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EUROPEAN ROADMAP OF PROCESS INTENSIFICATION

- TECHNOLOGY REPORT -

TECHNOLOGY: IMPINGING STREAMS REACTOR

TECHNOLOGY CODE: 3.2.3

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1. Technology

1.1 Description of technology / working principle

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

The concept of impinging streams has been known for a long time and goes back at least to an US patent from1889 entitled: Process for faciliating chemical reactions.
The basic principle is to have two streams consisting of single or multiple phases with an identical or a different composition and/or temperature and aligned along the same axis impinging on each other. The impinging results in a zone of high shear and turbulence resulting in excellent conditions for mixing, heat and/or mass transfer.
The principle of impinging streams has been applied to processes such as

- absorption and desorption of gases from liquids,
- chemical and biological reactions,
- combustion,
- crystallisation,
- dissolution of solids,
- drying of particles,
- formation of emulsions,
- gas-gas, liquid-liquid and solid-solid mixing,
- liquid-liquid extraction
- nucleation and granulation, and others.

Surprisingly, despite the large number of feasible applications of the principle of impinging streams, it has not found wide application in reactor technology

1.2 Types and “versions”

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

The principal layout of IS-reactors is given in Fig.1 for two streams of about the same density (US 2751335) and in Fig. 2 for two streams with a different density like e.g. a gas and a liquid stream (EP 0179478 A3).
The version shown in Fig. 3 consists of an impinging zone integrated into a loop reactor for a gas/liquid system with an external recirculation of the liquid. The ingoing streams are pre-mixed in two-phase jets resulting in an improved mass transfer performance and accordingly a higher reaction rate. The streams enter the impinging zone through one- or two-phase orifices or perforated plates providing for the desired velocity. The impinging zone may be bordered by discs or confined by a pipe with two or multiple entries of the streams in order to obtain a more or less defined impinging volume (DE 3818991 C1).
Other versions of the IS-reactor employ a variety of baffles or spherical shells with holes creating impinging liquid jets (US 4994242).

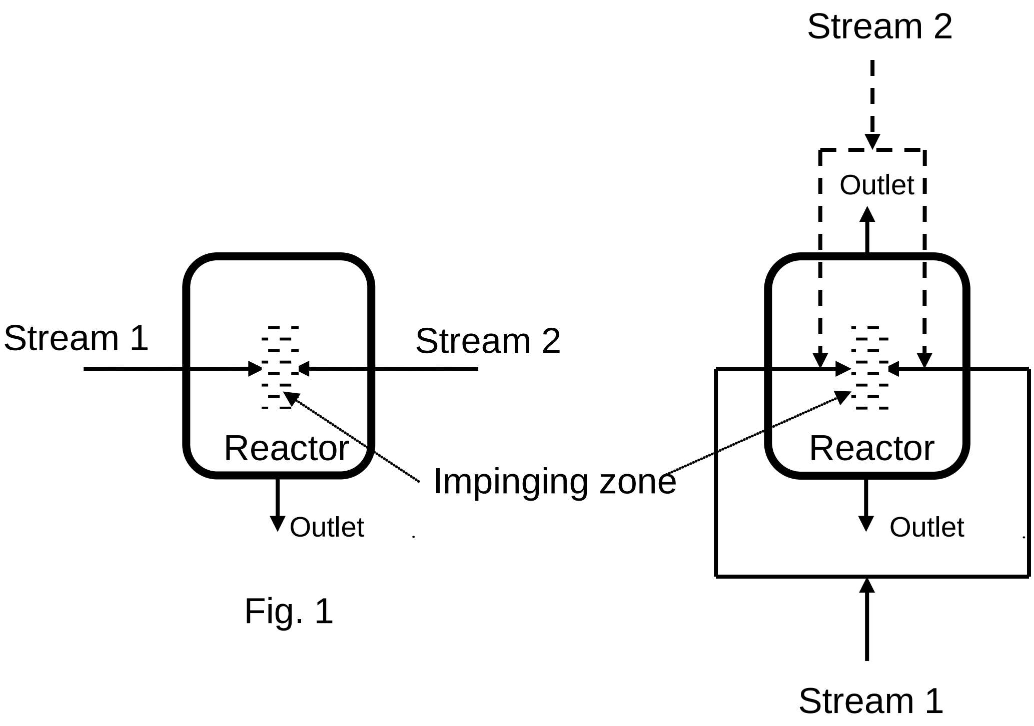

Fig. 1

Fig. 2

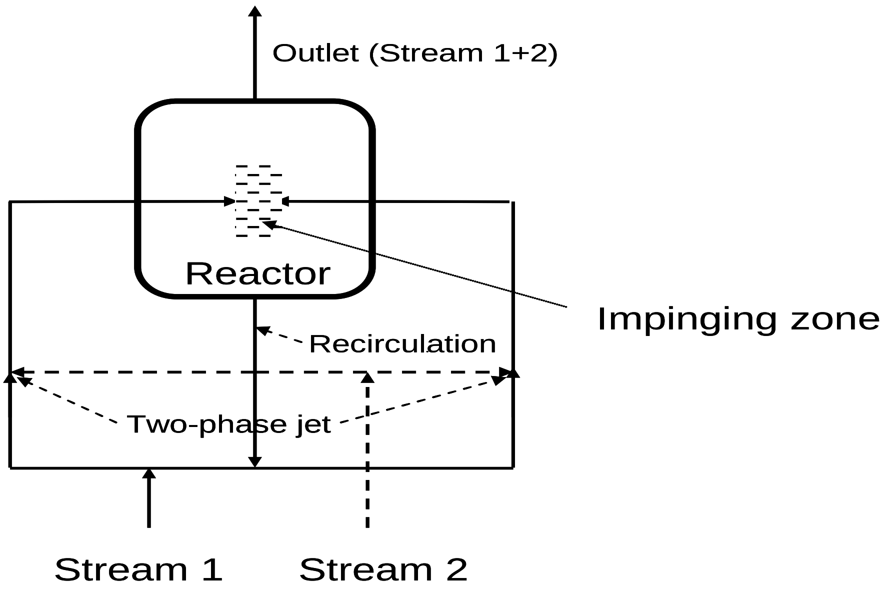

Fig. 3

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
Increased mixing	Depends on the energy input	The impingement creates microturbulence resulting in the break-up of the continuous phases and and thus intensive mixing.
Increased heat and/or mass transfer	Depends on the energy input	The impingement creates microturbulence which enhances convective and molecular transport.
Reaction	Depends on the energy input	High reaction rates due to an improved micromixing within the impinging zone.
Energy savings	Up to an order of magnitude depending on the kind of equipment and/or process	At a given energy input the ISR shows a significantly better mass transfer performance than other gas liquid reactors. A 50 % savings has been reported in gas-liquid reactions.
Cost savings	The improved momentum, energy and mass transfer results in a substantial reduction of the required reactor volume and thus costs.	A reduction in volume of up to 85 % has been reported in gas/liquid reactions.
Product quality	Crystallisation, production of micro- and nanoparticles	Particles with a narrow particle-size-distribution

1.4 Stage of development

As the principal layout of IS-reactors is rather limited, the design of gas/liquid- or liquid/liquid-reactors is well established. Development may be necessary and even require laboratoy or pilot plant studies in order to establish the optimal conditions for specific applications. This is in particular the case where solid products are involved which have to meet specifications like in crystallisation, granulation or nucleation.

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)

Processes involving the transfer of momentum, energy and/or mass including a large variety of chemical reactions are applied in almost all branches of the chemical and related industries and have reached a high standard. The global competition, however, necessitates a continuous upgrading of the existing technologies and the development of new and more efficient processes.

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)

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
Chemical	Air Products Chemox ™-SR reactor	Chemical oxidation	Reactor size: 20 m³	2002	• 85 % reduction of reactor volume • 50 % savings of energy • 30 % less ozone

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
				•

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)

A number of papers has been published on the potential applications of IS-reactors.

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?
Modeling and scale-up of in-dustrial-size reactors	Even though scale-up rules for designing tech-nical reactors on the basis of laboratory experi-ments have been proposed, the validity of these rules needs to be confimed for technical size IS-reactors.	R& D in cooperation with an applier of IS-reactors

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, pro-vide 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?

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
Tamir A.: IMPINGING STREAM REACTORS Fundamentals and Application, Elsevier,ISBN: 0-444-89400-4, 1994	Book	
Wu, Yuan: IMPINGING STREAMS Fundamentals, Properties and Applications, Elsevier, ISBN: 978-0-444-53037-0, 2007	Book	
Gaddis, E.S., A. Vogelpohl: The impinging stream reactor (ISR): a high performance loop reactor for mass transfer controlled chemical reactions, Chem. Eng. Sci. 47 (1992) 2877-2882	Paper	Fundamental paper on mass transfer
Sohrabi, M., A.M. Jamshidi: Studies on the Behaviour and Application of the Continuous Two Impinging Streams Reactors in Gas-Liquid reactions Journal of Chemical Technology & Biotechnology 69 (1997) 415-420	Paper	Theoretical study of the reaction of carbon dioxide with monoethanolamine
Sprehe, M., E.S. Gaddis, A. Vogelpohl: On the Mass Transfer in an Impinging Stream Reactor, Chem. Eng. Technol. 22 (1998) 19-21	Paper	Correlation of experimentally determined mass transfer coefficiemts
Mudimu, A.O.: Beitrag zur Modellierung und zum Scale-up des Prallstrahlreaktors, Ph.D. Thesis, Clausthal Technical University 1999	Research	Fundamental ex-perimental studies on the fluiddyna-mics and mass transfer in a 16 l and a 250 l reactor
Ranade, V.V.: Pushing the limits of existing re-actor hardware using computational flow model-ling: A case of oxyhydrochlorination reactor, Current Science 77 (1999)	Paper	Computational flow modelling
Mudimu, A.O., E.S. Gaddis, A. Vogelpohl: Gas Holdup in an Impinging-Stream Reactor, Chem. Engng. & Technol. 23 (2000) 661-663	Paper	Experimental study of the gas holdup in a pilot plant reactor
Rüütel, P.L., P. Barratt, V. White: Efficient use of ozone with the CHEMOX^{TM}-SR reactor, Air Products, Knowledge Paper No. 2	Report	Case study: Ozone oxidation of landfill leachate
Dehkordi, A.M.: Liquid-liquid extraction with chemical reaction in a novel impinging jets-reactor, AICHE J., 48 (2002) 2230-2239	Paper	Experimental study of mass transfer and reaction rate
Wu, Y., Y. Xiao, C. Yu: Submerged circulative impinging stream reactor, Chemical Journal on Internet 4 (2002) 44-47	Paper	Experimental study of micro-mixing and residence-time-distribution
Sohrabi, M., N. Fallah: Application of the spray type impinging streams reactor in two phase solid-lquid enzyme reactions,	Paper	Study of the isomerization of D-glucose to D-

Afinidad 61 (2004) 521-525, ISSN 0001-9704		fructose using immobilized glucose isomerase enzyme
Sohrabi, M., B. Zareikar: Modeling of the Residence Time Distribution and Application of the Continuous Two Impinging Streams Reactor in Liquid-Liquid Reactions, Chemical Engineering and Technology 28 (2005) 61-66	Paper	Modeling of the two-phase monosulfonation of toluene
Hu, L., X. Wang, X. Li, G. Yu, F. Wang, Z. Yu: The characteristics of liquid-phase methanol synthesis in an impinging stream reactor, Chem. Eng. & Proc. 46 (2007) 905-909	Paper	Laboratory scale study

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 prod-ucts targeted by the patent
US 410067 (1889)	H. Bower, USA	Process of facilitating chemical reactions (First patent on ISR's)
US 2751335 (1951)	J.A. Carver, W.F. Rollman, USA	Method amd Apparatus for mixing and contacting fluids
DE 0179 478 A3, DE 0179478 B1 (1985)	K. Stephan, Germany	Process and apparatus for absorption
DE 3818991 C1 (1988)	E.S. Gaddis, A. Vogelpohl, Germany	Process and apparatus for mixing of two fluids
US 4994242 + Foreign patents (1989)	Noram Engineering & Constructors LTD., Canada	Reaction of immiscible reactants: Nitration of aromatic hydrocarbons
EP 0529651B1 + Foreign patents (1991)	Montell Italia S.p.A, Italy	Process for reaction injection moulding of non-precatalyzed polymerizable monocomponent resins
DE 4418287 C2 (1994)	E.S. Gaddis, A. Vogelpohl, Germany	Process and apparatus for mixing of two fluids
EP 0369455 B1 + Foreign patents	Otto Oeko-Tech, Germany	Biological treatment of

(1995)		waste water
US 129359 (1998)	MicroFluidics International Corp., USA	Mixer/reactor for performing irreversible reactions
EP 1173265 + Foreign patents (2000)	Bristol-Myers Squibb Co., USA	Process and apparatus for the controlled crystallisation of pharmaceutical compounds
DE 10223567 (2002)	B. Penth, Germany	Production of micro- and nanoparticles by reactive precipitation
Pat. Appl. 20060147853 (2006)	Dow Chemical, USA	Feed nozzle assembly and burner apparatus for gas/lquid reactions
PCT/US2006/03768 (2006)	Greenfuel Technologies Corp., USA	Treatment of flue gas or other gas for removal of pollutants like SOx, NOx , CO_2, etc.

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
Institut für Technischen Umweltschutz, Technical University Berlin (Prof. S.-U. Geissen)	Germany	Research involving IS-reactors in gas/liquid and biochemical reactions
Institute of Clean Coal Technologies, East China University of Science & Technology, Shanghai	P.R.China	Research on liquid-phase methanol synthesis
Chem. Eng. Dept., Wuhan Institute of Chemical Technology, Wuhan	P.R. China	Research on fluiddynamics and applications
Aminkabir University of Technology, Chem. Eng. Dept., Tehran 15	Iran	Research and applications

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
Air Products	USA, GB	Producer of technical gases, supplier of IS-reactors for oxidation with ozone
Aker Kvaerner	GB	Manufacturer of wastewater treatment reactors
Microfluidics International	U.S.A.	Developer and producer of microfluidic components
Noram Eng. & Constr. LTD	Canada	Manufacturer of chemical plant equipment
Synthesechemie	Germany	Developer and producer of microfluidic components

5.2 End users

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

Potential end-users are all industries using chemical reactions, e.g. in particular the chemical and biochemical companies.

6. Expert's brief final judgment on the technology

(maximum 5 sentences)

IS-reactors have a high potential for increasing the space-time-yield of chemical and biochemical reactors in particular for heat or mass transfer limited reactions resulting in a significant reduction of investment and operationg costs. The theoretical basis for calculating the effect of impinging streams and the principal design of IS-reactors is well established.