & Sulzer Fluid Dynamics Laboratory	Switzerland	Fundamental and applied studies on Sulzer and new static mixers
Koch Engineeering Inc.	US	Fundamental and applied studies on static mixers
Chemineer Inc. Kenics Corp.	US	Fundamental and applied studies on static mixers
Koflo Corp.	US	Fundamental and applied studies on static mixers
Komax Systems, Inc.	US	Fundamental and applied studies on static mixers
Lightnin	US	Fundamental and applied studies on static mixers
Ch. Ross & Son Co.	US	Applied studies
Rutgers University, Dept, Chem. & Biochem. Eng., New Jersey	US	CFD studies, transport phenomena in static mixers
Rensselar Polytechnic Institute, Isemann Department of Chemical Engineering, New York	US	Transport phenomena in static mixers
The Ohio State University, Department of Chemical Engineering, Columbus	US	Transport phenomena in static mixers, applied studies
McMaster University, Dept, Chem. Eng., Hamilton	Canada	Transport phenomena in static mixers
Noritake Co. Ltd.	Japan	Applied studies
Nabco Corp.	Japan	Applied studies
National Institute of Advanced Industrial Science and Technology and University of Tsukuba (Institute of Applied Biochemistry), Tsukuba	Japan	Fundamental and applied studies on static mixers, microstructured mixers
Corporate R&D, LG Chem. Ltd., Daejeon	Korea	Transport phenomena in static mixers
BHR Group Ltd., The Fluid Engineering Centre, Cranfield	GB	Transport phenomena in static mixers
Imperial College London, Department of Chemical Engineering and Chemical Technology	GB	Applied studies
Lund University, Department of Food Technology, Engineering and Nutrition, Lund	Sweden	Applied studies
Bayer Technology GmbH	Germany	Fundamental and applied studies on static mixers
BASF AG	Germany	Fundamental and applied studies on static mixers
Siemens Axive GmbH	Germany	Fundamental and applied studies on micro static mixers
Universität of Budeswehr, Institut für Strömungslehre und Strömungsmas-	Germany	CFD studies

chinen, Hamburg		
Forschungszentrum Karlsruhe, Institute for Micro Process Engineering	Germany	Microstructured mixers
Institut für Mikrotechnik Mainz GmbH	Germany	Microstructured mixers
Vienna University of Technology, Institute of Chemical Engineering	Austria	Applied studies
Fluitec AG, Neftenbach	Switzerland	CFD studies
Ecolé Polytechnique Federale de Lausanne, Fluid Mechanics Laboratory and Department of Chemical Engineering, Lausanne	Switzerland	CFD studies
Swiss Federal Institute of Technology, Institute of Chemical Engineering, Zurich	Switzerland	CFD studies
Corvinus University of Budapest, Department of Food Engineering	Hungary	Applied studies
University of IASI, Department of Transfer Phenomena and Chemical Engineering	Romania	Applied studies
Rijksuniversiteit Groningen, Dept, Chem. Eng.	The Netherlands	CFD studies
Eindoven University of Technology, Dept. Chem. Eng.	The Netherlands	CFD studies, flow of viscous media
Twente University of Technology, Dept. Chem. Eng., Enschede	The Netherlands	CFD studies
Delft University of Technology, Kramers Laboratorium of Physical Technology	The Netherlands	CFD studies
University of Amsterdam, Department of Chemical Engineering	The Netherlands	CFD studies
Université Blaise Pascal, Aubiere	France	CFD studies, transport phenomena in static mixers
University of Nantes, Ecole Nationale d'Ingenieurs des Techniques des Industries Agricoles et Alimantaires in Nantes	France	Transport phenomena in static mixers, applied studies
CNRS-ENSIC-INPL, Centre de Genie Chimique des Milieux Complexes, Nancy	France	Transport phenomena in static mixers
Tsinghua University, Department of Chemical Engineering, Baijing	PR China	Microstructured mixers
Indian Institute of Technology, Dept, Chem. Eng., New Delhi	India	CFD studies, transport phenomena in static mixers
University of Mumbai, Department of Chemical Technology	India	Transport phenomena in static mixers

5. Stakeholders

5.1 Suppliers and developers

(Provide the list of key suppliers/developers in Table 9)

There are a great number of suppliers of static mixers, mostly licensed by the manufacturers. For instance, the ThomasNet (www.thomasnet.com) informs about 65 companies in the US, which manufacture, distribute and service static mixers whereby several companies offer many types of these devices. According to GlobalSpec (The Engineering Search Engine) 65 companies that manufacture and distribute static mixers are operating on the US market. 45 companies, which offer static mixers or system with static mixers exhibited their products at Mischer Expo in 2007. Therefore, in Table 9, only the manufactures that are best known on the market are mentioned and some other exemplary distributors worldwide. A country where headquarters of the company is located is given in the table. However, there are representatives of these companies and licensed companies all over the world. Manufacturers and developers are usually the same companies.

Table 9. Supplier and developers

Institute/Company	***Country***	**Remarks (mixers offered)**
Sulzer CHEMTECH Koch Engineering Co.	Switzerland, worldwide US	Sulzer mixers SMX, SMXL, SMXS, SMV, SMR, SMB-R, SMK-R, SMI, SMF, CompaX, KVM, Polyguard
Chemineer-Kenics	US, worldwide	Kenics mixers, KM, HEV
Koflo Corp.	US	Kolfo mixers
Komax Systems, Inc.	US, worldwide	A broad variety of Komax mixers
Lightnin	US, worldwide	Inliner series 45 and 50, N-form and other mixers
Ch. Ross & Son Co.	US, worldwide	LPD and ISG mixers
AdMix, Inc.	US	Admixer static mixer
Bartlett Engineering Co.	US	BMX. BMF and BMV mixers
Be.st GmbH	Germany	Sulzer and Kenics mixers
Brandywine Sales, LLC	US	MIXPAC, TAH and Sulzer plastic disposable static mixers
Ch. Ross & Son Co.	US, worldwide	LPD and ISG mixers
Cal Gavin Ltd.	UK	Hitran® flow turbulizer
ConProTec	US	STATOMIX® FM series
Electrolab Inc.	US	Sulzer mixers
EMI Inc. Technology Group	US	Cleveland Eastern mixers
Essiflo North America	US	Essiflo mixer
Fenix Process Technologies	India	Sulzer mixers
Flowtech Industries AG	Germany	Sulzer-like mixers for gases
Fluitec Georg AG	Switzerland	Fluitec mikromakro mixer, N-form and other mixers
Fluiten Deutschland AG	Germany	N-form and other mixers
JDMIX, Inc.	US	JDMIX mixers
JLS International Group	US	Sulzer and Komax mixers
Jongia N.V.	The Netherlands	SBM spiral type mixer (spiral ribbons on shaft)
Kam Controls, Inc.	US	Kam mixers
Lenntech	The Netherlands	Statiflo mixers
Mamko Design and Engineering Pvt Ltd.	India	Equivalents of Kenics, Sulzer, Ross and Komax mixers
Noritake Co. Ltd.	Japan	Kenics mixers, Noritake mixers
Pittaluga Static Mixers	Italy	Sulzer-like and LPD-like mixers. N-form mixers
Primix B.V	The Netherlands	Primixer (Quattro) Kenics-like mixer, N-form mixer
Ray Engineering Co. USA	US	Komax mixers
SPX Process Equipment.	US	Lightnin mixers
StaMixCo	US	Double-roof disk static mixer, SMN mixing nozzle and filter SMF, SMB-R Melt blender
Statiflo International Ltd.	GB, US	Statiflo series 900 channel mixer, Contactor motionless mixer with STM or STL elements
Striko Verfahrenstechnik	Germany	A variety of mixers
TAH Industries, Inc.	US	A variety of disposable mixers

U+A Process Engineering (UAPE)	US, Germany	A variety of mixers
United Equipment Technologies (UET)	US	Heliflo Kenics-like mixers

5.2 End users

(Describe the existing and potential end-users, other than those already listed in Table 2)

See preliminary remarks of section 5.1.

6. Expert's brief final judgment on the technology

There is many static mixers offered on the market and experience gained by the mixers' manufacturers, suppliers and maintenance doing companies is large. There are, however, areas that have not been explored to the end yet: (a) continuous mixing of solids (also with liquids), (b) static mixers as chemical reactors as recycle loop systems, polymerization towers and multitubular systems, (c) reactors for fast competitive reactions in the manufacture of fine chemicals and pharmaceuticalsn and (d) micromixers. Attempts to develop heterogeneous catalysts on the basis of static mixers (e.g., CBMiM mixer) are likely to start.

In the future, designing of new mixer geometries[4] of bounding surfaces and optimization of existing ones in respect to geometrical details and flow conditions will be done mostly by CFD techniques that have already become the most essential tool in understanding of mixer performance. The existing CFD software needs still much time but, hopefully, in the near future CFD codes will be able to treat heat transfer and molecular or eddy diffusion problems and reaction calculations with a sufficient accuracy for engineering practice. CFD will provide information on local phenomena inside the mixer that cannot be available by simple experiments. However, experimental verification of CFD computations are likely to be necessary due to non-ideality of numerical methods and data for calculations.

[4] If manufacturers were interested in new mixers. They have equipment to produce mixers of existing designs and new mixers mean additional costs for new equipment.