EUROPEAN ROADMAP OF PROCESS INTENSIFICATION

- TECHNOLOGY REPORT -

TECHNOLOGY: Hydrodynamic cavitation reactors

TECHNOLOGY CODE: 3.2.2

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1. Technology

1.1 Description of technology / working principle

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

Hydrodynamic cavitation can simply be generated by the passage of the liquid through a constriction such as orifice plate, venturi or throttling valve. When the liquid passes through the constriction, the kinetic energy/velocity of the liquid increases at the expense of the local pressure at the constriction. If the throttling is sufficient to cause the pressure around the point of vena contracta (point of lowest local pressure) to fall below the threshold pressure for cavitation (usually vapor pressure of the medium at the operating temperature), cavities are generated. Subsequently, as the liquid jet expands, the pressure recovers and this results in the collapse of the cavities. This phenomenon of generation, growth and rapid collapse of the cavities has been described as cavitation and in this particular case hydrodynamic cavitation. The main effects of cavitation phenomena can be given as generation of local conditions of high temperature and pressures coupled with very high intensity fluid turbulence. The intensity of cavitation generally depends on the geometry of the constriction and the flow conditions of the liquid i.e. the scale of turbulence and the rate of pressure recovery. Controlling the geometric and operating conditions of the reactor results in generation of required intensity of the cavitation so as to bring about the desired physical or chemical change with maximum energy efficiency as compared to its counterpart, acoustic cavitation based sonochemical reactors.

Hydrodynamic cavitation reactors are much simpler to design and also the scale-up is relatively easy as compared to their acoustic counterparts (sonochemical reactors). Few advantages of hydrodynamic cavitation reactors, in general as compared to the sonochemical reactors, can be given as; a) cavitation is uniform throughout the reactor due to efficient mixing and hence there is no problem of directional sensitivity, b) cavitation is at the shear layer of the bulk liquid and hence metal erosion problems are less severe, c) quantification and control over the design parameters is relatively easy, leading to optimization of the required cavitating conditions.

A dimensionless number known as cavitation number (Cv) has generally been used to relate the flow conditions with the cavitation intensity. Cavitation number can be expressed mathematically as follows:

$$C_v = \frac{P_2 - P_v}{\frac{1}{2}\rho v_o^2}$$

where P_2 is the fully recovered downstream pressure, P_V is the vapor pressure of the liquid and v_o is the velocity of the liquid at the constriction. The cavitation number at which the inception of cavitation occurs is known as the cavitation inception number C_{vi}. Ideally, cavitation inception occurs at $C_{vi}=1$ and there are significant cavitational effects at C_v less than 1. However, cavitation has been found to occur at a higher cavitation number (in the range 2 to 4) also, possibly due to the presence of dissolved gases or some impurities in the liquid medium. C_{vi} is also a function of the flow geometry and usually increases with an increase in the size of the constriction as well as with an increase in the pipe diameter. This can be attributed to the fact that with an increase in the diameter of the pipe, the length scale of turbulence increases thereby increasing the fluctuating velocity component (level of fluid turbulence downstream of the constriction) at same operating mean pressure drop. Though, cavitation can be achieved even at higher cavitation numbers, for maximum benefits from the reactor, the flow conditions and the geometry should be adjusted in such a way that the cavitation number lies below 1 but not very low leading to supercavitation resulting into vapor locking and no cavitational collapse.

1.2 Types and “versions”

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

The hydrodynamic cavitation reactors mainly differ in terms of the geometry and type of the constriction used for the generation of cavitation. The various lab scale/pilot plant scale reactors which have been used for the studies for different applications of cavitation process have now been discussed with relative merits and demerits.

1.2.1 Liquid Whistle Reactors:

The first reactor operation on the principle of hydrodynamic cavitation was using a liquid whistle reactor. One of the primitive uses of these types of reactors was mixing and homogenization. Here vibrations are generated in a steel plate as liquid passes over it at high velocity. The liquid couples itself with the vibrations to produce cavitation in the flow which results in highly efficient mixing. There are no moving parts and hence maintenance problems are very low. These reactors also suffer from shortcomings such as very low vibrational power, unavailability of an optimum irradiation frequency in the case of viscous materials and high pumping costs as well as erosion of the vibrating blade in the presence of particulate matters. Also, the reactor configuration does not offer flexibility in terms of selecting different operating geometries for controlling the cavitational intensity in the hydrodynamic cavitation reactor, as maximum effect is obtained at the natural resonating frequency of the vibrating blade.

1.2.2 High pressure homogenizer (HPH)

The high pressure homogenizer is basically a high pressure positive displacement pump with a throttling device which operates according to the principle of high-pressure relief technique. Typically, a High Pressure Homogenizer reactor consists of a feed tank and two throttling valves designated as first stage and second stage**.** The liquid from the feed tank is driven by a pump to the first stage valve. Pressure upto 1000 psi can be attained by throttling this valve. Further increase in the pressure is achieved by using the second stage valve. Upstream pressure upto 10000 psi can be obtained in the second stage. From the second stage valve the liquid is released into a low pressure region with the use of different types of pressure release valves and is then recirculated back to the feed tank. With an increase in the throttling pressure, there is a rise in the temperature of the liquid. To maintain the temperature at ambient conditions, a coil immersed in the feed tank can be used through which cooling water is circulated. There is a critical discharge pressure at which cavitation inception occurs and significant cavitational yields are obtained beyond this discharge pressure. It should be also noted that the value of critical discharge pressure leading to the desired cavitational effect is also dependent on the type of application and the geometry of the throttling valve. HPH are especially suitable for the emulsification processes in Food, Pharmaceutical and Bioprocess industries. Again, there is not enough control over the cavitationally active volume and the magnitude of the pressure pulses which will be generated at the end of the cavitation events (cavitational intensity), as the geometry of the pressure release valve is fixed.

1.2.3 High Speed Homogenizer (HSH)

Cavitation can also be generated in rotating equipments. When the tip speed of the rotating device (impeller) reaches a critical speed, the local pressure near the periphery of the impeller falls and gets closer to the vapor pressure of the liquid. This results in the generation of the vaporous cavities. The original research in hydrodynamic cavitation can be attributed to this effect, namely cavitation occurring on the propellers of the ship and erosion of the propeller blades caused by them (small reverse flows can bring the cavity on the impeller surface causing this erosion). Subsequently, as the liquid moves away from the impeller to the boundary of the tank, the liquid pressure recovers at the expense of the velocity head. This causes the cavities which have travelled with the liquid bulk to collapse. High Speed Homogenizer utilizes the above principle. Similar to High Pressure Homogenizer, there exists a critical speed for the inception of cavitation and significant cavitational effects are observed beyond this critical speed.

It should be noted that the energy consumption in these types of reactors is much higher and also flexibility over the design parameters is hardware dependent as compared to reactors based on the use of multiple plate orifice plates or such similar devices which has been discussed later.

1.2.4 Orifice Plates Setup

In these type of reactors, the flow through the main line passes through a constriction where the local velocities suddenly rise due to the reduction in the flow area resulting into lower pressures which may even go below the vapor pressure of liquid medium generating the cavities. The constriction can be a venturi, a single hole orifice, multiple holes on a orifice plate or a combination of orifice plates arranged in an sequential manner. In general the reactor (Figure 1) will consist of a closed loop circuit comprising of a holding tank, a centrifugal pump, controls valve and flanges to accommodate the cavitation chamber. The suction side of the pump is connected to the bottom of the tank. The discharge from the pump branches into two lines which help in control of the inlet pressure and the inlet flow rate into the main line. Care should be taken that the liquid lines must terminate well inside the tank, below the liquid level in order to avoid any induction of air into the liquid due to plunging liquid jets. The liquid flow at high velocity entering the tank ensures uniform mixing of the tank contents due to the intense circulation currents generated in the tank. The main line consists of a flange to accommodate the orifice plates, along with a hard glass tube next to these plates to make a visual observation easier. The holding tank is provided with cooling jacket to control the temperature of the circulating liquid.

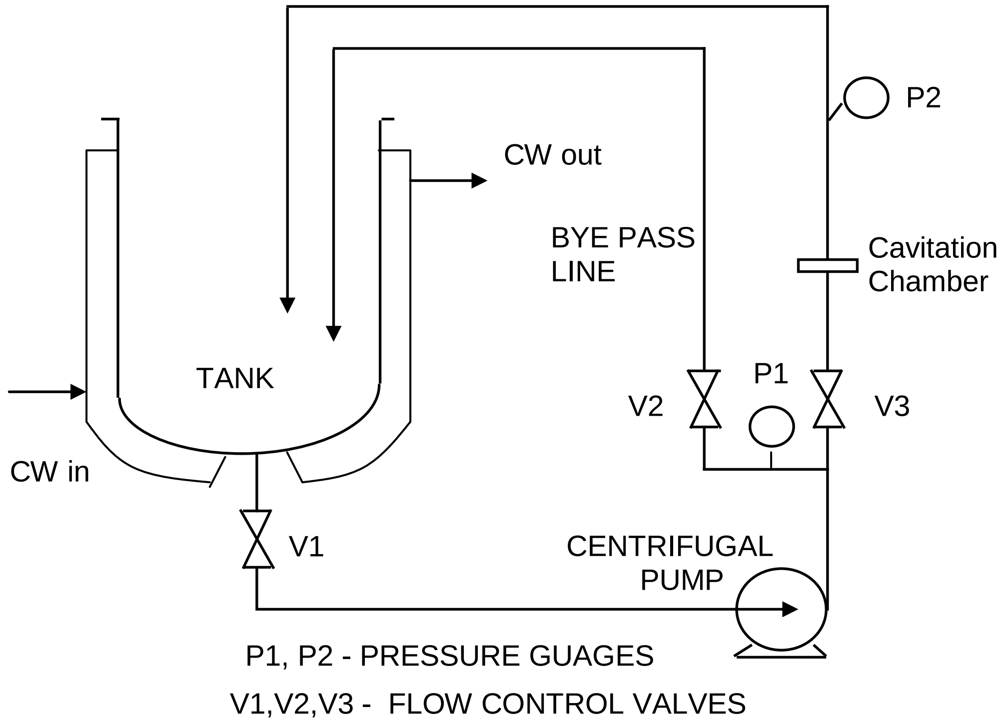

Figure 1: Orifice plate Hydrodynamic Cavitation setup

The design of the cavitation chamber depends on the cavitational intensity required for a specific application under question. Multiple hole orifice plates having different combinations of number and diameter of holes, varying free area offered for the flow can be used as a cavitation chamber**.** Such an arrangement helps in achieving different intensities of cavitation and also the number of cavitational events generated in the reactor is different. Thus, the set-up described above offers tremendous flexibility in terms of the operating (control of the inlet pressure, inlet flow rate, temperature) and geometric conditions (different arrangements of holes on the orifice plates). Thus, depending on the type of application and requirements, geometry and operating conditions can be selected in the hydrodynamic cavitation reactor. For example, cell disruption requires milder cavitational intensity whereas microbial disinfection of mixed culture micro-organisms would require very high cavitation intensities.

Sampathkumar and Moholkar (2007) have recently put forth a conceptual design of a novel hydrodynamic cavitation reactor that uses a converging–diverging nozzle for creating pressure variation in the flow necessary for driving bubble motion instead of the orifice plates as discussed earlier. The cavitation bubbles or nuclei are introduced in the water flow externally, upstream of the nozzle using a sparger. Different gases can be used for introduction of the bubbles. Also, the size of the gas distributor (usually a glass frit), flow rate of gas and the pressure of gas in the reservoir (or source) from which gas is withdrawn can be suitably designed to control the initial size of the cavitational nuclei which significantly affects the resultant cavitational intensity. Aim should be to generate as small size of nuclei as possible to maximize the intensity and hence the net cavitational effects.

From the discussion about various reactors done above, it can be easily concluded that the orifice plate set-up offers maximum flexibility in terms of controlling the cavitational intensity and can be suitably used for large range of applications, requiring different cavitational intensities.

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	50 % to order of magnitude	Cavitational effects can be generated highly energy efficiently as compared to the sonochemical reactors; also in some cases such as cell disruption and synthesis of biodiesel, order of magnitude higher energy savings have been reported as compared to the conventional approaches.
Less CO_2 emission	No data	Generally speaking, hydrodynamic cavitation reactors operate under ambient conditions so thermal/electrical energy input would be minimized resulting into overall less emission of CO_2 though exact quantification is lacking at this stage.
Cost Savings	No direct industrial data as a result of the observed competitive edge of the adaptation of technology. In some specific cases such as synthesis of biodiesel or other esters of fatty acids, one to two order of magnitude reductions in the processing costs have been observed.	The cost savings result out of the following advantages: 1. Faster processes leading to several fold reduction in the batch times 2. Higher product yield and selectivity 3. Higher activity of the catalyst as well as reduced effects of catalyst fouling 4. Use of ambient conditions as against requirement of high temperatures and pressures in conventional approaches
Increased yield/ selectivity	50 to 400%	As a result of the extremely short time scales (micro to nano) of severe conditions, side reactions are restricted. Also due to generation of free radicals, selective distribution of products can be achieved.

Increased Safety	Yes particularly due to the requirement of less severe overall operating conditions.	Safer operating conditions (no heating) and use of toxic chemicals and/or solvents can be avoided in some cases.
Defouling	No data available	Self cleaning system due to cavitational surface cleaning. In fact hydrodynamic cavitation reactors can be suitably used for treatment of biofouling in cooling towers
Reaction medium (solvent)/ catalyst savings	More than 100%	Prevention of catalyst deactivation due to surface cleaning, increased reactant transport due to shock waves and liquid jets reducing the diffusional resistances
Better Quality product	No data available on an industrial scale of operation due to competitive edge and secrecy issues	Due to increased selectivity and removal of trace impurities, tremendous benefits to the chemical processing industries. Use of free radical mechanism sometimes leads to selective product distribution (desired)

1.4 Stage of development

Hydrodynamic cavitation is generally observed to produce less intense cavitation especially as compared to the sonochemical reactors and hence the applicability of these reactors is limited. There is a good theoretical understanding of the parameters, responsible for controlling the dynamics of the cavity and hence its resultant effects. However, experimental design and efficient operation for variety of applications is still lacking. Also the technology as such has not been tested for chemical and physical processing applications especially the chemical synthesis. The only synthesis operation which has been sort of well established at industrial scale operation has been observed to be the synthesis of biodiesel and the efficacy of the process is order of magnitude higher as compared to the conventional approaches.

There is still no well defined scale up criteria for hydrodynamic cavitation reactors though some guidelines are available on the basis of gross parameters such as operating cavitation number, geometric similarity of the cavitation chamber etc. If the application under question is requiring lower intensity of cavitation such as microbial disinfection, cell disruption etc. or physical processes such as emulsification, homogenization etc., then the gross scale up criteria and generated cavitational intensities have been found to be adequate; however for organic synthesis or wastewater treatment applications, considerable work, which is system specific is required for this technology to get accepted in specialty chemical industry.

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)

In applications such as chemical synthesis, extraction, homogenization etc. where hydrodynamic cavitation reactors can give significant degree of process intensification, conventionally, multiphase reactors mainly mechanically agitated contactors are used with facility of heating/cooling jackets and/or coils depending on the process conditions and various heat transfer media such as steam or mineral oils are applied. Continuous processes are usually carried out in stirred-tank reactors in-series or in tubular flow reactors. For wastewater treatment applications generally biological oxidation is used which requires comparatively much longer treatment times.

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)

Use of hydrodynamic cavitation as a process intensification technology has been only a recent innovation and due to secrecy issues, actual plant data is not readily available. Table 2 presents some of the gross data with which our group was associated in the development process.

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
Consumer Products	Godrej Industries Ltd., India	Esterification and Trans-esterification reactions for synthesis of fatty acid esters (biodiesel and bio lubricants)	500 Tons per year	2005	Intensification of synthesis process, Similar effects with waste fatty acids which significantly reduces the cost of operation
Consumer Products / Specialty chemicals	Snow Tech Process Equipments Ltd., India	Esterification and Trans-esterification reactions, Synthesis of Medium Chain Triglycerides (MCT) and C_6 – C_{10} fatty acid methyl esters	1000 L capacity reactor	2006	Intensification of synthesis process and better energy efficiencies as compared to conventional approaches
Large Volume chemicals	Royal Energy	Synthesis of biodiesel	10,000 Tons per year	2007	Intensification of synthesis process

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

Industrial Wastewater treatment	DynaFlow Inc. Maryland, USA	Degradation of p-nitrophenol	1998	Cavitating jets are able to degrade the pollutant and the efficacy is order of magnitude more as compared to sonochemical reactors.
Biotechnology	UICT, India	Cell disruption for release of intracellular enzymes	2000	Highly energy efficient as compared to the conventional technologies but main problem in industrial scale operation exists in terms of non-suitability for high cell concentrations
All sectors	Alcoa, USA	Industrial cooling water treatment	2001 onwards	Use of hydrodynamic cavitation to successfully control scaling, corrosion, and microbiological growth in recirculating cooling water systems
Biotechnology	UCT, South Africa	Cell disruption of Brewer's Yeast; E-coli for release of intracellular enzymes	2005	Highly energy efficient as compared to the conventional technologies for release of intracellular enzymes such as β-galactosidase, acid phosphatase etc.
All sectors	Hyca Technologies, India	Prevention of Biofouling in the cooling towers	2006	Hydrodynamic cavitation can be effectively used for disinfection of micro-organisms mainly responsible for the accumulation of scales
Specialty chemicals	UICT, India	Preparation of nano-suspensions of rubber latex material	2007	Hydrodynamic cavitation reactors with multiple passes can be effectively used for size reduction and it is possible to generate nano-suspensions
All sectors	VRTX Technologies, USA	Industrial cooling water treatment	NA	Hydrodynamic cavitation can effectively treat the cooling water by disinfecting the micro-organisms. Number of case studies also provided
Shipping Industry	Hyca Technologies, India	Ballast Water Treatment	2007	Installation of hydrodynamic cavitation reactors on board for treatment of ballast water before being discharged into sea

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)

Hydrodynamic cavitation is mainly useful in chemical processing applications very similar to the sonochemical reactors and in general can be used for intensification of chemical synthesis operations. Hydrodynamic cavitation also enables processing under ambient conditions thus using less forcing conditions (temperature and pressure) as compared to the conventional routes. Hydrodynamic cavitation has been reported beneficial for hydrolysis reactions, esterification or trans-esterification reactions, polymerization/depolymerization reactions, oxidation reactions etc. Apart from chemical synthesis operations, hydrodynamic cavitation has been found to be useful in wastewater treatment applications such as destruction of p-nitrophenol, formic acid, phenolic compounds, decolorization of wastewater etc. Combination of photocatalytic oxidation or Fenton chemistry increases the utility/applicability of hydrodynamic cavitation reactors for wastewater treatment and chemicals such as pentachlorophenol (PCP), benzene, toluene, ethyl benzene, xylenes, cyanide, phenol, atrazine have been successfully degraded.

Cell disruption for selective release of the intracellular enzymes is another important application of hydrodynamic cavitation discussed in the literature. Hydrodynamic cavitation can be effectively used without any loss in the enzyme activity and that too at energy consumption levels substantially lower as compared to the sonochemical reactors and conventional techniques such as mixer-blender.

The beneficial effects of hydrodynamic cavitation have also been observed in the manufacture of paper from synthetic fibers, in intensification of pulp bleaching, preparation of highly-disperse sizes, treatment of suspensions of the fibrous materials, wastepaper deinking, improvement in flotation performance and synthesis of nanocrystalline materials. Use of hydrodynamic cavitation have also been demonstrated for obtaining free disperse system in liquids, particularly in liquid hydrocarbons as well as in production of liquid emulsion systems or suspensions.

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?
Engineering Design and Scale-up issues	There is still no well defined scale up criteria for hydrodynamic cavitation reactors though some guidelines are available on the basis of gross parameters such as operating cavitation number, geometric similarity of the cavitation chamber etc. Also there are no well established and generalized design guidelines for selection of geometric and operating parameters. It is the need of the hour that for a variety of applications, optimization should be carried out and some generalized guidelines for design and scale up be established.	R&D projects carried out at the Universities in collaboration with equipment manufactures and producers of large size hydrodynamic cavitation reactors.

Modeling and Scale-up Methodologies	Modeling of turbulence conditions downstream of the cavitation chamber and its effect on the bubble dynamics of cavitation phenomena is required. Dependency of the cavitational intensity on the geometric design needs to be well established with an aim of achieving optimized design. Use of recent advances in the modeling such as Computational Fluid Dynamics will lead to a better understanding of the cavitational effects. The next stage of modeling efforts is to link the observed cavitational effects with the theoretical predictions of bubble dynamics with the help of knowledge of chemical reactions occurring inside the bubble. Though, researchers have individually worked on each of the above aspects, a comprehensive modeling strategy is just evolving, which also needs to be validated using experiments over a wide range of applications.	The solution to this issue is only through the collaborative efforts of physicists, chemists, chemical engineers and the equipment manufactures. This can be done through "mission oriented projects" involving all the above mentioned departments of the University simultaneously
Applicability	Hydrodynamic cavitation is generally observed to produce less intense cavitation especially as compared to the sonochemical reactors and hence the applicability of these reactors is limited. Also, the technology as such has not been tested for a variety of chemical and physical processing applications especially the chemical synthesis. It is also required that means of intensification of the cavitational activity in the reactors should be developed involving higher and faster pressure recovery rates, making cavitational collapse more violent and intense, nearing acoustic cavitation. Some of these can be using a combination of hydrodynamic cavitation with sonochemical reactors or advanced oxidation processes.	R&D projects carried out at the Universities in collaboration with equipment manufactures and producers of large size hydrodynamic cavitation reactors.
Control Systems	The control of the hydrodynamic cavitation reactors requires the manipulation of the pressure field downstream of the cavitation chamber, which currently is being done by controlling the inlet pressure or the flow rate only on the basis of the feedback pressure signal. Reproducibility of the cavitational conditions in the reactor is also an undefined parameter; it is needed to map the cavitational activity using mean and fluctuating pressure measurements (use of hydrophones) and flow measuring devices (LDA, HWA etc.) and evolve a well defined approach for control of the hydrodynamic cavitation reactors.	R&D projects carried at the universities, in collaboration with 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?**

Lower cavitational intensity restricting the applicability	It is needed to investigate the use of intensifying parameters such as gases, solid particles and also combination of hydrodynamic cavitation with other processes such as sonication or UV irradiations for a variety of applications. Significant synergism can be obtained by the combined use of these processes especially where the controlling mechanism such as free radical oxidation is similar.	R&D projects carried at the universities, in collaboration with equipment manufacturers
Optimization protocol and design methodology	Generalized rules for optimization of operating and geometric parameters have not been yet established which also restricts the efficient design of large scale reactors. It is needed to do experiments at laboratory/pilot scale for each specific application which sometimes is time consuming and also expensive. It is required to have a perfect blend of theoretical understanding and experimental verifications for developing generalized recommendations for selection and design of hydrodynamic reactor configuration.	R&D projects carried at the universities, in collaboration with equipment manufacturers
Control	Remote control instrumentation system for large scale plant in assessing and controlling the uniformity of cavitational activity downstream of the cavitation chamber are required. Control logic, on-line control strategies are to be evolved.	R&D projects carried at the universities, in collaboration with equipment manufacturers

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
Hydrolysis of fatty oils: effect of cavitation, Pandit, A.B., Joshi, J.B., 1993, Chemical Engineering Science, 48 (19), pp. 3440-3442	Research paper	First published paper showing the beneficial use of hydrodynamic cavitation
Chemistry induced by hydrodynamic cavitation, Suslick, K.S., Mdleleni, M.M., Ries, J.T. 1997 *Journal of the American Chemical Society* 119 (39), pp. 9303-9304	Research paper	First paper showing the evidence of generation of hydroxyl radicals in hydrodynamic cavitation reactors
Optimization of hydrodynamic cavitation using a model reaction, Vichare, N.P., Gogate, P.R., Pandit, A.B. 2000 *Chemical Engineering and Technology* 23 (8), pp. 683-690	Research paper	Optimization of operating parameters for a orifice plate hydrodynamic cavitation
Hydrodynamic cavitation reactors: A state of the art review, Gogate, P.R., Pandit, A.B., 2001, *Reviews in Chemical Engineering,* 17 (1), pp. 1-85	Review	Covers overview of basic aspects including reactor configurations as well as detailed literature on applications

Hybrid cavitation methods for water disinfection: Simultaneous use of chemicals with cavitation, Jyoti, K.K., Pandit, A.B. 2003 *Ultrasonics Sonochemistry* 10 (4-5), pp. 255-264	Research paper	Combination of hydrodynamic cavitation with chemical disinfection techniques
A review and assessment of hydrodynamic cavitation as a technology for the future, Gogate, P.R., Pandit, A.B., 2006, *Ultrasonics Sonochemistry* 12 (1-2 SPEC. ISS.), pp. 21-27	Review	Useful information on theoretical analysis and process intensification of chemical synthesis operations
Numerical investigation into the chemistry induced by hydrodynamic cavitation, Krishnan, J.S., Dwivedi, P., Moholkar, V.S. 2006 *Industrial and Engineering Chemistry Research* 45 (4), pp. 1493-1504	Research paper	Theoretical aspects covering effect of operating parameters on cavitational intensity
A modified advanced Fenton process for industrial wastewater treatment, Chakinala, A.G., Bremner, D.H., Burgess, A.E., Namkung, K.C. 2007 *Water Science and Technology* 55 (12), pp. 59-65	Research paper	Combination of hydrodynamic cavitation with advanced Fenton processing

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
United States Patent 6,012,492 Method and apparatus for conducting sonochemical reactions and processes using hydrodynamic cavitation	Kozyuk O. V.	-
United States Patent 6,200,486 Fluid jet cavitation method and system for efficient decontamination of liquids	Chahine, G.L., Kalumuck, K.M.	-
United States Patent 6,502,979 Device and method for creating hydrodynamic cavitation in fluids	Kozyuk O. V.	-
United States Patent 6,221,260 Swirling fluid jet cavitation method and system for efficient decontamination of liquids	Chahine, G.L., Kalumuck, K.M.	-
United States Patent Application 2006/0118034 Hydrodynamic cavitation crystallization device and process	Kozyuk O. V.	Intensification of crystallization operation
United States Patent 6,869,586 Method of preparing metal containing compounds using hydrodynamic cavitation	Moser, W.R., Kozyuk O. V., Find, J., Emerson, S.C., Krausz, I.M.	Deals with nanostructured materials
United States Patent 5,860,942 Dental water irrigator employing hydrodynamic cavitation	Cox, D.W.	Application in Dental Science, Hand held device

WO9609112, Device for Generating Liquid Systems, in particular Emulsions, Suspensions or the Like, in a Hydrodynamic Cavitation Field	Kravets Boris K	-
WO2005108301 Ballast water system	Baerheim Gunnar; Foss Stein; Varenhed Kjell; Andersen Aage Bjoern	Application of cavitation for ballast water treatment
WO2007054956 and United States Patent Application 2007/0102371 An Apparatus for Disinfection of Sea Water / Ship's Ballast Water and a Method Thereof	A.C. Anil, S.S. Sawant, D. Ilangovan, R. Madhan, K.P. Venkat, A.B. Pandit, V.V. Ranade	Application of cavitation for ballast water treatment

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
Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT) and University of Zaragoza (S. Arroja, Y. Benito, C. Nerin)	Spain	Working on theoretical analysis and wastewater treatment applications
Indian Institute of Technology, Guwahati (V.S. Moholkar)	India	Working on theoretical analysis and wastewater treatment applications
Institute of Chemical Technology, University of Mumbai (A.B. Pandit, P.R. Gogate)	India	Working on theoretical analysis and applications including chemical synthesis, nanotechnology, leaching and wastewater treatment
University of Abertay Dundee (D.H. Bremner)	Scotland, UK	Working on experimental studies related wastewater treatment applications; a novel combination with advanced Fenton oxidation for process intensification
Zhejiang University of Technology (Z. Xu)	China	Some recent work on synthesis of biodiesel using hydrodynamic cavitation
University of Capetown (S.T.L. Harrison)	South Africa	Working on experimental studies on cell disruption for release of intracellular enzymes
Friedrich-Schiller-Universitat, Jena (B. Ondruschka)	Germany	Recent work on wastewater treatment applications using hydrodynamic cavitation

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
Hyca Technologies	India	Hydrodynamic cavitation reactors for chemical processing, ballast water treatment, prevention of bio-fouling
Five Star Technologies	USA	Reactors mainly for dispersions (Specialty inks, metal oxides, carbon nano fiber dispersions etc.)
Magnum Water Technologies	USA	Hydrodynamic cavitation in combination with AOP for wastewater treatment
Sonic Mixing	USA	Sonolator, which is similar to hydrodynamic cavitation reactor, for emulsion, blending and mixing
Hydro Dynamics Inc.	USA	Shock wave Power technology for synthesis of biodiesel, mixing operations, polymer synthesis, food processing industries etc.
HydroDynamic Technology Inc. and BioFuel Canada Ltd	Canada	Products for synthesis of biodiesel, petroleum refining intensification, fuel oil processing and pounding of grains in ethanol plants
BiodieselMach Ltd.	Ukraine	Products for synthesis of biodiesel using a 2 stage hydrodynamic compounder technology
VRTX Technologies	USA	Use of hydrodynamic cavitation for industrial cooling water treatment
Alcoa	USA	Use of hydrodynamic cavitation for industrial cooling water treatment

5.2 End users

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

Chemical Processing Industries: For intensification of chemical processing applications by way of either using hydrodynamic cavitation in a supplementary role (e.g. increased rates of mass transfers and/or mixing) or by complete replacement of the existing technologies (e.g. synthesis of biodiesel). Also there exists a possible use in avoiding bio-fouling which severely dampens the performance of the cooling towers.

Food Processing Industries: For homogenization, emulsification, mixing, aeration and scale free heating. Some of the specific target users can be those dealing with Production of Jellies, banana slurries, mixing and heating spices, and pasteurization of fruit juices.

Environmental Protection: For wastewater and water treatment mostly in combination with the existing Advanced Oxidation Processes or biological oxidation

Ballast Water treatment: Hydrodynamic Cavitation reactors also find utility in a ship to treat ship's ballast water that is being transported from one region to another. Translocation of organisms through ships (bio-invasion) is considered to be one of the important issues that threaten the naturally evolved biodiversity, the consequences of which are being realized increasingly in the recent years. Although many treatment technologies such as self-cleaning screen filtration systems, ozonation, de-oxygenation, electro-ionization, gas supersaturation, chemical treatments are adopted, they cannot limit the environmentally hazardous effects that may result from such practices. Hydrodynamic cavitation has been reported to be an effective technology for ballast water treatment and the design methodology for incorporation of cavitational reactors in actual ships needs to be worked out.

6. Expert's brief final judgment on the technology

(maximum 5 sentences)

Hydrodynamic cavitation technology has come of age from initial skepticism in the early to mid nineties to a well accepted fact that it can bring about intensification of processes such as emulsification, micro and nano suspensions, cell disruption, water disinfection through pathogen destruction etc., through the physical and mechanical effects of the cavitation phenomena. Hydrodynamic cavitation is a better choice as compared to the sonochemical reactors due to the fact that high velocity returning fluid jet can be used also for bringing out spatial uniformity due to the fluid mixing. The energy efficiencies of hydrodynamically cavitating reactors for their physicomechanical cavitational effects are found to be substantially higher. Newer designs of hydrodynamic cavitating chambers are being patented quite regularly, showing the renewed interest of the research community. However, for cavitationally induced chemical transformations, significant more work is required. Even though the laboratory scale studies have established the proof of concept in the utility of hydrodynamic cavitation for chemical transformations, large scale studies (due to large costs of the needed chemicals) are missing and area required before hydrodynamic cavitation gets accepted as a technique of intensification even for chemical transformations.