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EUROPEAN ROADMAP OF PROCESS INTENSIFICATION

- TECHNOLOGY REPORT -

TECHNOLOGY: ROTOR_STATOR MIXERS

TECHNOLOGY CODE: 3.1.4

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1. Technology

1.1 Description of technology / working principle

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

High speed rotor-stator devices have been widely used in the process industries as a process intensification tool to accelerate homogenisation, dispersion, emulsification, dissolution and mixing. The distinguishing feature is the close proximity of a high speed rotor to a stator where tip speeds up to 50m/s are possible, corresponding to shear rates of up to 100,000s^{-1} and energy dissipation rates ***(ε)*** of 10^4-10^5W/kg. The development of rotor-stator devices is characterised by the simple mechanical designs which makes their construction straightforward

Many industrial sectors are concerned with the manufacture of products, whose in-use performance is critically dependent upon the formulation and the microstruture. This microstructure is in turn critically dependent upon the "process history" and hence on the capabilities of the process equipment used. The term "microstructure" is used to mean the arrangement of material elements with respect to one another at a micron or sub micron scale, such as the mean size and size distribution of droplets in an emulsion, or the state of flocculation of a dispersion, or the size, shape and local orientation of particles, or microporosity. The term "process history" refers to the rates and the times of deformation by shear and/or extension and to the temperatures and rates of cooling and/or heating experienced by the product during manufacture. By implication this also refers to the process history of any intermediate phases that are formed as ingredients are brought together and mixed. Such arguments are also very relevant to chemical synthesis since variations in the local chemical composition may promote the formation of undesirable side reactions which will reduce yields. during manufacture.

It is particularly desirable to study the relative contributions of the distributive and dispersive mixing especially where more fluids of differing viscosities are concerned. Distributive mixing refers to that mixing operation in which the various components of the feedstock are distributed with respect to each other to produce a more uniform or homogeneous composition. Dispersive mixing refers to that mixing operation in which there is a physical breakdown of at least one component of the feedstock. Rotor-stator devices are particularly suitable for such an exploration since the different forms of mixing can be independently controlled through rotor speed and equipment design (e.g. rotor-stator clearance, configuration, geometery and multiple stages). Furthermore the state of the composition can be maintained for an extended period by a changing the residence time (i.e. the flow rate) to allow physical and chemical processes to go to completion.

1.2 Types and "versions"

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

Rotor-stator mixers can be used in both batch vessels and as continuous in-line devices. In the in-line configuration it is also possible to use them in a recycle loop around a batch mixer such that the product can pass through the in-line device multiple times. Rotor-stator devices immersed as a top entry mixer in a batch vessel are mechanically the simplest arrangement. In some cases it is more sensible to have them as a bottom entry mixer but here appropriate sealing is required. The efficiency of the mixer drops off as the vessel size becomes large (3-5tonne) and as the viscosity of the fluid increases (10,000cP). The limitations are a consequence of the progressively poorer bulk mixing in the main vessel although the operational range can, in some instances, be improved by installing additional agitation. Another consideration is that these mixers can become very large and heavy as a consequence of the motor size and the long length of shaft between the mixing head and the motor. For this reason a bottom entry mixer might be preferred to reduce the shaft length and hence some of the weight. Nevertheless the weight of mixer (top and bottom entry) may require additional mechanical support.

Continuous or in-line devices are similar to batch mixers but they are placed in a continuous or in-line configuration which may be single pass or in a recycle loop around a holding vessel so that the process fluid can be passed through the rotor-stator device several times. One of the main advantages of an in-line mixer is that for the same duty a much smaller unit is required than for the equivalent batch mixer. The arrangement is better suited to more viscous process fluids (eg 1,000,000cP). Different classifications are used by researchers and manufacturers but the following four are suggested here.

- Colloid mills consist of concentric cylinders, or more often cones, and in some instances as flat plates which provide a thin gap through which the fluid passes and in which it is sheared: the arrangement is similar to a Couette style of rheometer. The assumption is that there is no slip at the surfaces and that the shear field is uniform across the gap. The shear rates are amongst the highest in rotor-stator devices and so colloid mills tend to produce smaller particles sizes but at the expense of throughput. In some designs the surfaces of the rotor and stator have groves cut into the surface to reduce slip and also to improve the milling of solid particles. Suppliers include the FrymaKoruma.
- Toothed devices have rotors and stators made up of rings of intermeshing teeth arranged either on discs or as concentric rings. In order to improve performance there maybe up to 6 sets of rotor-stator. The process fluid is usually fed by an external pump into the centre and is forced radially outwards through the consecutive rings of teeth. Suppliers include IKA Werke and Charles Ross and Son Co.
- Screen based devices have rotors which have a pumping action so that often no pump is required to prime and pump the process fluid through the mixer. Centrifugal forces then drive the process fluid through the mixer where it is subject to a milling action in the machined clearance between the rotor and stator and hydraulic shear as the material passes through the perforations of the stator and the turbulent jets formed as the fluid exits the perforation. There are a range of rapidly interchangeable screens tailored for different operations and there can be multiple concentric rotor-stator arrangements (typically up to 4). Suppliers include Silverson Machines Ltd
- Cavity transfer mixers (CTM) were initially invented by RAPRA for thermoplastics blending operations and were latter modified by Unilever to reduce pressure drop before being used in manufacture of some food stuffs. CTMs provide exceptional distributive mixing at low shear rates.

Suppliers include Maelstrom Advanced Process Technologies although they supply other types as well

The introduction and adoption of rotor-stator devices has in fact been so rapid that the understanding of their operation is poorly developed. In their 2004 summary of the state of the art Atiemo-Obeng and Calabrese say that "The current understanding of rotor-stator devices has almost no fundamental basis. There are few theories by which to predict, or systematic experimental protocols by which to assess, the performance of these mixers. In fact there are few archival publications on rotor-stator processing". Consequently the development of rotor-stator devices can be characterised by pragmatic engineering solutions and "trial and error". However there is considerable scope for the design of a new generation of devices for the manufacture of 21st century products.

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	No data	Rotor-stator devices tend to require less energy per kg of material because the energy is delivered at the optimal time and in a focussed way. In addition higher viscosity fluids can be used so it is possible to process more concentrated process fluids. These transmit fluid stresses more effectively so that dispersion is more effective
CO2 emission	No data	Reduced due to improved energy efficiency. Also microstructure of the chemical product is optimal so that functionality of the product improves thereby reducing the amount of raw materials required to achieve the same effect.
Costs	No data	Smaller equipment footprint requires less space and may also reduce civil engineering costs associated with supporting large pieces of equipment

1.4 Stage of development

Rotor-stator mixers in general are relatively inexpensive, energy efficient and versatile and there is a wide range of rotor-stator designs available from different suppliers.

Rotor-stator mixers have gained popularity in response to industry trends in manufacturing and product quality. Initially the drive to increase production and asset utilisation required improvements in mixing and the other physical and chemical processes outlined earlier. This was rapidly followed by the opportunities of new and improved products where improved control over the assembly of products enabled the creation of wholly new microstructures and so products with improved performance (e.g. efficacy, appearance, taste, rheology, sensory). For example, the stability of an emulsion has been improved by reducing the particles size and resulted in a competitive advantage for the first users of the technology (this is now regarded as standard). A related benefit is the simplification of formulations since stabilising agents (e.g. thickeners) can be removed reducing formulation cost and complexity. Over time more and more complex mixers have been introduced to obtain further productivity and product advantages.

Future developments of rotor-stator devices are more likely to be driven by new chemical product opportunities and the need to realise these opportunities through sustainable processes. Key considerations include

- product quality & performance ensured by design & operation of effective & efficient processes
- ensuring consistent quality & performance across scales
- standardisation & validation of new mixers & equipment
- accelerate time to market and rapid roll-out through robust scale-up rules
- difficult to imitate cost structures by ensuring maximum functionality is obtained from the materials used whilst high throughputs are maintained
- extended proprietary position

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)

- High pressure homogenisers are static devices (i.e. no moving parts) which consist of a high pressure pump and a process unit comprising of small diameter channels or orifices or counter current or coaxial jets. They are rather poor distributive mixers and are better suited to dispersion of oils and breakup of agglomerates and so it is usual to supply the process fluid as a premix with uniform composition. A range of break-up mechanisms are implicated including turbulent shear, laminar flow extension and cavitation. Pressures of up to 300-400MPa (i.e. 4,000 bar) are possible and homogenisers work best with relatively low viscosity systems (up to 200cP). Particle sizes produced tend to be smaller than in a rotor-stator device though the size distribution can be significantly broader.
- High power ultrasonics relies on acoustic cavitaion in process fluids. Ultrasonics produces travelling sound waves which alternately compress and expand the fluid to the point where a cavitaion bubble can form. The subsequent collapse of the bubbles is extremely fast producing strong but short lived hydrodynamic shear forces in the vicinity of the bubble. Ultrasonics has been popular in the research lab where it is an extremely useful because of the intensity of the shear it can produce and its suitability for small volumes. Unfortunately these same features limit the industrial application of ultrasonics. The action of the ultrasonic devices is local and consequently even at fairly low volumes (1L) its necessary to move to an arrangement with additional agitation to ensure that the process fluid passes through zone of highest shear

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)

Rotor-stator devices are widely used in industry and it is not practical to list specific examples. Table 9 contains details of some suppliers where further details of customers and uses can be found. Operations that rotor-stator devices are use for include emulsification, dispersion of powders, dissolution, blending, mass transfer, chemical reactions, cell disruption and homogenisation.

Similarly the ranges of industry sectors where rotor-stator devices are used are broad and include food and drink, fine chemicals, pharmaceuticals, cosmetics and toiletries, catalysts, agrochemicals, oil and gas, lubricants, renewables such as biodiesel and waste water treatment.

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

Sector	Company - Process/ Product name/type	Short characteristic of application	Production capacity/ Plant size	Year of application	Reported effects

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 realization)

Sector	Who is carrying out the project	Short characteristic of application investigated, including product name/type	Aimed year of application	Reported effects
All	Consortium led by University of Liverpool	Ultra Mixing and Processing Facility	Operational 2008	Extremely high energy rotor-stator mixer
All	Consortium led by Maelstrom APT (FP7 proposal)	HEDON: High Energy Dispersion of nanoparticles	Proposal	New FP7 project proposal for commercialisation of novel CTM type mixer
All	BHR Group	DOMINO; Dispersion & manufacture of Nanoparticles	Start 07	New confidential industrial consortium starting 2007. Follow on from earlier consortium (HILINE)
All	University of Maryland	High Shear Mixing Research Program	Started prior to 03, still active	Confidential industrial consortium. Some publications but nothing detailed
All	Consortium led by BHR Group, including, Bayer, Unilever, C3M, Rockfield, and University of Birmingham, Poznan, Warsaw, Karlsruhr, and Loughborough	PROFORM: NMP4-CT-2004-505645; Transforming Nanoparticles into Sustainable Consumer Products through Advanced Product & Process Formulation.	Finishes 07 with implementation by partners 2008 on	• Rotor- stator devices are effective but do not achieve full dispersion • Mixer geometry is very important in achieving maximum dispersion rate. • There is considerable opportunity for further improvements

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)

Future developments of rotor-stator devices are more likely to be driven by new chemical product opportunities and the need to realise these opportunities through sustainable processes. A particular example which is attracting considerable attention is the manufacture and incorporation of nano materials to provide new product benefits. Nano materials are of interest across industry sectors food and drink, speciality and fine chemicals, polymer manufacture, pharmaceuticals, cosmetics and toiletries, catalysts, agrochemicals, inks, paints and dyes, bitumen, oil and gas, lubricants, renewables such as biodiesel, processing of nuclear waste and waste water treatment

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?
Design strategy based on mechanistic understanding of how materials & process interactions affect performance		
1. Systematic experimental protocols to generate physical models of optimal process	• An instrument quality process facility is required where the impact of differing amounts of distributive and dispersive mixer can be studied. • The purpose is to generate physical models of the optimal process steps	Collaborative approach through public funding to establish Open Access facility support by research programme to define protocols
2. Conceptual prototype equipment designs	• Generalised design rules which translate optimal process history into practical process solutions. • Design rules will need constant updating to reflect modern fabrication and assembly techniques	Collaborative R&D projects
3. Integration of modelling approaches including mesoscale, rheological and microstructural models	• Many chemical products are characterised by a multiphase microstructure that gives rise to strongly non-Newtonian behaviour at the macroscopic engineering level. Process Intensification also implies a move to more concentrated and multiphase materials at intermediate stages of manufacture. • The non-Newtonian behaviour arises partly from composition and partly from the microstructure. The microstructure in turn is a consequence of process history. In other words the rheology of the product depends on the microstructure which develops as a consequence of the flows. However the detail of the flows themselves are dependant on the rheology which is the target of the prediction	Academic research projects in • As a consequence a modelling framework is required which links the details of the flows with the rheological constitutive models and microstructural models • Development of refined microstructural models. This is a necessary precursor to the development of realistic anisotropic rheological models for such systems
4. Rheological characterisation	• Rheological measurement techniques need to be extended to process relevant deformation rates. Existing rheometric instruments have probably reached the limit of their capability.	Academics, rheometry manufacturers to develop instruments to measure rheology under process relevant conditions
5. Process equipment characterisation	• There is a lack of characterisation techniques of the flow patterns and action of rotor-stator devices. • Chemical reaction systems to quantify	Research projects in academy, including • new chemical reaction systems for micromixing

	micro mixing require considerable characterisation of rate constants before they are suitable and only just being considered for existing mixers and are non-existent for higher energy mixers. • Laser Doppler Anemometry requires optically clear equipment and fluids and some studies have been carried out (especially on batch versions).	• improvements in LDA (e.g. tighter clearances require better location of measurement position, increased data acquisition rates for higher deformation rates). • Wholly new measuring techniques.
6. Integration with other PI technologies	• Rotor-stator devices could be coupled with other process intensification technologies, (i.e., microwave, electric field, ultrasound) to exploit synergies	Scouting projects between technology champions
Design of process equipment		
7. Optimal design of rotor-stator geometries	• Designs have emerged by trial and error and heuristic observation and have then been refined by multiplication of rotor-stators and by a reduction of clearances and mechanical machining techniques have improved. It is not clear what features of these designs are critical in determining the properties of the product. • Some CFD tools are available for full 3D simulation of simple fluids in complex geometries. These should be used to support design of more radical changes in geometry	R&D projects between academy, equipment manufacturers and users. The role of equipment suppliers is to ensure that new designs are suitable for manufacture. End users are required to provide demonstrators which will encourage take up by broader industry base
8. Engineering models	• The formulation of engineering-scale models for high speed rotor stator devices that can be used for design and scale-up of manufacturing processes remains a very severe challenge, • Some progress has been made for relatively simple systems (emulsions, dilute polymers, wormlike surfactants) but the more complex systems (lamellar phase surfactants and concentrated non-Newtonian fluids) have hardly been treated at all and there is huge potential for significant further breakthroughs.	This challenge should be addressed by the academic chemical engineering community in collaboration with end users to ensure relevant systems are examined. See also 1,2 and 3
9. Increasing deformation rates by higher speed rotors or tighter clearances	• Performance of rotor stator devices has been improved by adding extra stages. Key operations (e.g emulsification & dispersion) are mainly a function of peak energy dissipation rates which suggests that higher rotor speeds are required • Direct drive electric motors can be driven at much higher rotor speed is an electrical inverter is available. However to meet ATEX rating for motors there is a limit of 4,000-5,000rpm • Mechanical multipliers such as pulleys are prone to slip and stretch of the belt • Mechanical design and machining of components to improved tolerances will be required to ensure that devices are stable at new operating conditions	Design and construction of devices. Should involve the equipment suppliers' supply chain for motors, bearing, seals etc…Also fabricators to ensure that modern machining techniques are employed to match required tolerances. See also 7.

New product opportunities		
10.Smaller particle sizes	• Rotor-stator devices can't reach the deformation rates of HP homogenisers, although their distributive mixing is far better. Colloid mills go some way to addressing this but sacrifice throughput.	R&D project to design machines with higher deformation rates and flow fields which ensure that all materials passes through the most energetic part of the mixer. See also 7 & 9.
11.Dispersion of high viscosity fluids	• Dispersion of high viscosity fluids in a low viscosity medium becomes problematic once the viscosity ratio >4-10. Extensional flow rates often cited as more effective than shear flows	R&D project to design mixers with flow fields which encourage break-up of viscous droplets. See also 2, 3, 7, 8 and 9.
12.Dispersion of nano dispersions	• There is considerable interest in the dispersion of solids in various fluids and in particular the dispersion of nano scale materials. Rotor-stator devices struggle to fully disperse materials. For some materials such as carbon nanotubes dispersion should be done without breaking the tubes. This implies much greater control over the flow fields.	R&D project to design machines with higher deformation rates and flow fields which ensure that all materials passes through the most energetic part of the mixer. See 7 and 9.
13.Control of size distribution	• Tighter size distributions Mean particle sizes and width of the size distribution are intimately linked and it is very difficult to break this relationship • Bimodal size distributions offer a means to manipulate packing fractions and consequently bulk properties such as rheology and flow.	R&D project. See also 3, 7 and 9

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?
1. Energy efficiency	Energy efficiency of all size reduction devices is poor with most of the energy being dissipated as heat: this is likely to get worse as we move to smaller sizes. There is a need to gain a fundamental understanding of the interaction of machine design and process materials to improve efficiencies. • How important is the design of the rotor-stator arrangement? • What is the most effective process strategy	• R&D project including multi disciplinary academic team and process engineers. Project should incorporate principles outlined in table 4 items 1, 2, 3, 5, 7 and 8
2. High speed seals	• Sealing at rotor speeds in excess of 6,000 to 10,000 can be problematic and lifetime drops dramatically with rotor speed. Higher speeds also result in frictional heating so that lubricants and cooling fluids are required. This poses a potential hygiene risk since if the seals fail the product may be contaminated with lubricant	• Machine manufacturers and their supply chain of component manufacturers. See also table 4 item 9
3. Production efficiency	• One of the attractions of rotor-stator devices is their high throughput which makes them suitable for high tonnage products. It is important to retain this feature	• Machine manufacturers in collaboration with end users
4. Engineering tools for scale up and scale down	• Scale-up approaches usually rely on maintaining one or maybe two parameters constant through the scales. Traditionally trials are conducted at production scale to prove performance and economic models – essentially successful trials reduce risk and increase confidence. However such trials can be extremely expensive, especially if the product must be scraped. • “Scale down” approaches map the performance of lab, pilot and production scale units to ensure that lab scale processes are run under realistic process conditions	• R&D projects See also table 4 items 1, 2, 3 and 8
5. Multi variate statistical process analysis in scale-up and scale-down	• Multi-variate statistical process analysis (MVSPA) is an important tool in chemical synthesis but not yet in chemical products. • Modern process control systems record a large amount of process data which often is discarded. Statistical tools exist to reduce the data into a simpler form which uniquely describes the manufacture of product-processes combinations. • It has already been used in some simple cases to speed up the introduction of new products using historical data of previous products and then to accelerate the roll out of	• Use of MVSPA and control is relatively well known in petrochemicals but more industry examples are required for chemical products • R&D projects are required to link MVSPA with additional tools (eg Basyian Logic) in order to take products from the lab bench, though

	products between factories. • Extension to follow products from lab to commercial scale would be new and challenging especially where for example the former is a batch process and the latter a continuous process • Use is encouraged by FDA Process Analytics Technologies (PAT) Guidelines for primary and secondary manufacture	pilot plant and into production plant
6. Instrumentation and control	• There are few instruments for the online measurement of product properties which are indicative of performance. Such instruments are in particular required for the real time control of continuous and semi-continuous processes and will be useful to monitor progress of batch processes. • FDA Process Analytics Technologies (PAT) Guidelines cite this as a particular challenge for the pharma sector. Their vision is to move from a recipe driven process (e.g. mix for 10min then shear…) to an end point driven process (e.g. when the viscosity is 100cP move to the next step)	• R&D projects are required and will predominantly be driven from pharma (as a consequence of FDA PAT guidelines). • Industry sectors where product quality can be damaged by over processing will also benefit e.g. food and drink industry. These sectors should support initiative though leadership might be from pharma
7. Slow introduction of new process technology	• New products which are dependant on new process technology often take a long time to come to market. Rotor-stator devices have a strong and positive profile in the industry which will encourage users to trial. However such equipment innovations should ensure that key features that customers value are not lost (e.g. high throughput).	• Collaborative projects between users and equipment manufacturers. • Consortiums & public funding to de-risk capital investment of demonstration prototypes
8. Mechanical manufacture and reliability	The most obvious developments of the technology are to either increase rotor speed or reduce clearances. This creates challenges for • component manufacturers (e.g. seals, bearing) regarding tolerance during construction and lifetime of components. In addition more exotic materials of construction may be required in order to preserve machined tolerances even with existing process fluids (e.g. wear from dispersion of fine silicas). • chemical products industry (i.e. the user) to ensure that where tight clearances exist process surfaces are not damaged by foreign bodies	• Machine manufacturers in collaboration with end users. See also table 5 item 2
9. Cleaning and hygiene	• There are few truly hygienic devices and a lack of reliable in situ means of determining the cleanliness of process equipment. Cleaning standards (EHDG) are based on cleaning in pipes rather than in the complex geometries of rotor-stator devices	• Regulations regarding standard should be reviewed regarding test protocols. • Academic & instrument manufacturers to develop on-line, in situ instruments to measure how clean process equipment is

4. Where can information be found?

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
1. Bourne J.R. and Studer M., 1992, Fast reactions in rotor-stator mixers of different size. *Chemical Engineering and Processing 31:285-296.*	Paper	Use of chemical reactions to characterise micromixing. Results indicate scale up on tip speed
2. Jaschke P., 1999, Stirring, mixing, but how. *Prozess 4: 102-103.*	Professional magazine	General article
3. Urban K., Wagner G., Schaffner D., Röglin D., and Ulrich J., 2006, Rotor-Stator and disc systems for emulsification processes, *Chem. Eng. Technol 29 (1): 24-31.*	Paper	Comparison of high pressure homogeniser, rotor-stator devices and disc turbine indicating strengths and weakness of devices
4. Cohen D., 1998, How to select rotor-stator mixers, *Chemical Engineering 105 (8):76-79, 1998.*	Professional magazine	Good general overview of rotor-stator devices. NB author is employee of Charles Ross and Son Inc
5. Bourne J.R., and Garcia-Rosas J., 1986, Rotor-stator mixers for rapid micromixing, *Chemical Engineering Research and Design 64 (1):11-17.*	Paper	Use of chemical reactions to determine micro mixing times. Times of around 1ms were measured
6. Sparks T.G., Brown D.E., and Green A.J., 1995 Assessing rotor/stator mixers for rapid chemical reactions using overall power characteristics. *1st International Conference on Process Intensification for the Chemical Industry, Paper 3.1.4.*	Conference	General article discussing power characteristics
7. Davies J.T., 1987, A physical Interpretation of drop sizes in homogenisers and agitated tanks, including the dispersion of viscous oils. *Chem. Eng. Sci., 42 (7): 1671-1676*	Paper	Key paper frequently cited. Correlates drop size against local power for various devices. Still representative of capability
8. Kowalski A, (2008), Power consumption of in-line rotor-stator devices. Chemical Engineering and Processing, publication date to be confirmed	Paper	Publication by this reports author presenting expression for accurate calculation of power draw
9. Atiemo-Obeng V.A. and Calabrese R.V. 2004, Chapter 8. Rotor-stator mixing devices *in Handbook of Industrial Mixing, editors Paul E.P, Atiemo-Obeng V.A. Kresta S.M, published by John Wiley & Sons, Inc*	Book / review	Recent summary of the state of the art by one of the principle researchers in the area pointing out the very poor state of understanding. See footnote for quote [1]
10.Meleson K., Graves s. and Mason T.G., 2004, Formation of concentrated nanoemulsions by extreme shear, *Soft Materials 2: 109-123*	Paper	Nanoemulsions prepared by multiple pass through high pressure homogeniser. Size width is broad even after multiple passes. Indicates that not all the fluid passes

[1] Quote "The current understanding of rotor-stator devices has almost no fundamental basis. There are few theories by which to predict, or systematic experimental protocols by which to assess, the performance of these mixers. In fact there are few archival publications on rotor-stator processing"

		through the highest energy /shear zone
11. Bałdyga J., Kowalski A.J., Cooke M. and Jasińska M., (2007), Investigations of micromixing in the rotor-stator mixer, *XIX Polish Conference of Chemical and* Process Engineering, Rzeszów, Poland, Sept 2007.	Conference presentation	Development of micromixng chemical reaction schemes
12. Bałdyga J., Orciuch W., Makowski L., Malski-Brodzicki, and Malik K (2007), Break-up of nano-particle clusters- process modelling. *1st International Conf. on Industrial Processes for Nano & Micro Products, April 07, London, UK*	Conference presentation	First of papers from Prof Baldyga's group on full 3D CFD of Silverson.
13.Guidance for Industry. PAT - A Framework for Innovative Pharmaceutical Manufacturing and Quality Assurance. Draft Guidance. http://www.fda.gov/ohrms/dockets/dockets/03d0380/03D-0380_emc-000003-02.pdf	Web document	Guidance for industry document with nonbinding recommendations from Food & Drug Administration Agency. Outlines vision for innovative pharmaceutical manufacturing and the technologies required to meet them

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.)

Table 7. Relevant patents

Patent	Patent holder	Remarks, including names/types of products targeted by the patent
WO03041848	AMERSHAM HEALTH AS	Mixing apparatus, i.e. rotor stator mixer
WO0104239, US6368366, US6368367, US6383237, EP1224248, JP2003504486T,	LUBRIZOL CORP	Aqueous hydrocarbon fuel formation
WO2007000610	MAELSTROM ADVANCED PROCESS TECHNOLOGIES	Apparatus for mixing e.g. viscose materials
FR2871711	PCM POMPES SA	In-line dynamic mixing device
WO2006125591	PHARES PHARM RES NV	Preparing oily carotenoid
WO9919376, AU9691898	PPG IND INC	Continuously produced rheology modifiers
US5632596	ROSS & SON CO CHARLES	Low profile rotor stator assembly for mixers and emulsifiers
US6000840	ROSS & SON CO CHARLES	Rotor-stator assembly for mixers and emulsifiers
EP 0799303	UNILEVER	Process For The Production Of Liquid Compositions.
EPA0048590 B1.	RUBBER & PLASTICS RESEARCH ASSOCIATION OF GREAT BRITAIN.	Extruder Mixer
EP0194 812	UNILEVER PLC	Chemical reactions & apparatus.
EP0340873	TWENTE UNIVERSITY	Mixer device with distributive mixing action

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
ETH Zurich, (Prof Eric Windhab)	Switzerland	Foods research group
University of Liverpool, (Prof Mathias Brust)	UK	New process technology development for creation and stabilisation of micro & nano structures and formulations.
University of Maryland, (Prof Richard Calabrese)	USA	High shear mixing research programme. Industrial consortium
University of Massachusetts Amherst (Prof Michael Malone)	USA	Product and Process Design. Improved conceptual process design strategies for the design of formulated chemical products
Warsaw University of Technology (Prof Jerzy Bałdyga)	Poland	Full 3D CFD simulation of Silverson. Characterisation of micromixing by chemical reations

5. Stakeholders

5.1 Suppliers and developers

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

Table 9. Supplier and developers

Institute/Company	Country	Remarks
Charles Ross and Son http://www.mixers.com/	USA	Manufacturer of mixing equipment and complete process systems
FrymaKoruma GmbH http://www.frymakoruma.com/	Germany/ Switzerland	Manufacturer of colloid mills & other processing machines & processing installations
IKA-Werke GmbH & Co. KG http://www.ikaprocess.com/main.html	Germany	Manufacturer of mixing equipment and complete process systems
Maelstrom Advanced Process Technology http://www.maelstrom-apt.com/	UK	SME interested in innovative new designs
Silverson Machines Ltd www.silverson.com	UK	Manufacturer of Mixing equipment and complete process systems

5.2 End users

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

End users are

- chemical product manufacturers who manufacture and sell directly to the public (eg foods, domestic paints)
- chemical product manufacturers who manufacture and sell to industrial customers (eg fine chemical, agrochemicals, paint to car manufacturer)
- utilities involved in the treatment of waste water and other effluent streams.

6. Expert's brief final judgment on the technology

(maximum 5 sentences)

- Rotor-stators devices are already extremely widely used across industry sectors due to their high throughput, versatility and relatively low cost and this familiarity is likely to allow for faster introduction of new innovations.
- Future challenges are significant and will probably be driven by the need of industry for new materials where quality and performance is ensured by design & operation of effective & efficient processes.
- Probably the most pressing need is in the use of nanomaterials where raw material productivity requires that particle sizes and size distributions are accurately controlled, where nanomaterials are fully and completely dispersed to ensure that full value is realised from their incorporation and where existing options such as high pressure homogenisers have inherent weaknesses.
- These opportunities indicate that a new more robust, systematic and generalised design methodology is required to generate physical models of product, process, equipment and crucially their interaction which can be used to generate new insights on the design of more effective process equipment and strategies and their commercialisation.