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# High-power ultrasonic processing: recent developments and prospective advances

Juan A. Gallego-Juarez *

*Instituto de Acústica, CSIC, Serrano,144, 28006 Madrid, Spain, jgallego@ia.cetef.csic.es*

**Abstract**

Although the application of ultrasonic energy to produce or to enhance a wide variety of processes have been explored since about the middle of the 20th century, only a reduced number of ultrasonic processes have been established at industrial level. However, during the last ten years the interest in ultrasonic processing has revived particularly in industrial sectors where the ultrasonic technology may represent a clean and efficient tool to improve classical existing processes or an innovation alternative for the development of new processes. Such seems to be the case of relevant sectors such as food industry, environment, pharmaceuticals and chemicals manufacture, machinery, mining, etc where power ultrasound is becoming an emerging technology for process development.
The possible major problem in the application of high-intensity ultrasound on industrial processing is the design and development of efficient power ultrasonic systems (generators and reactors) capable of large scale successful operation specifically adapted to each individual process.
In the area of ultrasonic processing in fluid media and more specifically in gases, the development of the stepped-plate transducers and other power generators with extensive radiating surface has strongly contributed to the implementation at semi-industrial and industrial stage of several commercial applications, in sectors such as food and beverage industry (defoaming, drying, extraction, etc), environment (air cleaning, sludge filtration, etc...), machinery and process for manufacturing (textile washing, paint manufacture, etc).
The development of different cavitational reactors for liquid treatment in continuous flow is helping to introduce into industry the wide potential of the area of sonochemistry. Processes such as water and effluent treatment, crystallization, soil remediation, etc have been already implemented at semi-industrial and/or industrial stage.
Other single advances in sectors like mining or energy have also to be mentioned.
The objective of this paper is to review some recent developments in ultrasonic processing to show the present situation and the prospective progresses of high-power ultrasonics as an innovative technology in many industrial sectors.

Keywords: High-Power Ultrasound, Ultrasonic processing.

* Corresponding author. Tel.: +33-915618806; fax: +33-914117651
*E-mail address*: jgallego@ia.cetef.csic.es

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## 1. Introduction

The development of new emerging technologies in different fields is at present one of the main challenges for the improvement of the quality of life in the world. Obviously, they have to be environment friendly and energy saving technologies to assure sustainability. High-power ultrasound can be considered as one of these technologies. In fact, its use for medical therapeutic purposes is a so rapidly developing area that it is regarded as a "boom". The application of ultrasonic energy to produce or to enhance industrial processes is also an emerging area that should be included within the "ultrasonic boom".

The industrial use of the ultrasonic energy has been explored since the middle of the 20$^{th}$ century, but only a few number of applications have been so far commercially introduced. However during the last ten or fifteen years a renewed interest for ultrasonic processing has appeared, particularly in those sectors where the ultrasonic energy may represent a clean and efficient tool for enhancing or producing effects. Such seems to be the case of relevant sectors such as food industry, environment, pharmaceuticals and chemicals manufacture, machinery, etc where power ultrasound is becoming an emergent technology for process development.

The potential of power ultrasound involves physical and chemical processes. Physical processes are mainly ascribed to mechanical effects of the high-intensity waves in any medium while chemical processes refer to chemical effects induced by ultrasonic cavitation in liquids. The latter processes are included in the term of sonochemistry. The general term for the whole area is sonoprocessing or ultrasonic processing

The possible major problem in the application of high-intensity ultrasound to industrial processing is the design and development of efficient power ultrasonic systems (generators and reactors) capable of large scale successful operation specifically adapted to each individual process.

In the area of ultrasonic processing in fluid media and more specifically in gases, the development of the family of power generators with extensive radiators has strongly contributed to the implementation at semi-industrial and industrial stage of several commercial applications, in sectors such as food industry, environment, process for manufacturing, etc. On the other hand, the development of cavitational reactors for liquid treatment in continuous flow is helping to introduce into industry the wide potential of the area of sonochemistry.

This paper deals with a review of some recent developments in ultrasonic processing to show the present situation and the progress potential of high-power ultrasonics as an innovative technology in several industrial sectors.

## 2. High-Power ultrasonic Generators: Recent advances

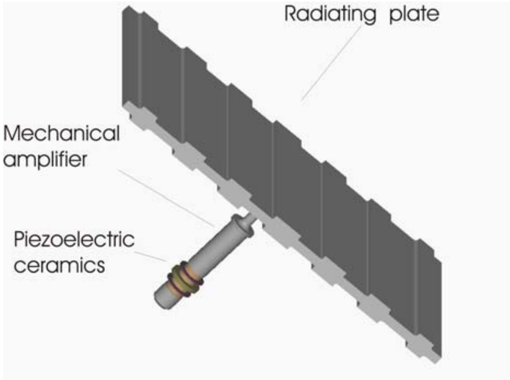
The basic piece of an ultrasound equipment is the generator. The ultrasonic generator is constituted by the electronic system and the electroacoustic transducer.

For the generation and application of high-intensity ultrasound to fluid or multiphase media special high power transducers are needed covering adequate requirements. The fluid media (specially the gases) present a low specific acoustic impedance and a high acoustic absorption. Therefore, in order to obtain an efficient transmission of energy, it is necessary to achieve a good impedance matching between the transducer and the medium, large amplitude of vibration and high-directional or focused beams for energy concentration. In addition, for large-scale industrial applications, high power capacity and extensive radiating area would be required in the transducers.

Trying to achieve such objectives, a new family of transducers which implement high-power capacity, efficiency and directivity control has been developed. This is the family of extensive radiating surface transducers which comprises several versions depending on the shape and/or the profile of the radiator. The main types of such transducers are: the stepped-plate, the grooved-plate, the stepped-grooved-plate and the cylindrical radiator.

The basic structure of such transducers is schematically shown in Figure 1. It consists essentially of a piezoelectrically activated vibrator which drives an extensive area radiator. The vibrator itself is constituted by a piezoelectric element of transduction in a sandwich configuration and a solid horn which acts as a vibration amplifier. The radiator is generally a vibrating plate of stepped, grooved or stepped-grooved profile. For special applications, the radiator can be a vibrating cylinder (Fig. 2). The extensional vibration generated by the transducer element and amplified by the mechanical amplifier, drives the radiator which vibrates flexurally in one of its axisymmetric modes. The extensive surface area of the radiator increases the radiation resistance and offers the vibrating system good impedance matching with the medium. In addition, the special shape and profile of the radiator permits the control of the vibration distribution and the radiation pattern in such a way that high directional, focusing, cylindrical or other kind of radiation can be obtained in order to produce high-intensity acoustic levels in the working area.

In the case of the stepped-plate radiators, the idea behind the design is to control the phase distribution to obtain piston-like directivity. The grooved-plate radiators are designed to obtain focusing beams). The stepped-grooved-plate radiators incorporate at the same time directional or focusing radiation together with a more homogeneous distribution of the vibration amplitude.



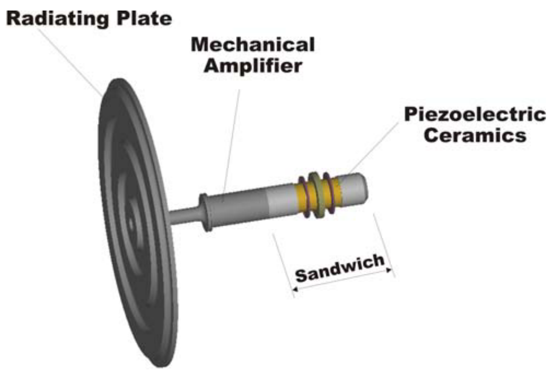




Fig. 1: Basic structure of the stepped plate and stepped-grooved plate transducers.

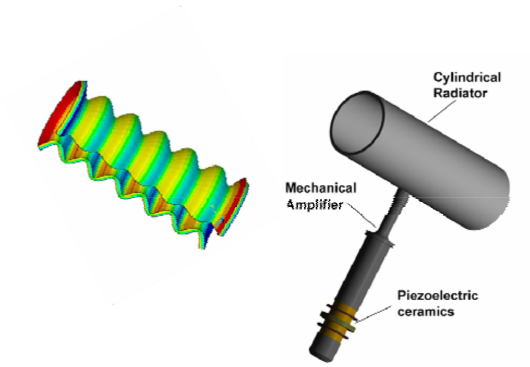



Fig. 2: Schematic of the Transducer with cylindrical radiator. FEM simulation of the cylinder vibration.

As well known, the flat-plate radiators have a poor directivity but are simpler in the design and construction. In addition, such radiators may be complemented with a system of waveguides to control the directivity of the radiation. In fact, the radiation of each internodal sector may be separated and conducted by means of parallel walls which are perpendicular to the plate surface and located on the nodal lines without touching the plate. In such a way the radiation generated by the flexural vibrating plate may be conducted to emerge all in phase on a perpendicular plane to the plate [1]

All these radiators may be done in circular, rectangular or any other shape.

For the radiation of high-intensity ultrasound into a fluidized bed flexional cylindrical radiators have been designed and constructed.

For sonochemical processing it is to be mentioned that a considerable progress has been made in recent years in the design and development of flow reactors for the production of cavitation at industrial scale. Devices as those developed by Accentus [2], Sonertec [3] and others have shown to be capable of providing high intensity insonation to the flowing liquid at large scale.

## 3. Ultrasonic Processing in the Food Industry

The application of power ultrasound to food processing technology is one of the most promising fields for the future progress of ultrasound. The clean action of ultrasonic energy as a mechanical non-contaminant non-ionizing radiation plays a determinant role in the continuous search for finding safer and higher quality production methods.

Within the broad range of potential uses of power ultrasound in food processing only very few processes have been already established at industrial level. To be mentioned some extraction processes and the extension of ultrasonic emulsification and homogeneization from cosmetics and pharmaceutical industries to the production of fruit and vegetable juices [4]. However some new processes in which we are directly involved have been scaled up and presently are very close to their commercial development. Such are the cases of defoaming, drying and supercritical fluid extraction processes.

### *3.1. Defoaming [5]*

Foam is a dispersion of gas in a liquid in which the distances between the gas bubbles are very small. Foam is frequently produced in the manufacture of many food products as result from the aeration and agitation of liquids, from the vaporization of the liquid and also from biological or chemical reactions. Foam is generally an unwanted by-product in industrial processes because they cause difficulties in process control and in equipment operation. A typical example is in the fermentation industry where foam represents one of the biggest problems**.** There are several methods to control foams, the most efficient is the use of chemical anti-foaming agents but they contaminate the product. Other methods involving mechanical, thermal or electrical devices are not very effective. High-intensity ultrasonic waves represent a clean and efficient procedure to break foam bubbles. The potential use of ultrasound for foam breaking was first introduced by using acoustic defoamers based on aerodynamic acoustic sources. However such devices presented many inconveniences as the need for high air generation capacity, control and sterilization of the air-flow and they often involve high energy consumption.

A new concept of a high-intensity ultrasonic defoamer is based on the use of the stepped-grooved-plate high-power transducer for air-borne focusing ultrasound. This system has been successfully tested for the control of excess foam produced in fermenting vessels (Fig 3) and in other reactors of great dimensions as well as on high-speed canning and bottling lines during the filling operation. Ultrasonic defoaming systems for frequencies of 21, 26 and 40 kHz to be used statically or dynamically by means of rotational or scanning devices are presently manufactured by a specialised Spanish company PUSONICS and worldwide commercialized.

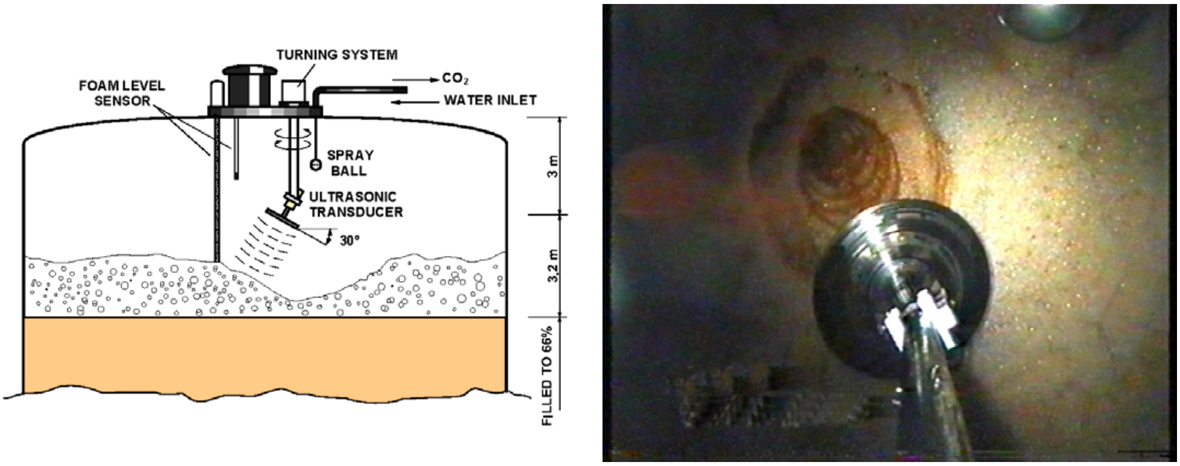



**Fig. 3**: Ultrasonic Defoaming

*3.2. Drying [6]*

An important process in food industry is drying or dehydration. Dehydration is a method for preserving food. For food dehydration the two main conventional procedures are hot-air drying and freeze-drying. Hot air drying is a widely used method but it can produce deteriorative changes in the food. Instead, in freeze-drying, where food pieces are first frozen and then sublimates, the product quality is maintained but the process is expensive.

High intensity ultrasonic waves can be used for the dehydration of food materials. The application of air-borne ultrasonic energy for drying materials has been explored for several decades. Nevertheless, few air-borne ultrasonic dryers were reported in the technical literature and apparently none of them was commercially used The main difficulties come from the efficient generation of ultrasonic energy in air and the transfer of such ultrasonic energy from air into the product due to the acoustic impedance mismatch.

On the basis of the new family of power ultrasonic generators, a new technology for food dehydration has been developed by using two experimental procedures: forced-air drying assisted by air-borne ultrasound and ultrasonic dehydration by applying ultrasound in direct contact with the material.

The drying procedure by air-borne ultrasound together with forced-air has been developed in two different techniques: a) by applying the stepped-plate ultrasonic generator, as air-borne radiator, in combination with forced air, and b) by applying the cylindrical-radiator transducer as a fluidized bed dryer.

The system was designed and constructed for the application of the stepped-plate generator in combination with forced air. It mainly consists of a hot- air generator, a stepped-plate power ultrasonic transducer for 20 kHz with the corresponding electronic generator and a flat plate parallel to the ultrasonic radiator, acting as a reflector for the formation of a standing wave and also as sample holder. The effect of the ultrasonic radiation is significant at low air temperature and diminishes when temperature increases. In general, it can be stated that the application of air-borne ultrasound is useful in increasing the efficiency of forced-air drying processes but this improvement seems to be relatively limited and it could be restricted to specific products such as heat-sensitive materials and/or to special applications where rapid drying at low temperature is required.


**Fig. 4**: Dehydration system.

The application of the cylindrical-radiator transducer as a fluidized bed dryer showed a similar effect but the ultrasonic radiation was effective only with air flow velocities up to about 2-4 m/s.

The procedure of ultrasonic dehydration by applying high-intensity ultrasonic vibration in direct contact with the food material aims at increasing the effectiveness of energy transfer [**7**]. The type of generator used is the flat-plate transducer or the grooved-plate transducer of rectangular shape (Fig 4). The good acoustic impedance matching between the vibrating plate of the transducer and the food material favours the deep penetration of acoustic energy. In this process the inside of the food material is subjected to high ultrasonic stresses which, due to the rapid series of contractions and expansions, produce a kind of "sponge effect" and the quick migration of moisture through natural channels or other channels created by the wave propagation which result in moisture release from the product. In addition, the production of ultrasonic cavitation inside the liquid may help to the separation of the moisture strongly attached. As an example of the application of this procedure figure 5 shows the kinetics of the dehydration process of different carrot samples by applying 100 W acoustic power.

The new experimental systems designed and developed for the different drying procedures constitute the basic models to be scaled up for industrial applications.

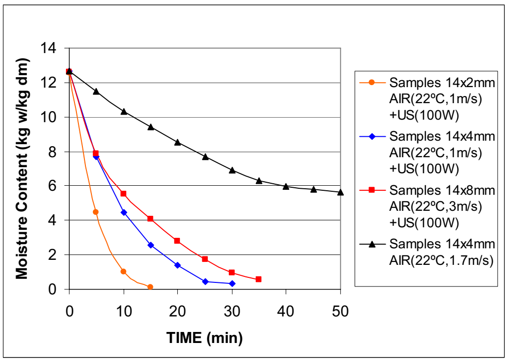



**Fig. 5**: Kinetics of the dehydration process of different carrot samples.

*3.3. Supercritical fluid extraction (SFE) [8]*

The use of supercritical fluids as extracting agents has been attracting wide interest for years and, in particular, supercritical carbon dioxide is considered nowadays as a very useful solvent in the extraction process because it is non-toxic, recyclable, cheap, relatively inert, and non-flammable [9], [10]. Nevertheless, fixed bed SFE of the extractable compound from solid matrix has a slow dynamics even when solute free solvent is re-circulated. The use of power ultrasound represents a potential efficient way for enhancing mass transfer processes. In addition, this is probably the only practical way to produce agitation in SFE because of the inability of using mechanical stirrers.

The application of ultrasound in SFE proposes both kinetics acceleration and yield improvement. A process on oil extraction from grounded almonds (55% oil content, wet basis) of different particle sizes (3-4 and 9-10mm) by using supercritical $CO_2$ and 20 kHz power ultrasound in a pilot plant of SFE constituted by four stainless steel high-pressure extraction vessels 5 litres in capacity show that the kinetics and the extraction yield were enhanced by 30% and 20% respectively (Figure 6). Important efforts are presently carried out [11] for the development of a pilot plant at semi-industrial level assisted by power ultrasound.

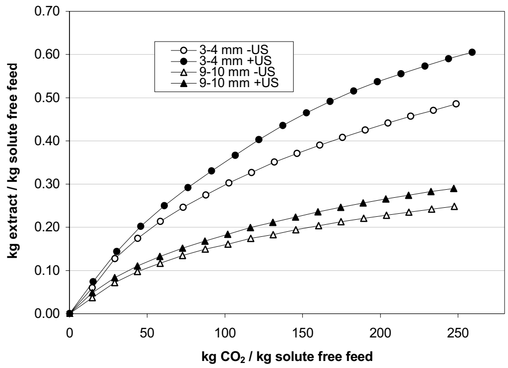



**Fig. 6**: Almond oil extraction kinetics using supercritical $CO_2$ with and without ultrasound. Particulate material of different sizes.

## 4. HIGH-POWER ULTRASOUND IN ENVIRONMENTAL PROCESSES

High-power ultrasound is a technology that offers several important possibilities to act as an efficient tool in processes for preventing or removing pollution. Applications in air cleaning, water purification, treatment of sludges, soil remediation and new sonochemical "green" processes, without hazardous substances, have strongly increased over the last few years. We will refer in this presentation to air cleaning and sludge filtration, two processes in which we have been actively involved.

*4.1. Air cleaning: fine particle removal [12].*

The presence of suspended airborne particles (specially very fine particles) in the environment, is generally undesirable and dangerous. In fact such tiny particles constitute a major health hazard because their ability to penetrate deeply in the respiratory tissues and their long stay in suspension. Therefore it is necessary to deal with them by precipitation of the disperse phase. Particle agglomeration by acoustic vibrations might have an important role to play in cutting down the concentration of solid and liquid particles in airborne powders, smokes, mists and exhaust gases in general.

Acoustic agglomeration and precipitation processes are governed by complex mechanisms of interaction that usually appear to be combined.

The majority of the experiments on the agglomeration and precipitation of airborne particles have been mainly focussed on the potential development of industrial systems. This is because of the interest in the control of environmental pollution. However the development of this process into an industrial application has been slow probably because of the lack of suitable full-scale agglomeration chambers. A great advance has been made with the development of the stepped-plate and the stepped-grooved-plate power generators which are able to create high-intensity acoustic fields adapted to any specific geometry of the agglomeration and precipitation chamber [13]. Such a system can be applied to any industrial process where control and precipitation of fine particles is required.

In one configuration stepped-plate generators operating at 20 and 10 kHz are placed in one of the walls of a parallelepipedic chamber designed to optimize the spatial homogeneity and intensity of the acoustic field distribution (Fig 7). The chamber dimensions are determined from the residence time requirements and the given flow rate of the gas or the aerosol to be treated which is passing axially through the chamber. The two different frequencies along the path of the aerosol represent an important feature because the frequency of the sound field is linked to the particle size which changes during the agglomeration process.

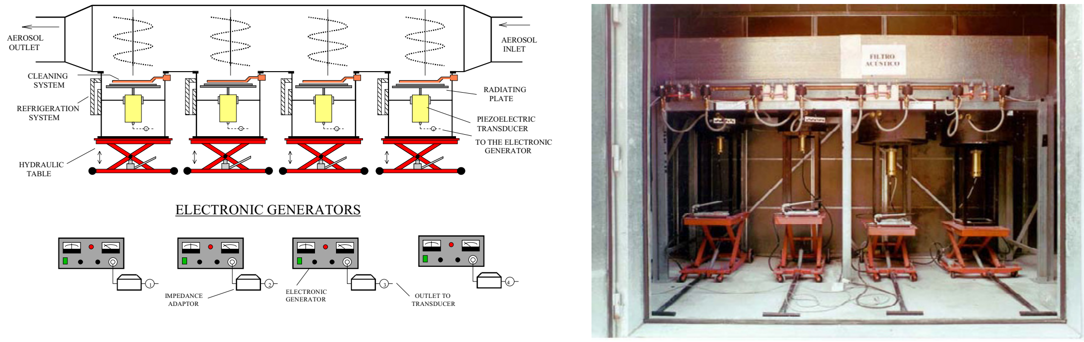



**Fig. 7**: Four-stage acoustic agglomerator.

The ultrasonic multifrequency chamber was investigated and developed as a pre-conditioning agglomerator/precipitator to be placed upstream of a conventional collector system (cyclone, electrostatic filter, scrubber, etc.). An electro-acoustic precipitator (EAP) system at semi-industrial scale was developed for the removal of sub-micron particles (mean particle diameter of 0.8 microns) from a gas stream. The system combines an acoustic module with four stepped-plate generators of two frequencies (10 and 20 kHz) and an electrostatic precipitator (ESP). In general, the improvement in the emission reduction when the acoustic filter works at its maximum power and frequency (4 transducers x 400 W and 20 kHz) can reach values of up to about 40 % of the mass and number concentration respectively, over the efficiency of the electrostatic filter. This can be considered a significant improvement particularly bearing in mind the very small size of the particles, the narrow gain margin let by the electrostatic filter, the low level of energy applied and the very short treatment time.

*4.2. Sludge filtration [14]*

One of the present requirements in sewage treatment is the dewatering of sludge. To that purpose conventional filtration techniques are not satisfactory because the phenomenon of fouling or blocking the pores is frequently produced. The accumulation of fine particulate material during filtration results in slow processing rates or in flux decline. As a consequence the residual moisture in the filter cake always remains high, and it is very difficult to remove. High-power ultrasonic processing may be effective in the release of the residual moisture. Ultrasonic energy directly coupled to the sludge to be dried causes alternative contractions and expansions in a similar way to a sponge when it is squeezed and released repeatedly (sponge effect). The alternating stresses make an effective deliquoring by creating channels for moisture migration.

Filtration of finely dispersed sludge is generally made by using a porous filtration medium and applying a driving force to achieve flow through it. The solid particles are retained on the surface or within the filtration medium while the liquid passes through it. Vacuum, pressure or centrifugation can be used to force the fluid flowing.

A typical filtration equipment is a rotary vacuum disk filter. The disk rotates about its horizontal axis and is partially submerged in a sludge container. The full operation covers the following stages: filtration and cake formation, cake deliquoring, material discharge and back flow washing. Filtration takes place as each section is submerged in the feed slurry. The vacuum draws liquid through the disk into the filtrate lines and solid particles settle on the external surface of the submerged sectors, forming a cake.

To improve conventional rotary vacuum filtration, power ultrasonics is applied during the second stage of the operation. The experimental system is shown in Fig. 8. It basically consists in one (or various) power transducer with an extensive area radiator which is placed parallel to the filter surface and very close to it in such a way that the radiating surface touches the cake during operation. The mechanical contact between the ultrasonic plate vibrator and the cake creates an acoustic coupling which favours the effective penetration of the ultrasonic energy.

The ultrasonic technique was tested with different acoustic powers to determine its performance. The effect of the application of ultrasonic energy has shown that improvements in solid concentration of the cake of around 6 % can be obtained with a relatively low power applied to the transducer (60W) and a short treatment time (2 seconds). By increasing the treatment time the dewatering effect can be even doubled. Such result represents a substantial additional improvement on the conventional dewatering effect.

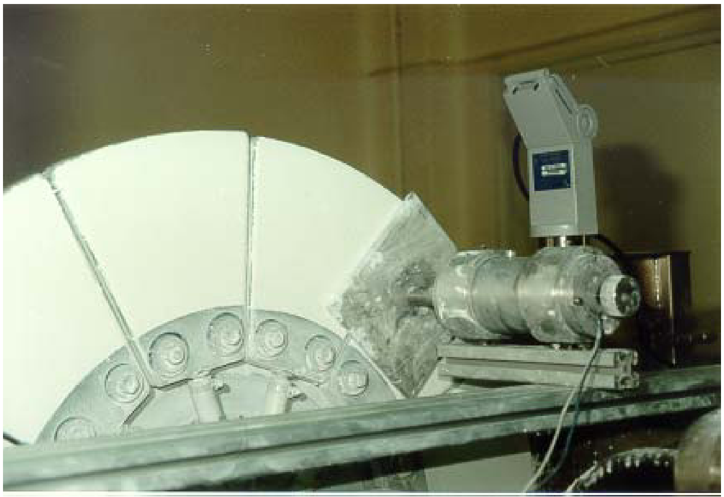


**Fig. 8**: Rotary vacuum disk filter assisted by power ultrasound

## 5. High-power ultrasound in manufacturing processes

The versatility of the ultrasonic energy allows it to be used in many different manufacturing processes usually as an additional tool to improve either the manufactured product or the process. We will present here three different manufacturing processes recently developed

### *5.1. Ultrasonic washing in textile manufacture [15]*

Textile manufacturing is a long process in which the main steps are yarn fabrication, fabric production and fabric processing. Fabric processing is a wet processing to improve the appearance and serviceability of the fabric. It includes several operations such as pre-treatment, dyeing, printing and finishing. After such operations it is usually required washing the fabric. The use of ultrasonic energy may help in speeding up the process and in improving the quality of the final product [16].

Following a detailed investigation about the use of the ultrasonic technology in cleaning textiles and aiming to the development of such industrial applications, a new procedure was developed and patented [17] in which the textiles are exposed to the ultrasonic field in flat format and within a thin layer of liquid by applying specific plate transducers. Such process has been implemented at semi-industrial stage. (Fig. 9)

Washing tests carried out with typical textile samples (EMPA-101) shows that the cleaning performance achieved (measured through the reflectance) even at relatively moderate acoustic intensities is more than double that obtained with a conventional washing machine while the energy consumption is very low (of the order of 0.1 kWh/ kg of textile).

**Fig. 9**: Semi-industrial ultrasonic washing machine

*5.2. Ultrasonic debubbling of liquid coating layers [18]*

Industrial coatings applied at high speed often contain bubbles from air entrapped during operation. Such bubbles will produce permanent surface defects after drying and, consequently, piece rejections in the production line. Chemical additives are generally used to alleviate the problem, but they are difficult to dose and, if not properly handled, can create problems which may be even worse than the air retention.

High-intensity air-borne ultrasound represents an adequate contact-less method to break the bubbles. The specific system developed is shown in Figure 10. It basically consists of a high-power stepped-grooved plate air-borne ultrasonic generator working at 21kHz and a visualization system to film and analyse the debubbling effect acoustically induced in the coating layer deposited over wood samples. The radiating plate of the transducer is placed parallel to the surface to be coated.

The debubbling tests at semi-industrial stage were carried out in a pilot coating curtain machine by coating oak, sapelly and melamine samples of about 150 $cm^2$ with industrial water based WAA2 (acrylic topcoat without defoamers) and ultraviolet solvent based FUVA2 (acrylic ground UV cured) coating liquids.

High debubbling efficiency was obtained for all bubble sizes with the water based application while the effect was more selective for the solvent based application where a strong influence of the bubble size was observed.

From the large number of experiments carried out with bubbles of different sizes and with different kinds of coating materials it seems evident that the new procedure, which is been patented [19] represents an efficient approach for the quick debubbling of thin coating layers.

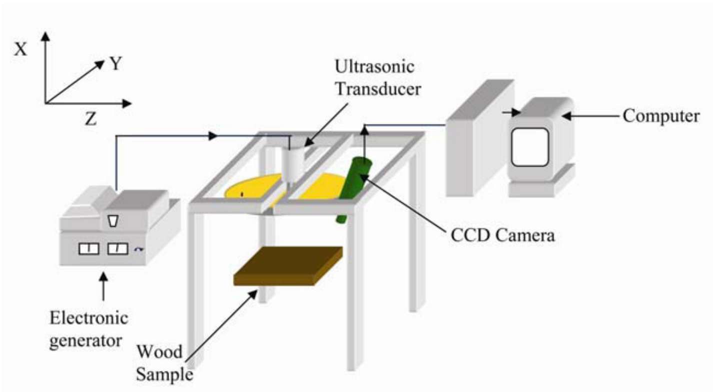



**Fig. 10**: Ultrasonic debubbling set-up

*5.3. Ultrasonic enhancement of pigment dispersion in paint manufacture*

Paint is a dispersion of small, coloured, insoluble particles (pigments) in a liquid medium composed of solvent and binder. Pigments are very fine powders that provide colour and the ability to hide the underline surface.

Good pigment dispersion is a critical factor in the manufacture of paint because it is a complicated and cost-intensive operation. The objective of dispersion is to incorporate homogeneously particles into a liquid system, to disagglomerate the pigment powder, to stabilize this dispersion and to assure that it remains stable during drying. Most of the paint properties are enhanced when the pigment particles are the smallest possible.

The application to this processing problem of a new technology based on power ultrasound offers a potential of innovation which is required in the paint industry. In fact, ultrasonic energy is a powerful dispersion tool as it can disagglomerate by cavitation pigment clusters at the microscopic scale, a scale which is impossible to reach with the conventional industrial equipment. The use of power ultrasound aims also to several other objectives such as the wetting of the pigment particles, a higher homogeneity of pigment dispersion, the decrease of the quantity of pigment and the acceleration of the process production.

By using the rectangular grooved-plate power ultrasonic generators, an ultrasound reactor to enhance pigment dispersion in paints, pastes and inks at industrial scale was recently developed in the frame of an European project [20] (Fig. 11). In such reactor the generation of ultrasound is provided by 3 transducers, mounted in line and in a closed chamber. They produce strong cavitation in a volume around the plate radiator up to about a distance of 8mm above and 8mm below from the radiator surface.

Trials performed with the prototype of ultrasound machine, sonicating with applied powers to the transducers in the range of 400W-600W and treating paint flows of 50 to 100 kg/h, proved the pigment disagglomeration effect and that better pigment dispersion can be obtained than with classical grinding machines.

The development of industrial ultrasonic equipments for paint manufacture will require the increase of the power capacity of the transducers.

**Fig. 11**: Ultrasound reactor for pigment dispersion in paint manufacture.

## 6. Conclusions

The review here presented has been focused on a limited series of sonoprocesses in which we have been directly engaged and that presently are at industrial or semi-industrial stage. There are many other processes, mainly in the sonochemical area, in which outstanding results at laboratory and even industrial scale have been also obtained. Therefore, it seems evident that the application of high-power ultrasound in processing is an expanding field which may cover broad and varied industrial sectors.

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