MACROSONICS: PHENOMENA, TRANSDUCERS AND APPLICATIONS

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ABSTRACT

The field of high-power sonics and ultrasonics is presently known as macrosonics. It comprises a great variety of applications which are generally related with the exploitation of nonlinear phenomena associated to the high amplitudes.

Advances in macrosonic applications are very much dependent on the development of suitable transducers and systems for the efficient generation of the effects to be exploited. Thus, applications in solids generally require high stresses to produce friction, heat and other secondary effects. Applications in liquids are generally based on cavitation and require transducers able to reach a certain sound pressure level (cavitation threshold) through a liquid volume. Applications in gases, which are generally based on particle velocity and radiation pressure, require high vibration amplitudes and good impedance matching.

This paper deals with some basic aspects of the macrosonic field and makes special emphasis on the transducers used and phenomena exploited for the development of new applications.

INTRODUCTION

The field of high-intensity applications of sonic energy, regardless of frequency, is presently known as macrosonics. As well known, acoustics may be divided in three main branches according to the frequency spectrum and the hearing characteristics imposed by the frequency, i.e., infrasonics which is the branch dealing with frequencies below those within the hearing range of the average person (0-20 Hz), sonics which refers to the audible range (20Hz-20kHz) Ultrasonics which covers the very wide range of vibratory waves from 20 kHz up to the frequencies associated to wavelengths comparable to intermolecular distances (about 10^{11}Hz).

The basic principles and equations of acoustics are adequate to explain the general behaviour of the three branches. Nevertheless, the special characteristic of the ultrasonic and infrasonic waves of being inaudible establishes a fundamental difference in their applications with respect to the audio-frequency field. However, besides frequency other wave parameters, as intensity, may influence broadly the phenomena related to the production, propagation and application of acoustic waves. As a consequence other classification of the acoustic field could be adopted, such as low and high-intensity acoustics.

From the point of view of applications, low-intensity waves are those wherein the primary objective is transmitting information through or about the medium, without modifying it. On the contrary, high-intensity waves are those which may produce changes in the propagation medium and that, generally, are applied with this purpose.

Macrosonics is then the part of acoustics devoted to high-intensity waves and their applications. The limit between low and high-intensity is difficult to fix, but it can be approximately established for intensity values which, depending on the medium, vary between 0.1W/cm^2 and 1W/cm^2.

High-intensity waves are finite amplitude waves and to describe their behaviour the equations of the nonlinear acoustics must be used. The applications of high-intensity waves are based on the adequate exploitation of the effects linked to nonlinear phenomena produced during their propagation.

The history of macrosonics is a part of the history of acoustics and, more specifically, can be considered as a part of the history of ultrasonics because macrosonics and high-power ultrasonics are in a great part coincident. The physical effects of intense waves were firstly noticed by Paul Langevin in 1917 making tests to develop an ultrasonic technique for the detection of submarines during the First World War. He realized that small fishes placed in the ultrasonic beam in the neighbourhood of the source were killed. Such tests were done by using a quartz plate sandwiched between two metal pieces, a new kind of piezoelectric transducer which is still considered a fundamental transducer for high-power applications. Following Langevin's work, which can be considered the birth of macrosonics, another important event that marked the initial development of macrosonics were the experiments of Wood and Loomis during the 1920s. Using a high-power oscillator and a quartz plate transducer, they conducted interesting experiments with high-intensity ultrasonic waves (200-500 kHz) such as formation of emulsions and fogs, flocculation of particles suspended in a liquid, levitation of matter, killing or damaging of small fish, etc. [1]. Following this pioneering work, the interest in the study of macrosonic effects increased steadily. More than 150 studies were published in the period 1927-1940 about different effects related with the high intensities. The main effects studied were emulsification and dispersion, coagulation, atomisation, chemical and biological effects and metallurgical applications [2]. In the period 1940-70 the development of new transducer materials (piezoelectric and ferromagnetic ceramics) and transducer structures (horn and prestressed piezoelectric sandwich) as well as the rapid advances in electronics made possible the production of commercial macrosonic systems for practical applications such as cleaning, plastic and metal welding, machining, emulsification, etc. Since 1970, the field of macrosonics, after the explosion of possibilities of the early periods, have grown more in terms of extension of the use of applications commercially introduced than in the development of new applications. Nevertheless, some specific topics have continued to be the object of the attention of research groups in such a way that new applications have been opened or are in the way to be opened. To be mentioned as representative topics the studies and applications in multiphase media, sonochemistry and medical therapy.

This work is aiming to review some advances in macrosonic applications developed on the last period. These advances will be framed within the progress made in the knowledge of basic phenomena and in the development of new transducer technology.

NONLINEAR PHENOMENA

As before mentioned, high-intensity acoustic waves are finite-amplitude waves and their applications are generally based on the adequate use of the nonlinear phenomena associated to the high amplitudes. The most relevant nonlinear phenomena related to high-intense acoustic waves are wave distortion, acoustic saturation, radiation pressure, streaming, cavitation in liquids and the formation and motion of dislocations in solids.

Distortion

The waveform distortion is the most characteristic nonlinear effect. Small amplitude signals propagate without change of shape because all points of the waveform travel with the same velocity c_0. In contrast, for a finite-amplitude wave the propagation velocity is a function of the local particle velocity, and therefore it varies from point to point on the waveform. As a consequence the relative position of the different points of the waveform changes during propagation and the wave becomes distorted. The profile of the wave is gradually changing up to a certain distance where it becomes multivalued, a situation that is physically inadmissible and really implies the formation of a discontinuity or shock (Fig. 1)

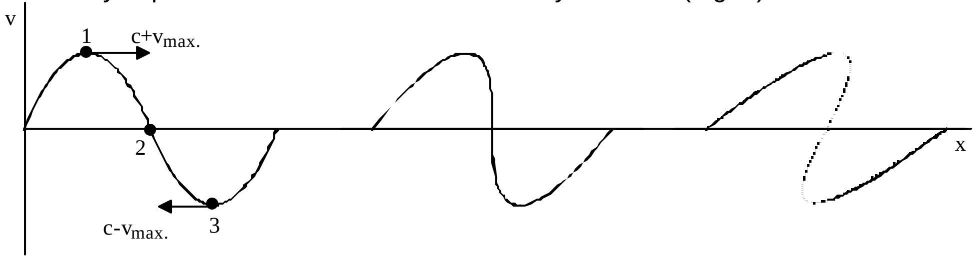

Figure 1. Distortion of the waveform

The propagation path of an original sinusoidal wave of finite amplitude in a thermoviscous fluid may be divided into three regions. In the first region, which extends up to the shock formation, the nonlinear effects dominates. The second region corresponds to the formation and

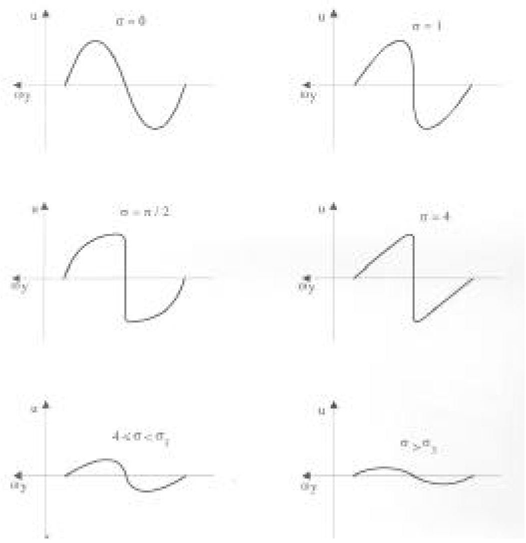

Figure 2. Evolution of the waveform in nonlinear propagation

propagation of a relatively stable sawtooth wave. Finally, in the third region, which is known as old age region, the decay rates due to nonlinear effects are balanced by ordinary absorption, and the wave becomes again sinusoidal. (Fig*. 2)*

Saturation

The attenuation of finite-amplitude waves is not constant: it depends on the source distance and increases with the wave amplitude. These effects are directly linked to the production of acoustic saturation, a phenomenon which limits the real ultrasonic energy which is possible to transport at a certain distance from the source. In fact, the wave distortion at a fixed point in the radiation field increases when the source amplitude increases. Consequently, the wave energy is transferred to higher-order harmonics which, since the absorption increases as the square of the frequency, are absorbed more intensely causing an excess of attenuation of the wave. This behaviour will determine that, over a certain value, any increase of the wave amplitude at the source will be compensated by its decay in the considered point. Therefore, there exists a limiting magnitude of the wave amplitude which can be reached at a fixed distance from the source in a given medium. For instance, in air at a frequency of 20 kHz the maximum sound pressure level which can be transmitted to a distance of 2m away from the source is 135 dB (re: 0.0002µbar), and at 5.7 m the level is only 121 dB [3]. Therefore, the great significance of the limiting value due to acoustic saturation in practical applications of high-power ultrasound should be emphasized.

Radiation Pressure

Steady forces acting on obstacles in a sound field are usually caused by a physical quantity which is known as the acoustic radiation pressure. Radiation pressure is characteristic of any wave process because it is related to the change in the magnitude of the momentum carried by a wave at a target. The resulting forces are generally weak for small amplitude waves. The nonlinearity of finite-amplitude waves introduces corrections which notably increases the magnitude of the effect. In this way, radiation pressure can be considered a nonlinear effect. The radiation force acting on a single obstacle in a medium is determined by the momentum flux through it and the constant component of this force is obtained by averaging it with respect to time. The calculation of the radiation pressure yields to different results depending on the conditions of the obstacle and the acoustic field. Thus, the radiation pressure exerted on a plane target by an ultrasonic beam confined by rigid walls preventing inflow of fluid into the beam is known as the Rayleigh radiation pressure. Instead, if the target is placed in the path of an unbounded ultrasonic beam, the time averaged force per unit area acting on it is called the Langevin radiation pressure. The action of radiation pressure forces on different obstacles or interphases in multiphase media represents one important mechanism in many effects produced by macrosonic waves [4].

Acoustic Streaming

Acoustic streaming is a nonlinear acoustic effect in which steady fluid flows are induced by finite-amplitude acoustic waves. In a high-intensity ultrasonic field steady flows are produced both in the free ultrasonic beam and near obstacles. In the latter case, the boundary layer has a significant influence in the development of the steady flows. Outside the boundary layer, in a traveling wave, the fluid flow away from the source at the center of the ultrasonic beam and in the opposite direction at the periphery. In a standing wave, a series of closed vortices are established between maxima and nodes.

Acoustic streaming seems to be mainly induced by radiation forces set up by absorption of the acoustic waves in the medium. However, other mechanisms, such as diffraction and nonlinearities of the acoustic field, may also contribute to this effect. [5]

Cavitation in Liquids

Cavitation may be defined as the formation, pulsation and/or collapse of vapor or gas cavities in a liquid under acoustic stresses. Acoustic waves of a certain intensity applied to a liquid may produce small cavities or bubbles because of the fluctuations of hydrostatic pressure they produce. In fact, during the rarefaction phase of the cycle the bubbles or cavities may be formed and during the compression phase they may collapse. Cavitation is a very complex process where a series of remarkable phenomena take place. Two types of cavitation are generally considered: stable and transient cavitation. In the stable cavitation, usually produced at moderate acoustic intensities, bubbles inside the liquid oscillate, generally in a nonlinear way, around their equilibrium size. This situation may be kept stable during many acoustic cycles and gas bubbles may grow. In fact, during the positive pressure half-cycle the gas inside the bubble will be compressed then diffuses from the bubble into the liquid. During the negative half-cycle, the effect is just the opposite: the bubble is expanded and gas diffuses from the liquid into the bubble. Nevertheless, the rates of these two processes are not equal because the surface area of the bubble is greater during rarefaction. Consequently, the bubble acquires some additional gas during each cycle. This process, which is a rectified diffusion, is applied for degassing of liquids: the bubbles grow, trapping the dissolved gas, rise to the surface of the liquid and escape.

The second type of cavitation, which is known as transient or inertial cavitation, is generated under high-intensity acoustic fields. During the negative pressure half-cycle, the effect of the restoring force produced in the bubble by the gas and liquid vapor becomes negligible with respect to the acoustic pressure and the bubble expands to several times its original size. Then during the compression half-cycle the bubble collapses violently and generally disintegrates into many smaller bubbles. The collapsing bubble develops very high temperatures (thousands of degrees) and pressures (thousands of atmospheres) which are important in many effects of high power ultrasound. The high pressures produce erosion, dispersion and mechanical rupture while the high temperatures are responsible for sono-luminiscence and sonochemical effects. In transient cavitation the motion during collapse is essentially inertia-controlled: empty cavities will collapse completely while in gaseous cavities the motion is cushioned by compression of the residual gas. [6, 7]

Dislocation motion in solids

Crystalline solids consist of regular periodic arrangements of atoms or molecules. Departures from regularity are known as defects. Point defects are defects involving one single atom or molecule. Dislocations are line defects.

High-intensity acoustic waves may affect the dislocational structure of solids. The propagation of macrosonic waves in a solid can set the dislocations into vibration. Dislocation line segment pinned by point defects might vibrate as a string under the action of the high stress. As this stress is increasing the lines bend with increasing amplitude until a critical value where catastrophic breakage occurs from the intermediate pinning points. At high stresses dislocation multiplication may occur. However only shear stresses having the proper orientation with respect to the slip system can produce this motion.

As well as dislocations, point defects can be produced by deformation and their concentration changes the elastic characteristics of the material.

These processes may produce the formation of microcracks and eventually failure of the material. [8]

TRANSDUCERS

Macrosonic transducers are narrowband transducers working generally at frequencies within the range 10 to 100 Khz with power capabilities of a hundred watts to several kilowatts and large vibration amplitudes. At present, most high-power transducers are of the piezoelectric type. Therefore, we will mainly focus our attention on this kind of transducers. Nevertheless, it is interesting to point out recent developments of new and promising magnetostrictive materials (rare earth compounds), which show a great potential for high-power transducers.[9]

Transducers are typically composite devices in which the core is a piezoelectric (or magnetostrictive) element, which changes dimensions in response to an electric (or magnetic) field. Other passive components complement the transducer structure to improve energy transfer. These components are generally made of metallic alloys.

In modern transducers, the piezoelectric materials generally used are piezoelectric ceramics. It can be shown that piezoceramics offer the highest electromechanical conversion and efficiency, and have, in general terms, the most favourable properties for high-power ultrasonic transducers.

Piezoelectric ceramics are materials constituting a conglomerate of ferroelectric crystallites which are randomly oriented They generally originate from a solid-state reaction of several oxides followed by high-temperature firing. After firing, a ceramic is isotropic and non-piezoelectric because of the random orientation and structure of the domains (regions within each crystallite in which the electric dipoles have common orientation). The ceramic material may be made piezoelectric by a poling treatment consisting of applying a high electric field in a chosen direction to switch the polar axes of the crystallites to those directions, allowed by symmetry, which are nearest to that of the electric field. After removal of the poling field, the dipoles cannot easily return to their original positions, and the ceramic will now have a permanent polarisation, and will respond linearly to applied electric fields or mechanical pressures as long as their magnitude is kept well below that needed to switch the polar axis.

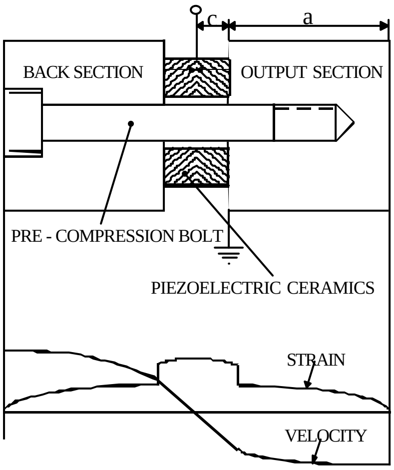

Fig.3: Structure of prestressed sandwich transducer

At present the most suitable and popular ceramic materials are lead zirconate titanates(PZT) of which various commercial versions are manufactured in different countries. There are also commercial compositions based on barium titanate, lead metaniobate and sodium niobate. The leading position of the lead zirconate titanates is due to their strong piezoelectric effect and high Curie point, together with the wide range of properties they offer simply by making small changes in composition. The PZT-4 and PZT-8 compositions are particularly adapted for high-power transducers [10]. The latter has remarkably low dielectric and elastic losses at high drive levels.

The most characteristic piezoelectric transducer for high-power applications is the well-known sandwich transducer, which is reminiscent of the Langevin transducer. When ceramics for narrow-band low-frequency applications were first used, the transducers consisted of simple piezoceramic blocks. However, this plain arrangement did no prove to be very useful, especially for high power applications, due to the low tensile strength of the ceramic and to the physical dimensions of the single-piece needed for such a low frequency. Because of these difficulties, Langevin's design was re-investigated and adapted to the new circumstances. The sandwich transducer is a half-wave resonant length-expander structure, which, in its simple version, consists of a disc, or of paired discs, of piezoelectric ceramics sandwiched between two identical metal blocks (Figure 3). When used in pairs, the piezoelectric ceramics are polarised in opposite directions and separated by an electrode connected to the high-voltage lead. The electrode is therefore located at a node. Coupling between the piezoelectric elements at the metal end-sections and increase to the tensile strength are achieved by mechanically prestressing the assembly in the axial direction by means of a bolt [11].

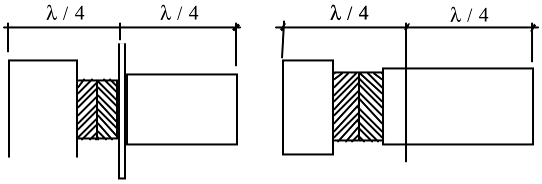

Fig. 4: Asymmetric sandwich transducers

In practice, the sandwich construction does not generally follow the symmetrical structure just described. In most applications the output and back sections are made of metals of different density in order to increase the vibration amplitude on the radiating face and to improve matching to the load. Other cases require the node, which is the supporting point, to be in one of the metallic sections. The result in all these cases is an asymmetric sandwich structure as schematically shown in Fig. 4.

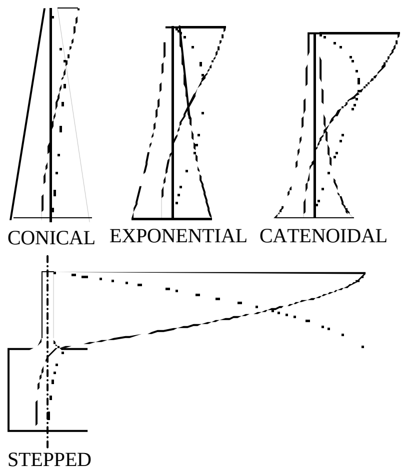

Fig. 5: Basic horn shapes and amplification effect

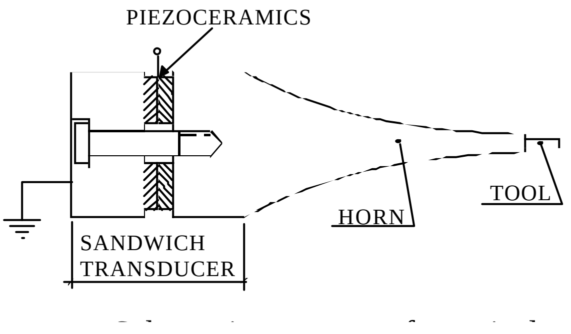

Fig. 6: Schematic structure of a typical ultrasonic processing transducer

High-intensity applications of sonic and ultrasonic energy in solids such as machining, welding, metal forming, etc. are based on mechanical effects as a result of particle motion. In these processing applications, the sandwich transducer is also used, but it also includes a metallic transmission line of special shape, which produces a displacement amplification at the working end. These transmission lines are formed by half wavelength resonant elements, called mechanical amplifiers or horns, which are generally stepped, conical, exponential or catenoidal (Fig. 5). The horn must be designed to resonate at the same frequency as the transducer which is to drive it. A schematic drawing of a typical processing transducer with one exponential horn is shown in Fig. 6. In the horn described in Fig. 5, the cross-sectional dimensions were assumed to be smaller than one-quarter or one-third of the wavelength, in order to obtain a pure extensional mode of vibration. Nevertheless, most applications require wide horns or horns of large cross-sections. In these cases, one of the main problems is to obtain a uniform amplitude distribution on the radiating face avoiding radial or lateral vibration modes. For this purpose, large horns are constructed with slots running parallel to the direction of longitudinal motion (Fig.7). This way, the large horn, can be considered as an array of narrow horns in which the apparent cross-sectional dimension of each element is less than a quarter of a wavelength. The slots are also useful for heat dissipation. [12]

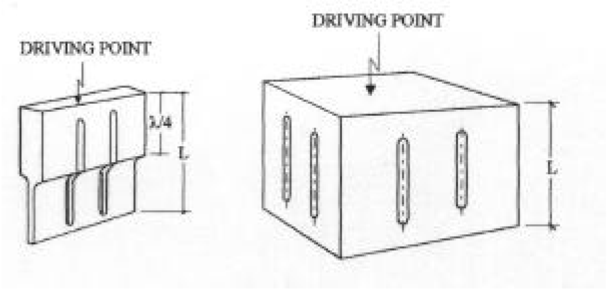

Fig. 7: Horns of large cross-section

The sandwich transducer, as described above, is employed directly for applications in liquids, such as ultrasonic cleaners and reactors. The use of single or multi-element sandwiches is widespread. Multi-element sandwiches incorporate an even number of piezoceramic discs (Fig. 8). In addition, the work-face area can be increased by tapering the output section. This can be useful in the matching of the transducer to its load. Most high-power ultrasonic devices are designed on the basis of different kinds of multi-element sandwich transducers and they are constructed very often in arrays of a number of elements in order to cover a large working area and to obtain the desired total power.

A new concept for the generation of ultrasonic energy in fluids has been introduced in recent years by means of the so-called stepped-plate transducer [13, 14]. Generation of ultrasonic energy in fluids presents problems related to the low specific acoustic impedance and high absorption of the medium. Therefore, in order to obtain an efficient ultrasonic transmission and to produce high pressure levels, it is necessary to achieve good impedance matching between the transducer and the fluid, large amplitudes of vibration and highly directional or

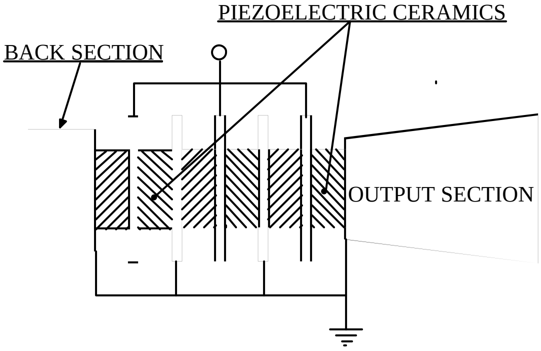

Fig. 8: Multi-element sandwich transducer

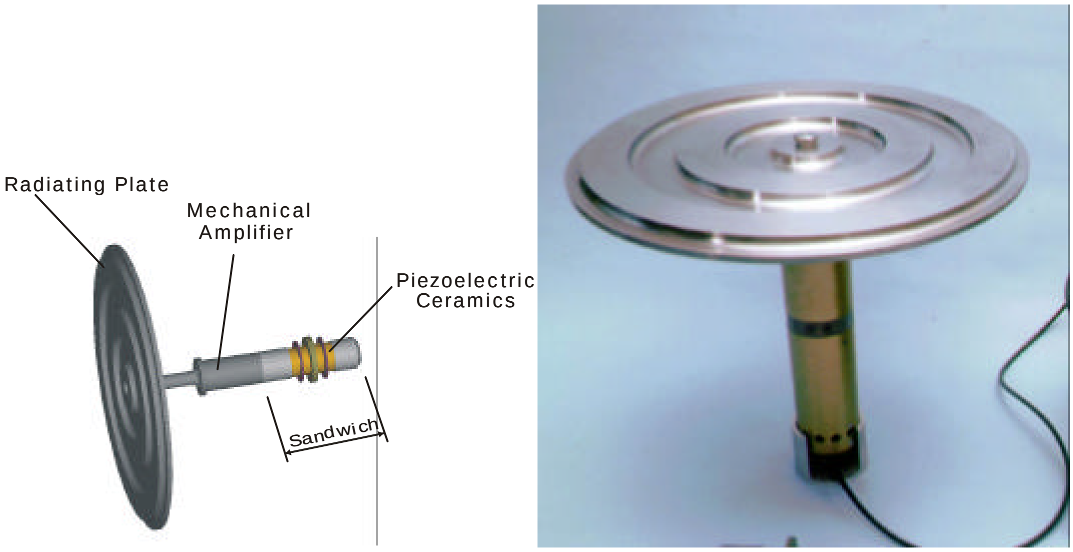

Fig. 9: Scheme and picture of the stepped-plate transducer

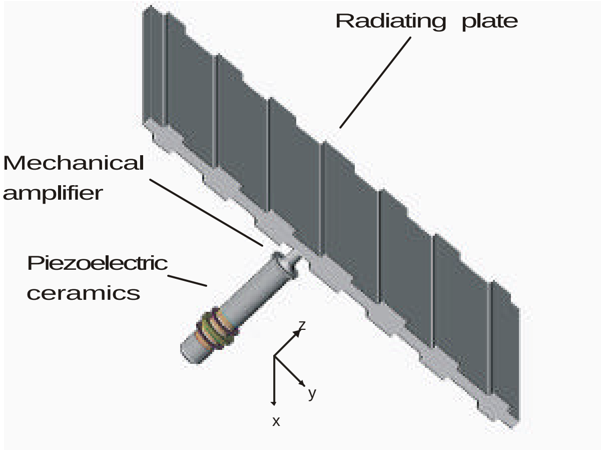

Fig. 10. Scheme of the double stepped rectangular plate

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. The existing high-power commercial transducers have many limitations to cover all the above-mentioned requirements. The development of a new type of stepped-plate transducer, in which these prerequisites have been attained, opens up new possibilities. The new transducer consists essentially of an extensive circular flexural vibrating plate of stepped shape driven at its center by a piezoelectrically activated vibrator (Fig.9). The vibrator, formed by a sandwich transducer and a solid horn, is similar to the one used for applications in solids. The extensive surface of the plate increases the radiation resistance and offers the vibrating system good impedance matching with the medium. The special shape of the plate permits, despite its flexural vibration, a piston-like radiation to be obtained. As is well known, a flat-plate radiator vibrating in its flexural modes shows a poor directivity, due to phase cancellation. Nevertheless, if the surface elements vibrating in counterphase on both sides of the nodal circles are alternately shifted along the acoustic axis, half a wavelength of the radiated sound, the radiation produced will be in phase across the whole beam. Following this procedure, it is possible, with adequate modifications of the plate surface, to obtain any acoustic field configuration. Focused radiators have also been constructed [15]. Stepped-plates vibrating up to seven nodal circles and diameters up to 70 cm have been designed and constructed. In the latest version of this transducer, efficiencies of around

80%, beam width (at 3 dB) of 1.5 degrees and power, capacities of 1 kW have been attained for the frequency range 10-40 kHz.

Looking for industrial applications and in order to increase the power capacity, a new model of transducer has been recently developed by using rectangular plate radiators with double-stepped profile. (Fig. 10)

Rectangular plates offer a more uniform distribution of vibration, and therefore higher power capacity, and the material needed for their construction (rolled titanium alloy) is more easily available than the forged titanium needed for the construction of circular plates.

Two different versions of rectangular plate transducer have been designed and constructed: one with a plate of 0.3x0.6m^2 for a power capacity of about 300W and other with a plate of 1.8x0.9 m^2 for about 2 kW (Fig. 11).

The doubled stepped profile was done with the purpose of using the back radiation of the plate with adequate reflectors. A picture of the 2 kW transducer with reflector is shown in Fig.12.

.These new transducers have to be driven by a special electronic system producing a signal lying permanently within their very narrow resonance frequency band [16].

Fig. 11: Two different rectangular plate transducers

Fig. 12: Photograph of the rectangular plate transducer with reflectors

APPLICATIONS IN MULTIPHASE MEDIA

As a consequence of the nonlinear phenomena previously described, a series of mechanisms may be activated by the macrosonic energy such as heat, agitation, diffusion, interface instabilities, friction, mechanical rupture, chemical effects, etc,. These mechanisms can be employed to produce or to enhance a wide range of processes that very much depend on the irradiated medium. In fact, a typical characteristic of high-intensity ultrasonic waves is their ability to produce different phenomena in different media in such a way that these phenomena seems to be opposite at times. This is, for example, the case of the application of power ultrasound to liquid suspensions for particle dispersion and to gas suspensions for particle agglomeration. This apparently contradictory behaviour is clearly due to the different media where the acoustic energy is applied and, consequently, to the different mechanisms that are activated.

Another characteristic of high-intensity ultrasonic waves is their capacity to work synergistically with other forms of energy in order to promote, accelerate or improve many processes. This is the reason why many practical applications of high-power ultrasound are not exclusively ultrasonic processes but ultrasonically assisted processes.

The use of high-power ultrasound in industrial processing is a promising area which, in a great part, remain still closed. A large number of ultrasonic processes, such as plastic and metal welding, machining, metal forming, etc, in solids or cleaning, atomisation, emulsification and dispersion, degassing, extraction, defoaming, particle agglomeration, drying and dewatering, sonochemical reactions, etc. in fluids, have been produced in the laboratory. Nevertheless, only a few of these processes have already been introduced in industry. This situation can be mainly attributed to the problems related with scaling up the ultrasonic processing systems which requires efficient and powerful ultrasonic transducers and a proper distribution of the acoustic field in the processed medium.

In fact, one of the challenges facing the field of Sonochemistry today is scaling up what is essentially a bench top technology for industrial use.

As a consequence of the development of a new technology of high-power sonic and ultrasonic generators for use in fluids and in multiphase media, we have been able to treat some specific industrial problems as: fine particle removal from industrial fumes, defoaming of fermenting vessels and canning lines, dehydration of vegetables, dewatering of slurries, washing of textiles. We will review briefly these applications and the nonlinear phenomena involved in their mechanics.

Fine particle removal from industrial fumes

Removal of fine particles (smaller than 1-2 microns) from industrial flue gas emissions is one of the most important problems in air pollution control. In fact, these tiny particles constitute a major health hazard because of their ability to penetrate deeply into the respiratory tissues and their character generally toxic. In addition these particles make up a significant proportion of the particulate emission and the conventional filtration systems, such as the electrostatic filters, are inefficient for these sizes.

Therefore, an improved technology is needed, specially at the present moment in which new more stringent legislation has been introduced in USA and in Europe.

As is well known, the application of high-intensity acoustic fields to an aerosol may induce collision and agglomeration of the suspended particles, giving rise to larger particles. The complex mechanism of the acoustic agglomeration involves orthokinetic and hydrodynamic interactions. The orthokinetic interactions are founded on the idea that collisions are produced by the different entrainment experienced by particles of different size or weight.

Hydrodynamic mechanisms are those which produce particle interactions through the surrounding fluid due to hydrodynamic forces. There are two main hydrodynamic mechanisms: mutual radiation pressure and acoustic wake effect [17, 18].

Therefore, acoustic agglomeration represents a promising procedure to precondition the fine particles before they enter into the conventional filters. Acoustic agglomeration has been widely studied but the development into industrial application has been slow. This is probably because of the complexity of the mechanisms involved and the lack of adequate full scale macrosonic agglomerators.

For more than 20 years we have been working on the theoretical and experimental aspects of this problem. After the construction and testing of numerous laboratory devices we developed a multifrequency agglomeration chamber of 3.5 m long and 0.5x0.7m in section, with four circular stepped-plate transducers of 10 and 20 kHz and an electrical applied power of about 350 W each one (Fig.13). The chamber was designed for flow rates up to 2000 m^3/h and was tested in a pilot installation together with an electrostatic filter for the treatment of fumes produced by a fluidised bed coal combustor.

The results of these tests showed that the introduction of the acoustic system improved the precipitation efficiency of the electrostatic filter, obtaining additional reductions of the fine particle of the order of 40% (in certain cases this value arrived up to 70%). [19]

As a consequence of the positive results in the pilot plant, we have continued the scaling-up of the system.

Recently, we have developed new agglomeration chamber based on the rectangular plate transducer of 2kW. This system has been designed for the treatment of flow rates up to about 10.000 m^3/h. [20]

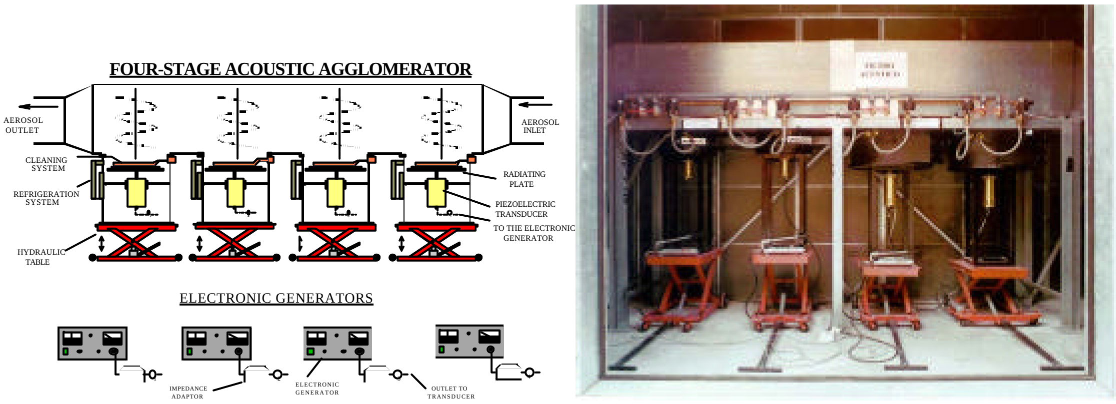

Fig. 13.: Scheme and photograph of the multifrequency agglomeration chamber

Defoaming of fermenting vessels and canning lines

Foams are frequently produced during various manufacturing processes and they cause, in general, difficulties in process control and in handling equipment. A typical example is in the fermentation industry where foam represents one of the biggest problems.

There are several conventional defoaming methods employing thermal, chemical, and mechanical effects. The thermal methods involve heating or cooling the foam, which generally is difficult and expensive. Chemical defoaming methods employ antifoam agents which produce a decrease in surface tension. They are generally, very effective but they cause the trouble of contaminating the process. Mechanical methods try to produce bubble rupture by any mechanical shock, by using rotating devices, air or liquid jets, vacuum systems, etc. are used as mechanical foam breakers. In general, the mechanical methods are effective only for coarse foams.

High-intensity sound and ultrasound is a clean means for breaking foams. The mechanisms of acoustic defoaming, which is insufficiently known, may be a combination of the high acoustic pressures, the radiation pressure, resonance of the bubbles, cavitation, streaming and atomisation from the film bubble surface.

Fig. 14: Defoaming of a fermenting vessel

The potential use of high-intensity ultrasound for defoaming has been known for several decades. Nevertheless, the process was not introduced in industry. This is probably because the acoustic defoamers used were generally based on aerodynamic acoustic sources which presented many difficulties for practical applications.

A new ultrasonic defoamer has been developed by using the stepped-plate transducer and it has been successfully applied to control of foam in fermenting vessels and on high-speed canning lines of carbonic beverages. The picture shows the application of the new system for the treatment of foam in reactors where the transducer rotates to increase the defoaming area (Fig.14). This technique was positively applied to control the foam in a beer fermenter of 6 m in diameter.

In canning beverages at high speed

foam is produced on the top of the can and to avoid liquid losses the ultrasonic radiation is focused on it and the foam excess is quickly destroyed. The new system was applied to control foam in the filling operation of cans with commercial beverages at a speed of more than 20 cans per second. The power applied was 300 W at 20kHz. Then the energy consumption was only of about 5 mW.h/can.

Dewatering of slurries

Solid/liquid separation is a topic of permanent industrial interest.

Dewatering is a process in which the water is removed from a product without changing its phase while in drying processes the moisture is removed by vaporization.

Solid/liquid separation in finely dispersed slurries is a process generally made by using a porous filtration medium and applying a driving force (vacuum, pressure or centrifugation) to achieve flow through it. The solid particles are retained over the surface of the filter medium while the liquid passes through it. In such a way the free water is separated but a certain moisture content remain in the interstitial spaces. This interstitial moisture is very difficult to remove.

We have developed an ultrasonic procedure for post filtration dewatering in ceramic rotary filters to release the remaining interstitial moisture. The ultrasonic process basically consists in applying the acoustic vibration generated by a plate transducer, directly in contact with the material to be dewatered and under a soft static pressure (Fig.15). Acoustic intensities in the range of 0.1-1 W/cm^2 were applied and the results showed that a reduction of the interstitial moisture of about 25% is achieved in only 10 seconds of treatment [21].

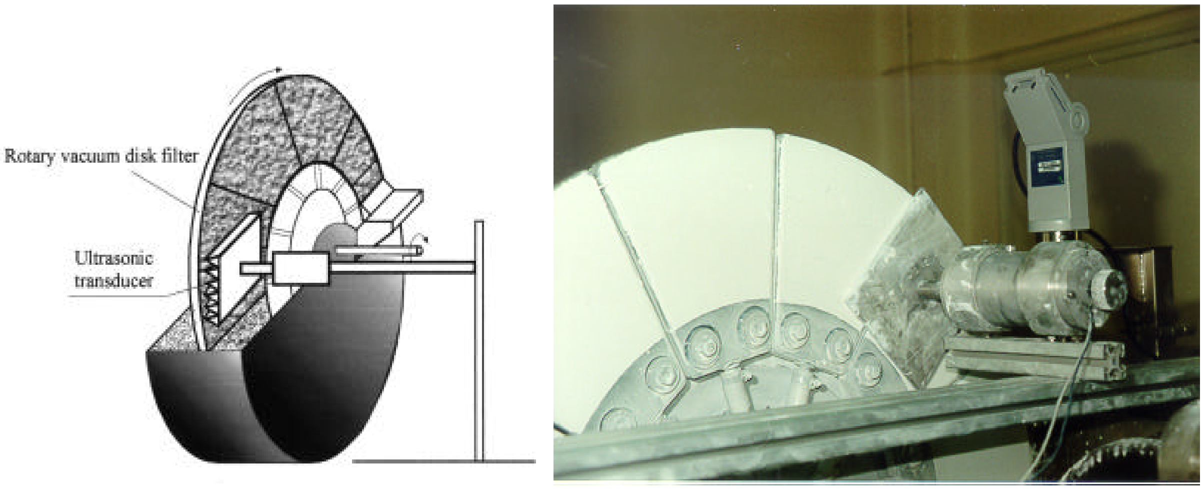

Fig. 15: Scheme and photograph of the rotatory filter assisted by ultrasound

Different effects seem to play a role in the mechanism of ultrasonic dewatering. First of all, the acoustic stresses produce a kind of “sponge effect” which facilitate the migration of moisture through natural channels created between solid particles. Small liquid droplets retained inside the capillaries can be removed by acoustic stress if they become greater than the surface stresses. In addition, air bubbles trapped in micropores can grow by rectified diffusion producing displacement of the liquid. Cavitation may be another important effect to separate colloidal and chemically attached moisture.

This procedure has been successfully applied for the industrial separation of TiO_2 fine particles (about 1 micron size) in water with mass concentrations from 25 to 40%.

Dehydration of vegetables

Dehydration is a method of preserving food. For food dehydration the two main conventional procedure 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 following similar mechanisms to those applied for dewatering.

We have developed a procedure based on the application of the ultrasonic vibration in direct contact with the samples and together with a static pressure. An air flow at about 1m/s and 22ºC was also applied to facilitate the removal of moisture. The results obtained with vegetable (carrot) slices of 2 mm in thickness and 14 mm in diameter by using ultrasound in comparison with the effect obtained by using forced hot-air at different temperatures showed clearly that the dehydration effect remarkably improved. In addition, by using ultrasonic energy the product quality is very well preserved. [22]

Cleaning of textiles

Cleaning of solid rigid materials is probably one of the best known applications of high-power ultrasound. Nevertheless, the use of acoustic energy in cleaning textiles offers more problems than in solid rigid materials. The fibres are more flexible, then the erosion effect is smaller. In addition, the structure of the fabric favours the formation of air bubble layers which obstruct the penetration of acoustic waves.

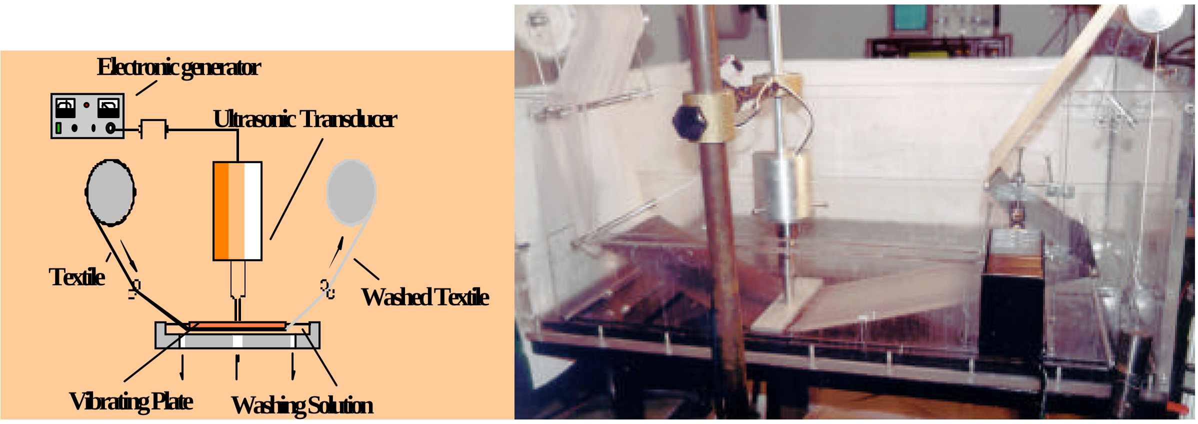

Fig. 16: Scheme and photograph of the continuous washing system

During several years we investigated the use of ultrasonic technologies for cleaning textiles in domestic washing machines. It was found out that the air content of the wash liquor is an important factor in such a way that by diminishing the amount of dissolved air highly improved wash results. In comparison to conventional methods, we obtained better cleaning in a shorter time. Nevertheless, practical problems impeded the commercial progress. Specifically, the acoustic washing system required high water level and small wash load in order to ensure penetration of the acoustic energy and homogeneous exposure of the load to the acoustic field.

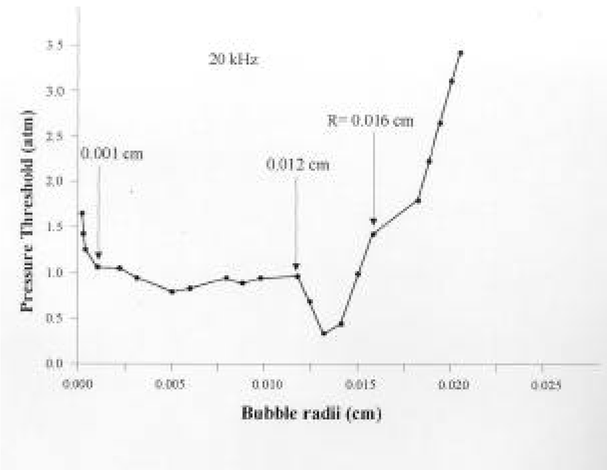

***Fig. 17**. Transient cavitation thresholds for different bubbles radii (Frequency 20 kHz)*

In order to overcome these practical problems and looking for industrial applications we developed a continuous washing system in which textiles are exposed to the acoustic field in a flat format and in almost direct contact to the radiating element of a high-power transducer [23]. The textile items are transported in a conveyor belt, passing them underneath the acoustic source. (Fig. 16) By using this system, the level of wash liquor needed was very low (sufficient to damp and wet the samples). At the same time, the prerequisite of degassing the water would become unnecessary. This is probably due to the strong action of vibrating stresses expelling the bigger bubbles from the inside of textiles.

It is clear that the main washing mechanism is cavitation, essentially cavitation produced by the very small bubble nuclei existing in the liquid. In fact, if we compute the cavitation thresholds for single bubbles of different radii at 20 kHz (Fig. 17) it can be observed that bubbles with radii within the range 0.001-0.012 cm exhibit a similar threshold pressure for the onset of cavitation. Therefore, the bubbles included within this wide size range could be the cause of a great cavitation activity as they will act as nuclei to produce a simultaneous collective transient cavitation when the threshold level is reached. We called this cavitation in a gassy liquid as "strong transient cavitation" [24].

The washing results obtained with the new system showed that the wash performance of a series of representative stains as well as test monitors was significantly better than those obtained with the conventional methods.

OTHER CURRENT MACROSONIC APPLICATIONS

Major research initiatives carried out recently by other groups have been mainly devoted to sonochemical and biomedical applications generally based on the exploitation of cavitation effects. Length limitation of this article prevent a detailed discussion of all developing research lines. However, we will briefly describe here some of the most relevant developing topics.

Syntesis of manostructured materials and the formation of very fine particle matter is an interesting and promising area with a wide field of possibilities for industrial applications (catalytic devices, recording materials, colloidal suspensions, etc) and biomedical uses (nanocapsules of proteins for transporting therapeutic compounds, genes or other agents). Bubble collapse in liquids creates unique high-energy conditions in such a way that volatiles compounds decompose inside a collapsing bubble and the resulting atoms agglomerate from nanostructured materials. Also cavitation implosion causes particles to drastically reduce in size [25].

The use of sonic energy for water treatment is another growing area of application. High intensities produced by cavitation implosion destroy bacteria by disrupting biological cell walls. In addition, macrosonic energy may enhance the effects of chemical biocides by breaking up and dispersing bacterial clusters [26]

New options for commercial applications are offered by thermoacoustic engines and refrigerators [27]. The variations of pressure and velocity produced in a gas by an acoustic wave are also accompanied by temperature variations which can be used for the production of thermoacoustic effects. Such thermoacoustic effects which are very small at low acoustic intensities, can be significant at high intensities. At present research efforts in thermoacoustic applications are carried out by different groups. One of the pioneers is the condensed matter and thermal physics group at Los Alamos National Laboratory in USA who is engaged in the development of thermo-acoustic technology looking for alternatives to conventional systems. Engine with no-moving parts and refrigerators have been constructed by using acoustic intensities as high as 190 dB [28].

In medical applications the already well established technique of lithotripsy is a landmark in the use of sonic energy in therapy. Extracorporeal shock wave lithotripsy is based on the generation of high-intensity acoustic pulses outside the body and focusing them through the skin and body wall onto the stone. The idea of kidney and gall stones fragmentation by using acoustic energy was reported for the first time in the 1950s. The first positive attempts were made by using low frequency ultrasound of 20kHz in direct contact between transducer and stone. Nevertheless, the major advance for the introduction of acoustic lithotripsy was reached in the 70s by using shock waves, single strong ultrasonic pulses of several tens of MPa and short rise time. The use of shock waves in practical systems was first carried out by two german groups, one at the Dornier Company and other at the University of Saarbrücken, who respectively developed devices with a spark gap discharge under water in an ellipsoid and a toroidal ring ellipsoid driven by an explosion wire. On February 1980 the first extracorporeal lithotripsy was performed on a man. Since then several millions of such patients have been treated [29]. Besides the original systems, lithotripters work with other different sound sources, such as piezoelectric or eddy current generators. Focusing is done by reflection on ellipsoids or paraboloids, by acoustic lenses or by direct focusing. The mechanism of shock wave lithotripsy is not completely understood but it seems that compressive and tensile forces together with cavitation are the main effects to be considered. A similar technique to lithotripsy has been used for cancer therapy. The acoustic energy can be focused on cancerous tissue within the body to destroy it.

Finally, some words about the application of macrosonic waves for hemostasis, a recent therapeutic technique which offers excellent prospects. It has been demonstrated that high-intensity ultrasonic beams focused on a small area, can be used to induce coagulative necrosis in tissues where bleeding is produced in such a way that punctures and laceration in animals can be successfully closed. The intensities needed are higher than 1000W/cm^2. L. Crum and his group at the University of Washington in Seattle has obtained clear experimental results by using adequate focusing transducers in the range of 3 to 5 MHZ [30]. They have been able to stop moderate and profuse bleeding in pigs from vessels ranged in size 2-10 mm in diameter in a period of seconds. The ultimate goal of the Crum's group is to develop a non-invasive image-guided transcutaneous device to treat external and internal bleeding in humans.

Acoustic hemostasis seems to be the results of the large and quick temperature rise induced by the high intensities. The success of this technique may be due to the capability of penetration of the acoustic waves into tissues to reach volume cauterisation instead of surface cauterisation. In addition, possible damage in the interior walls of the vessels is prevented from the low acoustic absorption in blood and the cooling effect of the blood flow that make the temperature inside the blood vessel low compared with that in the tissue.

CONCLUSIONS

Macrosonics is a wide and expanding field. Nevertheless, up to the present moment only a restricted number of applications have been introduced in industry and probably the most promising fields of application are yet to be developed. In this paper we have reviewed some recent advances which in a great part are in the intermediate stage between laboratory and industry. The future of this field is very much dependent on three main factors: the knowledge and control of the nonlinear phenomena involved in the mechanisms of the different applications, the development of adequate and specific transducer technology, and the capacity to scale-up the systems.

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