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EUROPEAN ROADMAP OF PROCESS INTENSIFICATION

- TECHNOLOGY REPORT -

TECHNOLOGY:
Supersonic Gas-Liquid Reactors

TECHNOLOGY CODE: 3.2.8.1

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1. Technology

1.1 Description of technology / working principle

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

The Supersonic Gas-Liquid Reactors enable to achieve very high mass transfer fluxes within a limited volume by utilizing the supersonic shockwave to disperse gas into tiny bubbles (micrometer range). Volumetric mass transfer coefficients as high as 6 s^{-1} can be realized in those reactors.

1.2 Types and "versions"

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

Basically, three types of Supersonic Gas-Liquid Reactors can be distinguished:

<u>Reactor with two-phase gas-liquid flow</u>
In such reactor liquid stream is accelerated in a Venturi nozzle to supersonic velocity. The liquid flow sucks the gas into the nozzle, while the supersonic shockwave produces a fine dispersion of tiny bubbles. The Supersonic Gas-Liquid Reactor with two-phase flow has been developed and patented by Praxair Inc. This type of reactor is shown in Fig. 1.

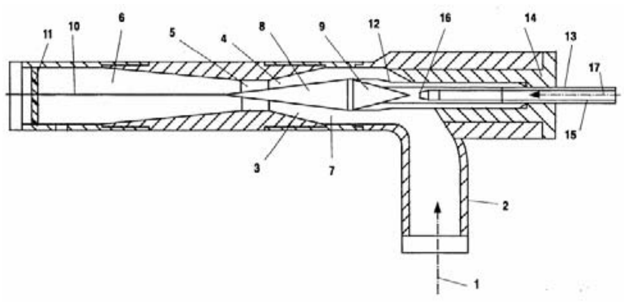

Fig. 1. Supersonic Gas-Liquid Reactor with two-phase flow patented by Praxair.

<u>Reactor with gas nozzle submerged in liquid pool</u>
In this type of reactor gas stream is injected under high flow velocity (slightly lower or equal to the sonic velocity) into the liquid pool, via a specially designed injection nozzle. An example of such nozzle is the one developed at DSM and applied on commercial scale in one of its fermentation processes. The DSM nozzle is shown in Fig. 2.

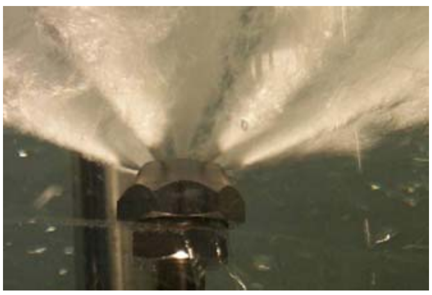

Fig. 2. Supersonic Gas-Liquid Reactor with gas nozzle submerged in liquid pool, developed at DSM.

Reactor with gas flow nozzle external to the liquid pool

This type has been developed by Praxair and is used exclusively as the so-called CoJet (Coherent Jet) technology for injecting the oxygen into the molten steel bath in the electric steel furnaces. Gas stream accelerated to Mach 2 velocity impinges on the surface of the steel bath from the distance of 1-1.5 m, where the concentrated momentum of the oxygen beam dissipates as fine bubbles (Fig. 3).

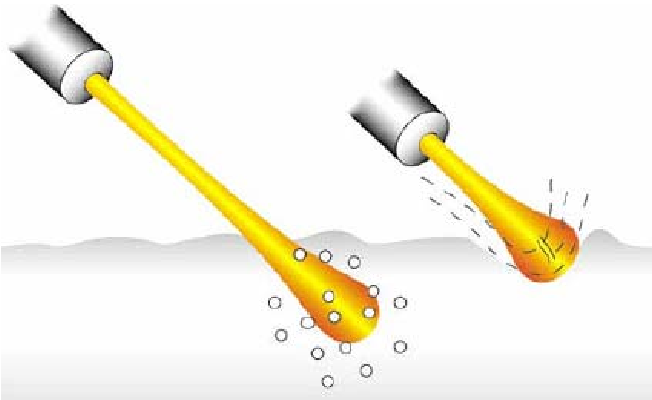

Fig. 3. Praxair's CoJet technology (left) and simple supersonic jet (right)

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 savings	No data available	Pressure drop in the Praxair's reactor is in he range of 1.4 – 1.7 bar; CoJet technology is reported to decrease electrical energy consumption in electrical steel furnaces
Less CO_2 emission	No data available	CoJet technology decreases carbon monoxide emission by up to 40%
Cost savings	No data available	
Increased production capacity	**2-fold** increase of fermenter capacity reported in the aerobic fermentation process at DSM	
Increased safety	No data available	Safety increase can result from: • Smaller inventory of chemicals in equipment • Possibility of instantaneous carrying out fast exothermic reactions, due to high mass transfer rates

1.4 Stage of development

The technology has already been applied on commercial scale. Surprisingly, however, very little fundamental research has been carried out so far, to enhance the understanding and provide quantitative description of the underlying phenomena.

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)

Standard reactor types used for gas-liquid reactions include stirred tanks, bubble columns and packed columns of various configurations. For effective contacting and mass transfer between gas and liquid in case of fast and very fast reactions static mixers (see Technology Report 1.1.4), static mixer reactors (see Technology Report 1.2.5) and ejector-based reactors (see Technology Report 3.2.1) are used.

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)

The technology has been applied on commercial scale. DSM used its supersonic nozzle to inject oxygen into its industrial-scale fermentation unit (see Figure 3).

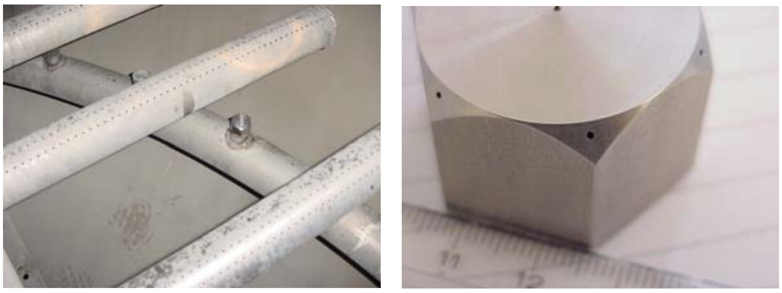

Fig. 3. Supersonic injection nozzles installed in the DSM fermenter.

It can also be expected that Praxair's two-phase flow design has found commercial applications although no published information on this subject is available.

On the other hand the CoJet technology of Praxair has already been applied in more than 70 electric steel furnaces worldwide.

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

Sector	Company/Process (type)	Short characteristic of application	Production capacity /Plant size	Year of application	Reported effects
Food ingredients	DSM	Oxygen injection in aerobic fermentation	No data	2003	• 2x more capacity from the same reactor volume
Steel industries	Various (>70)	Oxygen injection in electric steel furnaces	No data	1999-2007	• Up to 40% decrease coal monoxide emissions • (unspecified) energy savings

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,)

No demonstration projects on Supersonic Gas-Liquid Reactors are known.

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

Sector	Who is carrying out the project	Short characteristic of application investigated	Aimed year of applicati on	Reported effects
				•

2.4 Potential applications discussed in literature

(Provide a short review)

The literature on Supersonic Gas-Liquid Reactors is very limited. Cheng (1997) discussed the two-phase flow reactor in application to very fast oxidation processes. Groen et al. (2005) describe the development and application of the DSM nozzle in fermentation processes. Technical leaflets of Praxair provide descriptions of the CoJet technology applied in Electric Steel Furnaces.

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. 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?
Fundamental knowledge	No publications have been identified describing a more fundamental research to gain a better understanding of the underlying phenomena, e.g. relation between nozzle geometry, flow conditions and average bubble diameter, etc.	R&D projects carried at the universities, in collaboration with chemical, biochemical and steel industries, as well as equipment manufacturers
Modeling and scale-up methodologies	No information published so far	R&D projects carried at the universities, in collaboration with chemical, biochemical and steel industries, as well as equipment manufacturers

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?
Small irradiation depth of supersonic gas stream in liquid, limited gas-plume size	The question is how the reactor volume should be arranged (e.g. positioning of the nozzles), in order to maximize its utilization	This challenge should be addressed in the university R&D projects
Minimum pressure on the gas feed side	Optimization of supersonic nozzles is needed to minimize energy consumption due to gas compression.	As above
Uniformity and high percentages of finely dispersed bubbles, control of coalescence	Bubbles should be small and uniform in size. The question is how to eliminate generation of large bubbles and minimize coalescence	As above

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
Cheng, A. T. Y., 1997, A high-intensity gas-liquid tubular reactor under supersonic two phase flow conditions, in Process Intensification in Practice – Applications and Opportunities, (Semel, J. (ed.), (Mechanical Engineering Publications Limited, Bury St Edmunds, UK), pp. 205-219	Research paper	
Groen, D. J., Noorman, H. J. and Stankiewicz, A., 2005, Improved method for aerobic fermentation intensification, in Proc Int Conf Sustainable (Bio)Chemical Process Technology, Delft 27-29 September 2005, Jansens, P. J., Green A. and Stankiewicz A. , BHR Group, 2005, pp. 105-112	Research paper	
Various technical leaflets by Praxair	Technical leaflets	CoJet technology

4.2 Relevant patents and patent holders

(Provide the list of relevant patents in Table 7)

Table 7. Relevant patents

Patent	Patent holder	Remarks
US 4,867,918: Gas dispersion process and system	Union Carbide Corporation	
US 5,061,406: Gas/liquid dispersion	Union Carbide Corporation	
US 5,954,855: Method for electric steelmaking	American Combustion, Inc.	
US 6,096,261: Coherent Jet injector lance	Praxair Technology, Inc.	

4.3 Institutes/companies working on the technology

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

No institutes are known to work specifically on the development of supersonic gas-liquid reactors.

Table 8. Institutes and companies working on the technology

Institute/Company	Country	Remarks
Praxair, Inc.	U.S.A	Developing CoJet technology

5. Stakeholders

5.1 Suppliers and developers

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

Praxair is the only know supplier of commercial-scale supersonic devices for gas-liquid dispersing

Table 9. Supplier and developers

Institute/Company	Country	Remarks
Praxair, Inc.	U.S.A.	Probably the only developer and equipment manufacturer of supersonic gas-liquid dispersing devices .

5.2 End users

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

Potential group of end users includes companies operating in the chemical and biotechnological sectors, executing mass-transfer limited gas-liquid reactions.

6. Expert's brief final judgment on the technology

(maximum 5 sentences)

Supersonic flow presents a promising method for intensification of gas-liquid contacting in chemical reactors. Its application potential covers not only oxidation and fermentation processes, but can be extended further on other reaction types, such as hydrogenations. Although energy savings resulting from this technology are not expected to be particularly large, it may lead to smaller and safer processes, with higher product yields due to shorter contacting times. Some fundamental questions concerning the underlying mechanisms and the optimization of supersonic gas-liquid reactors should be answered in the appropriate R&D programs.