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EUROPEAN ROADMAP OF PROCESS INTENSIFICATION

- TECHNOLOGY REPORT -

TECHNOLOGY:
Oscillatory baffled reactor and continuous oscillatory baffled reactor technologies

TECHNOLOGY CODE:

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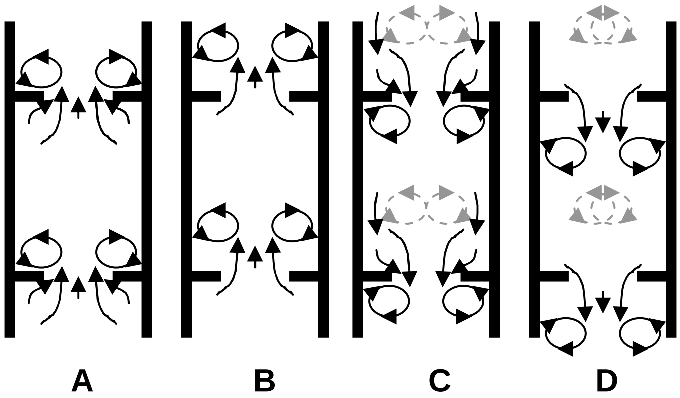
1. Technology

1.1 Description of technology / working principle

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

The Oscillatory Baffled Reactor (OBR) technology generally consists of a cylindrical column containing equally spaced orifice baffles and superimposing with fluid oscillation. Vortices are generated when fluid flow past through the baffles as shown in Figure 1, enabling significant radial motions where events at the wall are of the same magnitude as these at the centre. The generation and cessation of eddies creates uniform mixing in each baffled cell, collectively along the column. The fluid mechanical conditions in an OBR are generally governed by two dimensionless numbers: the oscillatory Reynolds number ($Re_o = \frac{2\pi f x_o \rho D}{\mu}$) and the Strouhal number ($St = \frac{D}{4\pi x_0}$), where D is the column diameter (m), ρ the fluid density (kg/m^3), μ the fluid viscosity (kg/ms), x_0 the oscillation amplitude (m) and f the oscillation frequency (Hz). The oscillatory Reynolds number describes the intensity of mixing applied to the column, while the Strouhal number is the ratio of column diameter to stroke length, measuring the effective eddy propagation.



A = Start of up stroke
B = Maximum velocity in up stroke
C = Start of down stroke
D = Maximum velocity in down stroke

Figure 1 Mechanism of mixing in an OBR

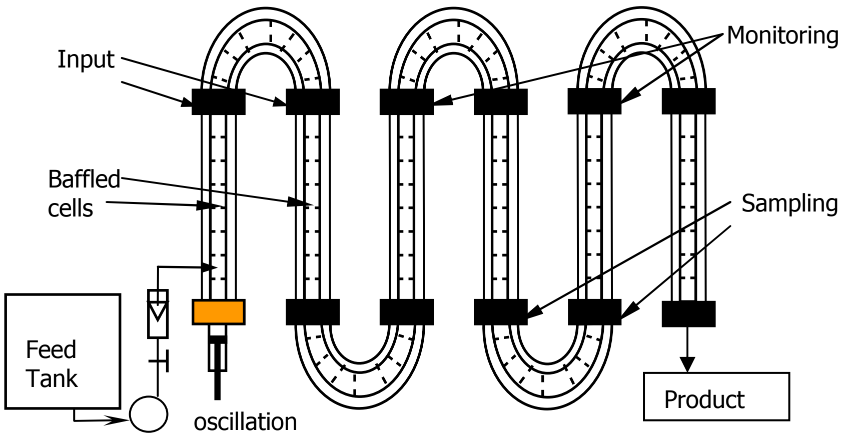


Figure 2 The schematic of COBR^{TM}

By connecting baffled cells in series, a continuous oscillatory baffled reactor (COBR™) is created, as shown in Figure 2. As each baffled cell acts as a continuous stirred tank reactor (CSTR), with a large number of baffled cells plug flow condition is achieved under laminar flows (low flow rates). When solid particles are present in a liquid phase, uniform and efficient suspension and transportation of solids is obtained along the length of COBR. When a gas phase is involved, very good mixing and dispersion of the gas into the liquid occurs to give an exceptionally high surface contact area and a substantial increase in gas hold up and gas residence time, enabling enhanced mass transport characteristics. Due to plug flow conditions achievable in COBR™, it also offers superior heat transfer rate. Note that the black boxes as shown in Figure 2 can be used for inputting, sampling, monitoring and outputting. The jackets along the COBR™ provide heating/cooling in either an individual or integrated manner so that different or same thermal profiles can be established along the length of the COBR™.

1.2 Types and "versions"

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

There are three types of oscillatory baffled reactors: OBR™, COBR™ and TBR™.

Oscillatory baffled reactor (OBR™) --- the description of OBR has already been given in 1.1. OBR is related to batch and fed-batch operations, and generally operated vertically. In OBR, the oscillation can be achieved by either using a piston or bellows arrangement at the base of the column or moving a set of baffles up and down the column at the top.

Continuous oscillatory baffled reactor (COBR™) --- The COBR™ is for the continuous processing and operations, and can be operated horizontally, vertically or at any angle. The key difference between the COBC™ and other tubular devices on the market is that the mixing in the COBC™ is governed by the **oscillation**, not the **net flow**, allowing plug flow conditions under laminar flows (low flow rates). This enables much more compact reactor design and configurations with significant reduction of reactor volume/space; and accommodates much longer residence time (in terms of hours) while generates much less pressure drops in comparison to other tubular devices. Under plug flow conditions, the significantly enhanced mass and heat transfers can also be realised in COBR™.

Tubular baffled reactor (TBR™) --- the TBR™ is effectively the same as the COBR™ except that there is no oscillation required. The mixing is achieved by the net flow component together with the presence of orifice baffles. Vortices are created between the baffled cells when the net flow flows through the orifices, creating uniform mixing along the length of the TBR™. For shorter reaction times, a TBR™ can be employed without the use of fluid oscillation. Other advantages in mass and heat transfers as in a COBR™ can also be obtained.

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
Space savings	>90%	The footprint for producing the same amount of product is significantly reduced in comparison to traditional STR, due to plug flow conditions achieved in COBR™ under laminar flows.
Less side products	~90%	Less waste is generated through greater process optimisation and control in COBR™ because of plug flow conditions.
Higher yield	Up to 20%	Higher yield is achieved in COBR™ due to fewer side reactions taking place; less losses through unnecessary changeovers and clean-down; and less out-of-spec product produced. The result is higher yield of product.
Energy and utility savings	~75%	Due to the uniform mixing in COBR™, much less energy and utility are required as compared to traditional STR.
Significantly increased safety	No data available yet	Much less usage and storage of solvents and reactants in COBR™ comparing to traditional STR.
Capital costs	~50%	Plug flow in COBR™ is achieved under laminar flows (low flow rates), which enables much more compact reactor design and configuration, and results much smaller footprint, hence less capital costs.
Consistent product quality	No data available yet	The highly reproducible fluid mechanical conditions in COBR™ enable consistent product quality.
Reaction time	Up to 90%	Due to the more uniform mixing, enhanced mass and heat transfers within COBR™, significant reductions of reaction time are achieved, which again enables much more compact reactor design.
Catalyst savings	Up to 100%	In some cases, such as in oxidation of a flavour compound, catalyst is completely eliminated in the process.

1.4 Stage of development

No long just laboratory scientific related research, the applications of OBR™, COBR™ and TBR™ technologies to real industrial processes have been very active. NiTech Solutions Ltd, a spin off company from Heriot Watt University, Edinburgh, UK, is the world's leading authority on delivering process improvement benefits through the use of baffled reactor technology, and has success commercial applications in liquid-liquid (e.g. trans-esterification, water purification, organic synthesis), gas-liquid (e.g. oxidation, hydrogenation), solid-liquid processes (e.g. acetylation, crystallisation, carbonation, flocculation) (see further later) as well as heterogeneous catalysis, fermentation and waste water treatment.

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)

Batch stirred tank reactors (STR) have been the workhorse in manufacturing chemicals and pharmaceutical products over the last 80 years.

Continuous processes are usually carried out using STR in series or some form of tubular flow reactors operating at high flow rates, e.g. incorporating static mixers.

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 contrast to traditional STR technology, the OBR™/COBR™/TBR™ technologies have a linear scale up principle, allowing fast and easy conversion from bench to commercial scale. The technologies are platform technologies, enabling a wide range of applications, from chemicals to food and drinks, from pharmaceutical APIs to biofuels, covering small throughput as little as 30 ml/min to bulk rate as large as 4 tons/min. The table below summarises some of the commercial COBR™ applications.

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
Speciality chemicals; Pharmaceuticals; Food; Water; Biofuels; Energy	NiTech's clients	i) Continuous separation of one of the products in a reversible reaction to allow fuller reaction ii) Controlling temperature and input dosages to perform a highly exothermic and explosive reaction iii) Mixing a coagulate in raw water in order to remove colour iv) Controlling input dosages and control pH continuously to maintain suspension	Volumes of COBR™ from 20 to 800 litres	2004-2007	• ~95% reduction in space/volume • ~50% savings in capital costs • ~75% savings in energy & utility costs • ~90% reduction of reaction times • Enable to suspend and transport up to 50% solids in liquid • ~90% reduction in emission

		of high solid concentrations v) Manufacturing a speciality chemical (solid) involving multi-stage and multiphase reactions vi) Manufacturing of API involving solid, liquid and gas phases; vii) Crystallisation of food to extract high value product			• Much less usage and storage of solvents • ~90% reduction of crystallisation time • ~80% reduction of filtration time • Consistent product quality • Consistent polymorph • Flexible and lean manufacturing

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
Chemicals	NiTech Solutions Ltd and Centre for Process Innovation (CPI), UK	Various hydrogenation and oxidation reactions at elevated pressures	2005	• Consistent product yield • 99% retention of catalyst • Significantly less usage of hydrogen • Much more efficient process • Easy start-up and shut-down • Significantly more safer operation
Chemicals and pharma	NiTech Solutions Ltd	Continuous crystallization	2007	• 50% savings in capital costs • 75% savings in energy & utility costs • Significantly reduced crystallisation time • Significant reduced filtration time • Consistent crystal morphology • Controlled crystal size and size distribution

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)

The COBR™ are platform technologies and unique in comparison to other tubular flow reactors on the market in that mixing is not driven by net flow, allowing plug flow achievable under laminar flow conditions. This offers significantly enhanced mass and heat transfers, much better process control during processing; while accommodating much longer residence times with less pressure drops.

The products that can be manufactured with this technology include:

Bulk chemicals, e.g. polymers, monomers, dimmers
Fine chemicals, e.g. dyes, pigments, paints, emulsions
Speciality chemicals, e.g. flavours, additives, adhesives, functional materials
Agro-chemicals, e.g. fertilizers
Pharmaceuticals, e.g. drug ingredients, APIs
Cosmetics, e.g. beauty products, daily products
Food, e.g. ingredients, starch, sugar, additives
Drinks, e.g. spirits, alcoholic drinks, soft drinks

The list is just for indication, and by far not conclusive.

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)

NiTech are the world's leading authority on baffled mixing technology and no other organisation has the breadth or depth of understanding that NiTech do. NiTech have tackled a number of technological development issues, such as oscillation under pressure; linear/non linear oscillation; on-line continuous temperature control; on-line continuous pH control; on-line gas-liquid, liquid-liquid and solid-liquid separations; techniques for feeding extreme materials and etc.

Table 4. Technology development issues

Issue	Description	How and by whom should be addressed?
Robustness	As the COBR™/TBR™ installed in industries are still relatively young, the data on robustness can only be generated through time, e.g. operating COBR™ for days, months and years.	NiTech's clients are generating data. NiTech too is conducting similar tests.
Cross-contamination	When manufacturing multi-pharmaceutical products using one COBR™/TBR™, is there any cross contamination problem? If so, how to measure it and how to prevent it from happening.	This issue is being addressed via an EPSRC industrial CASE PhD student award between Heriot-Watt University,

		UK and NiTech. The project started in October 2006.
Automatic control systems for commercial scale COBR^{TM}	Due to the uniform mixing and plug flow conditions generated in COBR^{TM}/TBR^{TM}, it provides a highly reliable and consistent environment for measurement. Majority of the lab scale automatic control systems can be adopted in commercial COBR^{TM}/TBR^{TM}	NiTech contracts out the work for control systems for commercial COBR^{TM}/TBR^{TM}.

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?**
Feed solids directly into COBR^{TM}/TBR^{TM}	There is a small fraction of organic synthesis and reactions that require a direct feed of solid reactant into liquid, while the majority of the operations accept the feed of solid-slurry. Under these circumstances, a robust feed mechanism is needed, in particular, when gas is forbidden within the system.	R&D projects for universities in collaboration with companies such as NiTech, as NiTech have some knowhow on this area.
Dealing with liquids with very high densities	So far a specific density of 1.8 has been tested in OBR^{TM} and 1.45 in COBR^{TM}.	Different reactor designs may be needed, which should be addressed by universities in collaboration with companies such as NiTech, as NiTech have extensive knowhow on this area.
Dealing with liquids with very high viscosities	So far 5000 cPs are the top ceiling for COBR^{TM} operations; over 50,000 cPs for OBR^{TM}.	Different reactor designs may be needed, which should be addressed by universities in collaboration with companies such as NiTech, as NiTech have extensive knowhow on this area.
Dealing with reactions that generate significant amount of gases	Depending on processes, ~30% v/v gas has been tested in COBR^{TM}/TBR^{TM}.	As gas dampens the propagation of fluid oscillation, different reactor designs are needed. R&D projects for universities in collaboration with companies such as NiTech, as NiTech have extensive knowhow on this area.

Modelling	Modelling of fluid mechanical conditions within a baffled cell has been carried out at relatively low oscillatory Reynolds numbers for single phase fluid. The challenge would be to extend the modeling for two and multiphase fluids.	R&D projects for universities in collaboration with companies such as NiTech, as NiTech have extensive experimental data.
Dealing with reactions with very long intrinsic reaction times	The overall reaction time consists of the intrinsic and external reaction times; the latter is the direct result of poor mass or heat transfer, and is generally significantly longer than the former in industrial batch operations. Due to plug flow conditions in COBR^{TM}/TBR^{TM}, there is of minimum mass or heat resistances, allowing the intrinsic reaction time to be designed and operated in COBR^{TM}/TBR^{TM}. However, for reactions with very long intrinsic reaction times, would continuous operation be the ideal solution?	R&D projects

4. Where can information be found?

4.1 Key publications

(Provide the list of key publications in Table 6)

There are a number of publications relating to the science of the OBR, but few on that of COBR, and very few publications on applications.

It should be noted that the science and application of oscillation to enhance flow can be back dated to 1940s, and the pulsed packed columns, pulsed plate columns and reciprocating plate columns have also been around since 50s for extraction. However, the research on using *oscillation* in conjunction of *orifice baffle inserts* in tubular devices to generate *mixing* started in 80s at Cambridge University, the UK, under the direction of Professor Malcolm Mackley. The key publications refer to the latter.

Table 6. Key publications on the technology

Publication	Publication type (research paper/review/book/ report)	Remarks
Dickens, A.W., Mackley, M.R. and Williams, H.R., 1989, Experimental residence time distribution measurements for unsteady flow in baffled tubes. *Chem. Eng. Sci*. 44: 1471-1479.	Research paper	First paper in the field from Prof. Mackley's group
Mackley, M.R. and Ni, X., 1991, Mixing and dispersion in a baffled tube for steady laminar and pulsatile flow. *Chem. Eng. Sci*. 46: 3139-3151,	Research paper	First paper in continuous flow
X. Ni, Y. Zhang and I. Mustafa, 1999, Correction of polymer particle size with droplet size in suspension polymerisation of methylmethacrylate in a batch oscillatory	Research paper	First paper in application

baffled reactor. *Chem. Eng. Sci.*, 54: 841-850.		
Howes, T., Mackley, M.R. and Robert, E. P.L., 1991, The simulation of chaotic mixing and dispersion for periodic flows in baffled channels. *Chem. Eng. Sci.,* 46: 1669-1677.	Research paper	First paper on modeling fluid mechanical condition in OBR
X. Ni, D. Mignard, B. Saye, J.C. Johnstone and N. Pereira, 2002, On the evaluation of droplet breakage and coalescence rates in an oscillatory baffled reactor. *Chem. Eng. Sci.*, 57: 2101-2114.	Research paper	First paper on modeling droplet breakage and coalescence in OBR
X. Ni, M.R. Mackley, A.P. Harvey, P. Stonestreet, M.H.I. Baird and N.V. Rama Rao, 2003, Mixing through oscillation and pulsations -- a guide to achieving process enhancements in the chemicals and process industries", *Chem. Eng. Research & Design*, 81: 373-383.	Review paper	First review paper in the field

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**
US 4832500: Mixing apparatus and processes	National Research Development Coporation	This was the 1st patent in this field from Prof Mackley's group.
US 5439991 A method of mixing heterogeneous system	BP	Olefins
US 6429268: Method and apparatus for phase separated synthesis	NiTech Solutions Ltd	
EP 1076597: Method and apparatus for phase separated synthesis	NiTech Solutions Ltd	
WO 136850: Method and apparatus for fluid-liquid reactions	NiTech Solutions Ltd	
WO 057661: Improved apparatus and method for applying oscillatory motion	NiTech Solutions Ltd	
WO 060412: Improved apparatus and method for temperature controlled processes	NiTech Solutions Ltd	
PCT 002808: Plug flow tubular mixing apparatus and method	NiTech Solutions Ltd	
PCT 000753: Apparatus and method for applying oscillatory motion	NiTech Solutions Ltd	
GB0706908: Online separation	NiTech Solutions Ltd	

4.3 Institutes/companies working on the technology

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

Note that all the University research groups listed below were associated with Prof Mackley at Cambridge University, UK one way or other.

Table 8. Institutes and companies working on the technology

Institute/Company	Country	Remarks
NiTech Solutions Ltd	UK	NiTech are the world's leading authority on baffled mixing technologies and on commercialization of COBR™ and TBR™
Cambridge University	UK	Prof Mackley's group with broad range of research activities on sciences
Heriot-Watt University Edinburgh	UK	Prof. Ni's group with broad range of scientific and technological research activities on OBR/COBR/TBR.
Newcastle University	UK	Focus on biodiesel
Manchester University	UK	Interest in modeling of OBR and application to electrochemistry
Queensland University	Australia	Interest in modeling of OBR and application of mineral processes
Universiti Kebangsaan	Malaysia	Interest in pulp bleaching process and waste water treatment
University of Cape Town	South Africa	Interest in bioapplications

5. Stakeholders

5.1 Suppliers and developers

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

No suppliers of commercial-scale COBR™ and TBR™ are known. NiTech Solutions Ltd has the capability of supplying full solutions up to pilot scale reactors, and is working with engineering firms either recommended by their clients or associated with NiTech to supply commercial continuous reactors. Table below lists some potential companies of the latter.

Table 9. Supplier and developers

Institute/Company	Country	Remarks
Zeton BVL (www.zeton.com)	The Netherlands & Canada	Zeton provides state-of-the-art lab scale reactor systems, pilot plants, demonstration plants and small scale commercial plants for the process industries worldwide.
Foster Wheeler (www.fwc.com)	Global	Foster Wheeler is a leading global engineering and

		construction contractor and power equipment supplier.
Robbins & Myers Inc (www.robbinsmyers.com)	USA/Germany	Robbins & Myers is a leading supplier of highly engineered, critical equipment and systems for global energy, chemical and industrial markets.
CEL (www.cel-international.com/)	UK	CEL is a medium-sized company offering consultancy, design, engineering, procurement, construction/project management and validation services principally to the process and manufacturing industries.
Cambridge Reactor Design Ltd (www.crduk.com)	UK	CRD is a small-size equipment manufacturer based in the UK.
Haycock and Hague Ltd (www.haycockandhague.com)	UK	Haycock and Hague is a UK based business, specialising in services and engineering solutions for process related industries and the commercial and manufacturing sectors whilst maintaining its core business of pipework fabrication.

5.2 End users

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

Bioprocessing → e.g. cell fermentation, photo-synthesis and cultivation

Energy → e.g. production of hydrates, CO_2 sequestration, production of hydrogen and fuel cell materials

Biomedical → stem cell migration

6. Expert's brief final judgment on the technology

(maximum 5 sentences)

COBR™ and TBR™ are viable process intensification technologies for reducing wastes in a wide range of aforementioned industries from small to large scales and for reaction times ranging from seconds to hours. The wastes are anything but the essentials to add value, such as reduction of reaction time, volume, emission, out-of-spec products, capital and running costs and etc. Due to the compact size of COBR™ and TBR™, it also provides the unique means of lean and flexible manufacture.

The technologies have already been installed in a few of companies in fine chemical, food and pharmaceutical industries. There is now a considerable momentum built up, and it is envisaged that more companies would consider adopting COBR™ and TBR™ technologies to improve their performance and efficiency in production, energy/utility and waste management in the next few years. On the long term, this technology could also be used in cell fermentation, stem cell migration, cultivation of cyanobacteria for generation of hydrogen, fuel cell applications and hydrates for either CO_2 sequestration or H_2 economy, etc due to the uniform mixing, plug flow condition and low shear environment.