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EUROPEAN ROADMAP OF PROCESS INTENSIFICATION

- TECHNOLOGY REPORT -

TECHNOLOGY:
Static mixer reactors for continuous reactions

TECHNOLOGY CODE: 1.2.5

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1. Technology

1.1 Description of technology / working principle

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

Static mixers as mixing devices

The science and technology behind the use of static mixers as mixing and micro-mixing devices has been reported in a number of sources and it has been assumed that these principles are covered in TR report 1.1.4. This report is therefore covering the extension of the theory only applicable to the use of static mixers as reactors to avoid any overlap with other areas of the TR reports.

Introduction to static mixers as reactors

Static mixer reactors provide excellent heat and mass transfer. The mass transfer is provided by the insertion of static mixers designed to improved plug-flow and micro-mixing at high (turbulent mixers) or low (laminar mixers) Reynolds numbers. The excellent heat transfer comes from the detailed design of heat/cool coils and jackets around the static mixers.

The use of static mixers as reactors has been recognised by certain industries for many years. As an example, highly viscous polymerisation reactions are carried out in static mixer reactors, giving higher product quality and consistency over other reactor types.

Classification of mixer types

The static mixers available on the market can be classified into groups as follows: helical-type, bar-type, hole-type (Ross ISG), wafer-type (SMV) and baffle-type (HEV). The most commonly used are the helical-type (e.g. Kenics) and bar-type (e.g. Sulzer SMXL) mixers. The helical mixer splits the flow and turns both halves through 90^o, the next element then splits each half again, and so on. The bar-type units tend to split flow into many segments very early and continue to split and recombine the flow through each element and onto the next. The bar-type units are considered to be higher intensity than the helical units, however this comes with a higher pressure drop.

The emerging area of micro-mixers as static mixer reactors, e.g. the caterpillar mixer, will not be covered in this report as it is expected to be covered in TR reports 1.1.5 and 1.2.2.

Mixing uniformity of reagents

The key to a good reaction is getting the mixing time of reagents equal to or better than the inherent reaction time, thereby allowing reactions to proceed at their natural reaction rate. For homogeneous systems this is typically achieved by a large degree of micro-mixing between the reagents at the inlet to the reactor, and can be achieved by using a high-intensity mixing device. The science to explain how efficient mixers are at blending two streams has been reported previously, e.g. coefficient of variation (CoV). The pitch and intensity of a static mixer determines how quickly the streams can be well-mixed, for example the SMX units will achieve better mixed systems in less distance than the helical type units.

Degree of plug-flow & residence time distribution (RTD)

When using static mixers as reactors a key requirement is often to ensure good plug-flow. This prevents back-mixing of products with reagents, which may cause side-reactions, for example in the simple reaction $A+B \rightarrow C+D$ and $C+B \rightarrow$ waste, where C is the desired product, it would be desirable to prevent C and B mixing. Typically B is in high concentration at the start of the reactor and C at the end, so less back-mixing would result in more of the preferred product. In an ideal plug-flow environment each element of fluid experiences the same conditions as it passes through each stage of the reactor irrespective of time.

An approximation of how close a system is to plug-flow can be given by the Reynolds number correlation. A system Reynolds number will determine whether flow is in laminar (low Reynolds), transition or turbulent (high Reynolds) regime. A higher Reynolds number would be required for plug-flow. The dimensionless Reynolds number is a product of channel diameter, fluid density and fluid velocity divided by the viscosity. Therefore highly viscous and low flowrate systems are typically laminar even in small diameter channels, whereas in other systems higher Reynolds numbers can be achieved by using smaller diameter pipes (although this has a pressure drop impact). In laminar flow the fluid in the centre of the channel travels much quicker than the fluid at the wall, and thus a significant level of back-mixing occurs. In fully developed turbulent flow this effect is reduced and the velocity of fluid across the channel is more uniform, however boundary layers on the pipe walls are still observed.

For turbulent flow systems a static mixer will provide additional micro-mixing capacity and prevent/minimise boundary layer effects. In laminar flow a static mixer will break the velocity profile and simulate a plug-flow regime. The performance of the static mixer is still dependent on the bulk fluid velocity, density, viscosity and pipe diameter, as well as dependent on the mixer type. A more intense mixer will provide a better approach to plug-flow than a less intense device.

The residence time distribution models presented by Danckwerts (1953) are a good method of expressing the variation in residence time experienced by various elements of a fluid in a reactor system. To determine the residence time variation a tracer is injected at time zero into the start of the reactor and the concentration of tracer is measured at the outlet over time. The result is a normal distribution curve with the width directly related to the degree of plug-flow seen in the reactor. For example a fully laminar regime would provide a very wide normal distribution curve (significant back-mixing spreads the tracer), whereas a true plug-flow system would see the same tracer spike that was injected at the start. The models can be displayed in exit concentration form, E(t), or in cumulative form F(t).

Residence time distribution is often further quantified using the Bodenstein (Bo) number (sometimes referred to as the Peclet mass-transfer number). The Bodenstein number is a measure of the width of the residence time distribution in accordance with the Danckwerts dispersion model, and can be summarised as the ratio of bulk transport through the reactor to the axial dispersion coefficient. For an ideal CSTR (continuous stirred tank reactor) Bo=0 and for an ideal plug-flow system Bo=infinity. In practice, a Bo>100 would be considered a plug-flow system, equivalent to 50 CSTR's in series.

Heat transfer design

For many chemical reactions an accurate control of reaction temperature is essential in forming the correct products and minimising side reactions. For static mixer reactors this can be especially important, as changes in localised conditions can quickly lead to undesired reactions and potential safety concerns. The high intensity mixing means observed reaction rates are typically quicker as it is not mixing limited, this can result in high heat generation. The static mixer reactor must be able to dissipate this heat quickly to avoid local hotspots.

The rate of heat release in a reactor is often highest in the most intense mixing sections, typically at the start of the reactor when the streams are first mixed together. Heat transfer requirements at intense mixing inlet may be critical and require separate heat transfer systems than the remainder of the reactor. For example, use of lower temperature coolant removes heat intensely in this area, whereas it would overcool and slow the reaction down later, and therefore a different temperature coolant may be used for the remaining part of the reactor. Alternatively separate equipment with higher heat transfer intensity may be required just to remove initial heat of reaction, however consideration must then be given to the separation distances between one reactor and the next to ensure the reaction is under control.

Multi-phase systems and droplet size

Many static mixer designs perform well in homogeneous systems whilst others have been designed specifically for use with two immiscible fluids. In this case characterisation of performance is dependent on the droplet size produced, particularly as mass transfer across the droplet surface often controls the reaction rate. In this case small droplets are preferred (more surface area) to keep the reaction rate high.

There is limited information and research on the use of static mixer reactors for gas-liquid and solid-liquid reactions. In the case of gas-liquid systems the mixing performance has been documented, however this has not been extended to reacting systems.

In the case of solid-liquid systems a further sub-classification is required, systems where solids are fed into the reactor (where feeding equipment to provide a consistent stream is not available) and systems where solids are generated in the reactor. When solids are generated by a reaction the design of the static mixer can be very important, as increased surface area can act as a filter for the solids, causing blockage. In this case the static mixer type may be different in the early part of the reactor, when less solids are present but intense mixing is required, than towards the end of the reactor.

Fluid flow and pressure drop considerations

In addition to the fluid flow profile mentioned above consideration should be given to the affect the static mixer has on the pressure drop in the system. Choosing different static mixer elements for the reactor may improve the RTD profile, but it will likely cause an increased pressure drop across the reactor increasing the size of feed systems. The optimum design of a static mixer reactor should be considered in terms of the full system and not just an optimised reactor design.

Instrumentation and measurement

Continuous static mixer reactors will often require a high level of process monitoring and control. This reflects the level of precision control required during the reaction. Characterisation of temperature profiles and product profiles required throughout the reactor may result in instruments being incorporated into the design. This is an area that requires significant development, particularly for small-diameter systems where the presence of instrumentation and sensors can disrupt the process.

Understanding chemistry to choose structure & whole process design

There are various levels of structure that must be considered in equipment selection and design. Below are a series of typical reactions and how these reaction conditions affect the choice and design of the reactor:

1. Some processes need very precise conditions to achieve the optimum reaction, for example the rate of competing side reactions will increase substantially if the temperature moves out of defined narrow bands. In this case a reactor must be

chosen that is capable of very precise control, e.g. micro-reactors, specially designed static mixer reactors, etc, and the specific reactor should be designed to maximise its effectiveness at precise control. However if there are no competing side reactions under operating conditions then a simplified static mixer reactor may be more appropriate.

2. Some reactions are sensitive to products further reacting to unwanted materials, unless they are removed or isolated quickly. In this case it is more important to prevent back-mixing and a high mixing-intensity static mixer could be used. It is important to recognise the relative rates of preferred and unwanted reactions before making the decision to invest in more intense static mixer technology.

3. Some reactions may also be inhibited from by-products of the main reaction. In this case the presence of the by-product may be reducing the reaction rate significantly and therefore extending the size of the reactor exponentially to achieve a set yield. Intermediate or continuous removal of the by-product may be desirable, or alternatively the reactor can be reduced in size to accept a lower yield, with a separation and recycle provided. This will reduce the yield through each pass of the reactor but when you consider the full reactor system (inc. recycle) the yield is high and the equipment much smaller. This is often cost effective as it keeps the reaction rate high in the reactor. A similar approach of restricting reaction time can also be useful in preventing formation of by-products that may cause downstream issues.

Information similar to that described above is required when choosing the right reactor technology and assists the designer in specifying the details of the specific equipment within that technology.

Theoretical models applicable to static mixer reactors

Levenspiel's (1998 3rd edit) text on 'Chemical Reaction Engineering' provides a series of models to explain and predict the behaviour of reactor systems. Particular attention is drawn to the tank-in-series and dispersion modelling sections as they provide an excellent overview of how to select and design appropriate reactor systems.

1.2 Types and "versions"

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

Sulzer Chemtech market the SMR reactor in which the static mixer elements are actually the heat transfer coils. This design is very useful for high viscosity systems where excellent mixing, low pressure drop and good heat transfer are primary considerations.

A number of static mixer suppliers also market multi-tube heat exchanger reactors. These designs use a traditional shell-and-tube heat exchanger with static mixers inserted into the tubes. These tubes can then be used in parallel or series depending on the design of headplates or external piping.

Static mixer suppliers also offer mono-tube reactor arrangements, where a single jacketed tube has static mixer elements inserted. Multiple mono-tube arrangements of various lengths can then be added to increase the available residence time.

Static mixer reactors typically contain an intense mixing section, to promote the reaction, followed by a less intense section of mixer, to ensure plug-flow is 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
Approach to plug-flow for low Reynolds number systems		The reasons why plug-flow are important is covered in section 1.1, and static mixer reactors can achieve acceptable plug-flow conditions for high viscosity and low flowrate systems
Compact	Orders of magnitude smaller than batch mixers	Less floor space, lower energy consumption, shorter residence time (less material at reaction conditions), better control
Virtually no maintenance		No moving parts
Flexible operating flow range		Fixed size can operate across a wide flow range, giving user flexibility to turn plant up or down to meet product demand
Lower capital cost		Less material to manufacture the equivalent of a batch vessel, quicker to produce and significantly cheaper. Need to quantify the cost against other PI technologies, but typically this is the most cost effective for reactions seconds to minutes reaction time. Cost is directly related to length and therefore very long residence times become more expensive (over other PI technology)
Enhanced reaction conditions (temp & pres)		Higher pressures and temperatures are possible in static mixer reactors versus batch vessels and some other PI reactors. Operating conditions are available to ten's bars and hundreds of °C
Energy saving		Continuous operations offer energy savings over traditional batch processes. In addition static mixer reactors are low energy consumption devices as the mixing energy is generated by the feed pump system
Increased yield and selectivity		Plug-flow conditions maximise the preferred reaction route, thereby reducing impurity generation. This results in a better product quality

1.4 Stage of development

Static mixer reactors have been used in a variety of applications since the 1970's, typically for mixing streams prior to reaction.

The use of static mixers for polymerisation reactions is reasonably well developed (typically using mixers of 25mm and above).

The use of static mixer reactors for pharmaceutical and fine chemical small-scale continuous processes is much less developed but has received significant research and development attention in the last few years. However, many companies and universities are focussed on the use of static mixer reactors for improving specific processes, without addressing the need for improvements in the design of the static mixer equipment being used.

Heat transfer design

Maintaining the reaction in a temperature controlled zone (the main issue with multiple mono-tube and external flow direction piping systems) is an issue for static mixer reactor design. Therefore further development effort in this area is required.

RTD and yield considerations

Choosing the right static mixer design for a reactor is not particularly well understood. There is literature reporting the similarities between mixers for mixing duties and this is often confused with the use of mixers for reaction duties. For example, the difference between the required length of helical and bar-type mixers to achieve the same CoV may be small (the mixing duty), but the difference between these two mixers for maintaining plug-flow in a long reactor can be significant (the reaction duty). Many suppliers and users do not appreciate this difference in the available information and can therefore be selecting a mixer based on the wrong information.

Cost/benefit of static mixer reactors over other PI technologies

Static mixer reactors appear favourable over other PI technologies for short residence time (seconds to minutes) and medium exotherm reactions. This is due to the relatively low investment cost. Also many static mixer element designs are commercially available and further development reactor systems should make this an attractive technology. However an assessment of industry processes is needed to confirm what percentage of reactions could be carried out in static mixer reactors.

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)

Tubular reactors (empty pipes) are often used at high flowrates in the turbulent regime. These could benefit from the higher mixing and heat transfer intensity that static mixers provide.

For small-scale applications, that would typically be in the laminar flow regime in ¼” to 1” lines, there is no single continuous reactor design currently in widespread use. At this scale many reactions are conducted in stirred batch vessels with heating/cooling jackets or coils with limited heat and mass transfer capability. There are a number of options for reactor technologies that may replace batch vessels; this includes micro-channel devices, macro-channel devices, static mixers, oscillating flow reactors, spinning discs and cones, spinning tube-in-tube, etc.

The advantages of static mixer based systems are:

- Easy to inspect/clean
- Can be very cost-competitive for the correct processes
- Can meet a range of reaction times (seconds to minutes) – where many industry reactions would fit
- Fit into current industry standards, e.g. PED
- Established technology in larger volume process industries – perceived as lower risk
- Variety of mixer types available for fine tuning reactors to process requirements
- Larger number of suppliers available ensures competitive pricing
- No moving parts, resulting in lower maintenance and higher energy efficient in comparison to other technologies

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)

Historically static mixers have been used for their mixing ability but more applications of static mixer reactors have emerged in the last 5years.

The commercial use of static mixer reactors in the polymer industry is well documented and other specialist applications have been reported. However the emerging interest into the use of static mixer reactors has been during small-scale trials (laboratory and pilot-plant) and it is expected that many more commercial applications will be utilised in the next 5-10years.

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

Sector	**Company - Process/ Product name/type**	**Short characteristic of application**	**Production capacity/ Plant size**	**Year of application**	**Reported effects**
Polymerisations				1980s onward	Major area of use with multiple users who have seen improved control and quality
Specialty chemicals and Pharmaceuticals	Confidential (various)			Last 3yrs	Opening up new chemical routes not previously accessible in batch equipment. Improved control of reactions

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.)

Table 3. Demonstration projects related to the technology (existing and under realisation)

Sector	**Who is carrying out the project**	**Short characteristic of application investigated, including product name/type**	**Aimed year of application**	**Reported effects**

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)

There are a variety of reactions currently carried out in a range of industries that could benefit from the use of static mixers. Below are a series of specific examples drawn from the literature;

1. The use of ionic liquids and static mixer reactors for isobutane alkylation to produce high quality trimethylpentanes has been reported in Oil & Gas journal, 2006. This is one example of many where static mixer reactors have the potential to be used in large petrochemical and refining operations. Static mixer reactors in this area tend to be in the turbulent regime and the mixer is used as a mass transfer improvement device.

2. A number of publications in the last 5years have referenced the use of continuous and static mixer based reactors for significant improvements in pharmaceuticals and fine chemicals production. Given the pressure to reduce cost of manufacture in this industry the static mixer reactors future looks promising. These reactors are typically characterised by low flowrate and low viscosity systems (laminar) where static mixers are used to contact reagents and then maintain plug-flow. One example of this is the use of jacketed static mixers for oxidation reactions reported at the AIChE 2006 technical program.

3. The characterisation of static mixer reactors for the production of biodiesel has been reported (ASABE 2007). This is an example of static mixer reactors being used for emerging technologies and access to reactions that may not be feasible or possible in conventional equipment.

Static mixer reactors can be applied to a range of chemical reactions across many of the process industries, and are receiving increase attention and focus in new areas.

3. What are the development and application issues?

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?
Cost/Benefit analysis of various static mixer designs	Static mixer designs range in the mixing intensity they provide under different flow regimes. Users are often concerned that the increased cost of more intense mixers may not provide an equal benefit in performance. Suppliers are reluctant to invest in performance testing for residence time distribution (RTD) without knowing the market potential	Ideally an industry collaboration or university would be better suited to completing this comparison. A standard experimental set-up could be used.
Matching performance at laboratory and plant scale	Manufacturing techniques make some static mixer elements only available at ½” or 1” diameter and above. This is too large to see the benefits for typical development flowrates (especially for high value chemicals).	Suppliers must focus on manufacturing methods or industry must identify alternative products which match a static mixers performance at smaller scale, e.g. caterpillar micromixers etc.
How applicable is the technology to industry requirements (appropriate level of structure for industry)	An assessment of industry processes is needed to characterise and classify reactions into groups. This analysis can then indicate the potential market for static mixer reactors over other competing technologies, as each technology might be more appropriate for a specific set of industry reactions	This survey can be carried out by the EU or similar industry body where confidentiality of specific results can be maintained and only generalised reports made available. The key is to get the survey questions correct to understand the base chemistry and not just the observed practices (i.e. some reaction times are

		shorter than carried out in traditional equipment).
Multi-phase systems	The science behind which static mixers may be applicable to different ratios of multiple phases has not been reported	University and industry collaborations could determine this science
Availability of appropriate instrumentation	Often reactions need continuous monitoring inside the reactor and the instrumentation and sensors to achieve this and how they are integrated into equipment needs further development	Collaboration between instrument suppliers and equipment suppliers is needed in this area, with input from users on the actual requirements.
Availability of 'exotic' materials	Process intensification often results in more arduous process conditions and the requirement for exotic materials, e.g. hastelloy, tantalum, PTFE, etc	Suppliers need to be aware of number of applications requiring these materials to invest in the development of this product range.

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)

There have been numerous publications and presentations in the last 5 years where people have used static mixer reactors for significant processes improvements. On this basis the challenges in moving into this area appear small. However, more emphasis should be placed on using the optimum mixer and reactor design (compared to other static mixer reactors) rather than just reporting the benefits of static mixer reactors over conventional equipment.

Table 5. Challenges in developing processes based on the technology

Challenge	**Description**	**How and by whom should the challenge be addressed?**
Lack of investment by suppliers to understand background science	Static mixers have been designed for intense mixing of two streams and not necessarily for optimum RTD performance. They need to be convinced of the potential market demand for them to invest in further characterisation	An industry overview of the potential for static mixer reactors may convince people to invest.
Confidentiality of research companies	End users of static mixer reactors are developing novel solutions to gain competitive advantage and will be reluctant to make the data and designs available outside their organisations	Information gained from University research can be published with governing body support
Commercial & academic influences	There are numerous competing technologies in the area of process intensification. Companies developing novel solutions for a specific application will look for a wider use (even though other technologies may be more applicable). This can also occur when the developer is unaware that other technologies are more appropriate to the end user.	Published science, with appropriate review and approval, enable final users to make independent judgments on which technology is more appropriate.

4. Where can information be found?

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**
Levenspiel, O. 1998, 'Chemical Reaction Engineering', 3rd Edit, Wiley-Interscience	Book	Numerous models are presented for the design of reactor systems
Thakur, R.K. et al., 2003, 'Static mixers in the Process Industries – A Review', Trans IChemE, Vol 81 (part A), August, 787-826	Review Paper	Thorough analysis of static mixer applications
Streiff, F.A. and Rogers, J.A, 1994, 'Don't overlook static mixer reactors', *Chemical Engineering*, June, 76-82	Feature report	Good overview of static mixer reactor use in many industries
Bayer, T., Himmler, K. & Hessel, V., 2003, 'Don't be baffled by static mixers', *Chemical Engineering*, May, 50-57	Feature report	Good overview of static mixer design
Brechtelsbauer, C. and Ricard, F., 2001, 'Reaction engineering evaluation and utilization of static mixer technology for the synthesis of pharmaceuticals', *Organic process research & development*, 5, 646-651	Research paper	Excellent report on static mixers in small-scale Pharma production
Tauscher, W., 1996, 'Static mixing and reaction technology', *Chemical and Petroleum Engineering*, Vol 32 (3), 224-237	Review paper	Good overview of static mixer applications in bulk chemicals and petroleum industries
Paul, E.L, Atiemo-Obeng, V.A., and Kresta S.M. ed., 2004, 'Handbook of Industrial Mixing: Science and Practice', Wiley Interscience	Book	Multiple references to static mixers
Green, A., 2004, 'Inline and High-Intensity Mixers', In: *Reengineering the chemical plant – Process Intensification*, edited by Stankiewicz, A. and Moulijn, J.A., New York – Basel: Marcel Dekker	Chapter in book	Mainly focused on initial mixing and not maintaining plug flow
Meyer, T., David, R., Renken, A and Villermaux, J., 1988, 'Micromixing in a static mixer and an empty tube by chemical method', *Chem. Eng. Sci.*, Vol 43 (8), 1955-1960	Research paper	Good overview of static mixers and use of Bodenstein correlation
Liu, Z., Zhang, R., Xu, C., and Xia, R., 2006, 'Ionic liquid alkylation process produces high-quality gasoline', *Oil & Gas Journal*, October	Report	Use of static mixer reactors in gasoline industry
Thompson, J.C., and He, B. B., 2007, 'Biodiesel production using static mixers', *Trans. of the ASABE*, 50 (1), 161-165	Research paper	Characterisation of static mixer reactors for Biodiesel production

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.)

There are multiple patents related to the use of static mixer reactors in developing continuous synthesis routes for various chemicals, however these are related to a specific use of static mixers and are therefore excluded from this patent list below. This list refers to the holders of specific designs of static mixer reactor.

In addition the specific design of static mixer elements are subject to patents, however these should be covered in the TR report sections associated with static mixers and have therefore been excluded from this list.

Table 7. Relevant patents

Patent	Patent holder	Remarks, including names/types of products targeted by the patent
WO02072254: Reactor apparatus and mixing inlet and methods	BHR group	Flexreactor
WO2004/130551: Reactor enabling residence time regulation	Phoenix Chemicals Ltd	Variable residence time reactor

4.3 Institutes/companies working on the technology

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

Major suppliers of static mixers are conducting limited research into the use of static mixers as reactors (limited investment due to the need to see the potential market).

Operating organisations in the fine chemical and pharmaceutical industries consider the use of static mixer reactors as a way of lower manufacturing costs and are currently involved in confidential research.

Organisations in biodiesel and gasoline production are investigating the use of static mixer reactors for major improvements to emerging processes.

In summary many process industry companies have planned or active research into the use of static mixer reactors.

Table 8. Institutes and companies working on the technology

Institute/Company	Country	Remarks

5. Stakeholders

5.1 Suppliers and developers

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

The list of suppliers provided will all provide static mixer elements and some will extend this to mono-tube and multi-tube devices.

Table 9. Supplier and developers

Institute/Company	Country	Remarks
Sulzer Chemtech	Switzerland	SMXS, SMXL monotube and multitube reactors, SMR
Chemineer - Kenics	USA & UK	Kenics KM and KMX
Koflo	USA	Series 246, 250, 275, 330
Fluitec	Switzerland	CSE-W and CSE-X
Statiflo	UK	Series 100 to 800
Charles Ross & Son Co	USA	ISG and LPD/LLPD
Admix	USA	SAN

Komax	USA	A and M Series
Verder	Netherlands	VMV, VML, VMS, VMD
EMI/Cleveland Eastern	USA	Sanitary helical
Dr. B. Pittaluga	Italy	XP, VP, X, XL, H
Eesimix	Singapore	
JLS International	USA, UK, Germany	Helical and high shear

Additional stakeholders in the development of static mixer reactors would include the manufacturers of traditional equipment (shell-and-tube heat exchanger suppliers can fabricate the reactor and fit in sub-contract supplied elements). Major design companies/consultancies are interested in understanding the basic technology required to design static mixer reactors to ensure equipment configurations can match their customers and the industries needs.

5.2 End users

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

The petrochemical and refining industries have used static mixers as mixing devices for many years. The polymerisation industry has been using static mixer based reactors for accurate control of main reactions for many years.

Potential future end users include the fine chemicals and pharmaceutical manufacturing companies as this technology is useful for many reaction stages currently carried out in these industries. The biofuels market may also benefit from the use of static mixer reactors. In addition, the refining and petrochemical industries can benefit from the more intense heat and mass transfer provided by turbulent static mixers to reduce the size of process plant and reduce fouling issues due to poor mixing. This is a particularly favourable to static mixers as they are commercially available at the larger diameters needed for these industries.

6. Expert’s brief final judgment on the technology

(maximum 5 sentences)

Static mixers have historically been used as mixing devices. However the use of these devices for chemical reactions is gaining momentum based on the benefits observed in trial work.

Static mixer reactors offer a low cost intense reactor system when compared with other process intensification technologies. They are particularly cost-effective solution for small-scale processing of reactions with residence times from seconds to minutes, for highly viscous systems and where boundary layers can be formed affecting flow (e.g. fouling from agro products). Static mixer reactors can exist alongside other novel PI technologies. Specifically high intensity micro and macro channel reactors to cover shorter residence time and highly exothermic reactions and less intense oscillating flow reactors, etc for longer residence time reactions.

Choosing the appropriately structured reactor depends on understanding process requirements. Static mixer reactors can be improved and used in a wider range of applications with further development, i.e. improved heat transfer, etc. However they will also be relevant for many chemical reactions even at the current stage of development.

The key development areas of understanding the RTD profiles and mixing performance of different mixer types, improving the science behind multi-phase system behaviour and improved heat transfer designs will contribute to making this technology easier to access for all industries.