Technical Report RT-ATCP-02

Ultrasonic cleaning: *overview and state of the art*

ATCP Physical Engineering
www.atcp-ndt.com / ha@atcp.com.br
São Carlos - Brazil

Author: Antônio Henrique Alves Pereira (Pereira A.H.A.)
[Reviewed and published online on April 5 of 2010]

INTRODUCTION

The necessity of cleaning systems for the removal of contaminants is present in various sectors, from the industrial, passing through services up to the hospital sector, mainly for maintenance of equipment and devices, for products surface preparation for reuse or for cleaning processes during the manufacture. The main types of cleaning systems can be divided into 8 groups [1]:

- Alkaline
- By solvents
- By emulsions
- By bath of molten salts
- Ultrasonic
- Acid
- Mechanics
- By pickling

The selection of the cleaning system is usually determined by the following variables [2]:

- Nature of the contaminant
- Nature of the object to be cleaned
- Degree of cleanliness required
- Geometry of the objects to be cleaned
- Quantity and frequency
- Necessity of automated processes
- Environmental restrictions and standards
- Costs and budget available

A detailed discussion of all aspects of industrial cleaning processes can be found in ASM Handbook, Volume 5 - Surface Engineering [1].

Of the mentioned systems, the cleaning by bath of molten salts and by solvents have suffered a highlighted decline in recent decades in developed countries due to increasing restrictions on the use of toxic and aggressive substances to the environment. The main alternative to the use of these processes has been the acid, alkaline or emulsion cleaning, together with the mechanical and ultrasonic cleaning. Besides being less harmful to the environment and health, these processes facilitate the deployment of automated systems [2].

In Brazil, until the 90s, the most sophisticated cleaning systems (automated and ultrasonic) were imported and used, mostly, by multinational companies who bought them in their countries of origin. The simplest systems were developed and used by small and medium enterprises, are often similar to the first imported analog versions. With the acceleration of globalization in the 90s and the ecological constraints, there arose a great demand among small and medium enterprises for more efficient cleaning systems that collaborate with the increasing competitiveness of its products and to be environmentally friendly, such as ultrasonic and automated systems for medical and hospital applications. This new market niche has already been successfully explored in Brazil for several Brazilian and foreign companies.

OVERVIEW

The technology of ultrasonic cleaning uses the cavitation and momentum transfer, induced phenomena's by the propagation of acoustic waves of high intensity, with frequencies above the human audible limit (approximately 18 kHz) in liquid media [3-4]. It is the most efficient non-abrasive method for cleaning and do not uses chemical dissolution of the substrate [4]. Associated with other methods such as alkaline, acid or emulsion's cleaning, the ultrasonic cleaning is capable of removing more complex contaminants without compromising the integrity or damage the surface that is being cleaned, is particularly effective in cleaning objects with cavities, holes and recesses [2]. Today is extensively used in the metalworking, automotive, aerospace and optical industries, for the removal of metallic and fatty residues of machining process and handling [4,5].

In Figure 1 we can see a typical industrial system for ultrasonic cleaning. There are three tanks in series: The first performs a coarse cleanup (with ultrasound of 25 kHz), the second removes microscopic particles that resist the action of the first (with ultrasound of 40 kHz), and the third one rinse, avoiding drying of any remnants of previous solutions of the tanks (which would limit the efficiency of the process). In this system, the ultrasonic sources are coupled to the bottom of the tanks and excited by a generator. The automation of this configuration is not complex, just a robot with two degrees of freedom to perform the movement of baskets of parts over the three tanks.

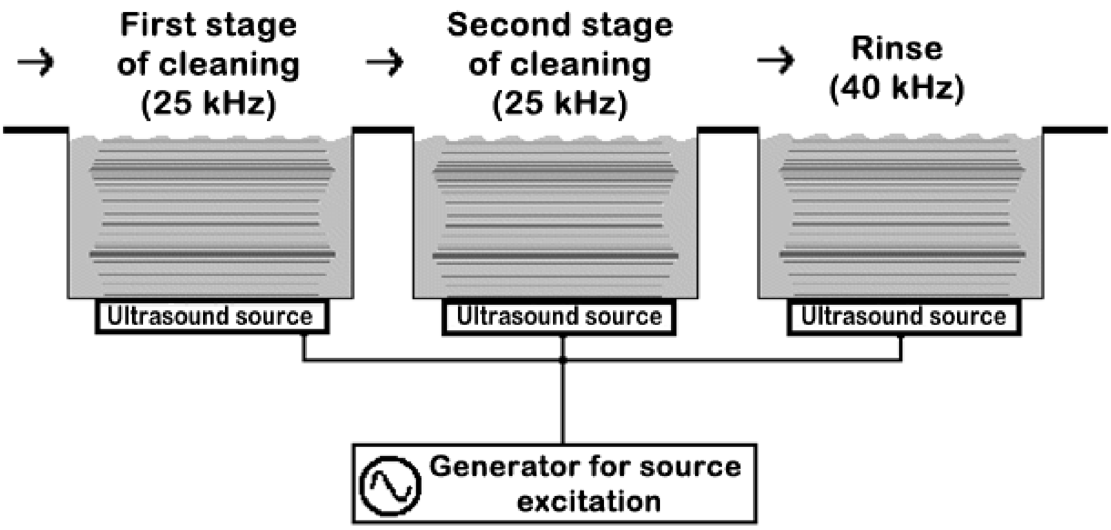

Figure 1 - Typical industrial ultrasonic cleaning system with two cleaning tanks (25 and 40 kHz respectively), and one for rinse.

In Table I we can see a comparison between the main cleaning processes used in the metalworking industry [1]. Undoubtedly, the ultrasonic cleaning is the state of the art in efficiency and repeatability, and leaves no doubts about its convenience and cost of operation, but is the most expensive technology.

Despite high costs, the demand for ultrasonic systems is growing rapidly, driven mainly by the previously mentioned environmental restrictions of the other technologies. The world's largest manufacturers are multinationals like Crest, Branson and Amsonic. In Brazil, stand out Unique and CTA of Brazil, and several manufacturers of small equipment for laboratories and clinics (equipment with just one tank of up to 5 liters).

Table I - Comparison between main cleaning processes used in the metalworking industry [1]. The range of notes goes from 1 to 10. To a better relative performance corresponds a higher note.

	Manual	Immersion	Emulsion	Spray	Spray+Immer. Automated	Ultra-sonic
Practicability	2	7	7	5	9	*7*
Cleanliness	4	3	5	7	7	*10*
Reproducibility	3	6	6	8	9	*9*
Cost	7	8	7	5	4	*1*
Operation cost	5	8	8	7	6	*6*

MACROSCOOPICAL ASPECTS OF CLEANLINESS

Cleanliness, in general, consist in remove permanently contaminants from a substrate, which may be the surface of any object. To carry out cleaning, you must perform work to remove the contaminants, breaking chemical bonds and overcoming the force of electrical attraction and Van der Waals, and ensure that this removal is permanent, preventing the electrical attractive force re-deposit contaminants [6]. Therefore, the cleaning of a substrate is not a simple task, especially if: The required degree of cleanliness is high, the contaminants are chemically inert, object to be cleaned has recesses and cavities or cannot undergo chemical or mechanical abrasion.

In cleaning systems by ultrasound, who performs the job of removing contaminants and keep them away from the substrate (usually with chemical help) are two phenomena of the propagation of high-intensity sound: Cavitation and momentum transfer. The macroscopic behavior of these phenomena in the cleaning process are as follows [2,5,7]:

- Increasing the dispersion and dissolution of solid films and liquids
- Erosion
- Fatigue and breakdown of contaminant layers
- Removal of air bubbles of small pits and grooves

Cavitation is the main effect on systems that operate at frequencies up to 100 kHz, and momentum transfer in systems operating at frequencies near 1 MHz (known as megasonics systems).

Dispersion and increase of the dissolution of solid films and liquids

Figure 2 shows the initial and evolved condition of a substrate immersed in a static chemical bath. Since the action of the bath only occurs at the interface, via dissolution, as the bath reacts with the contaminant forms a saturated layer, leading to reduced dissolution rate or even the stagnation of the process, making essential the mechanical action. When the object to be cleaned has a complex geometry, with cavities and crevices, often the mechanical agitation generated by air bubbles, propellers or agitators, is not enough, requiring the use of ultrasound.

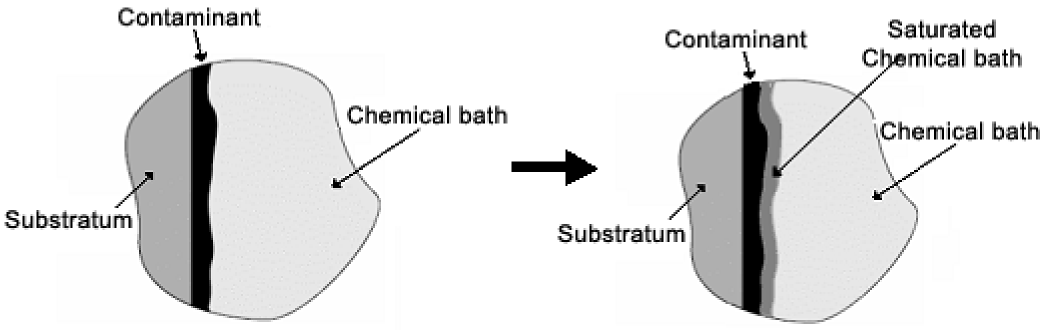

Figure 2 - Initial and evolved condition of a cleaning system where the substrate to be cleaned and the chemical bath are static.

With the presence of an ultrasonic field of high intensity in the liquid medium, the phenomenon of cavitation takes place, which we can briefly describe as the appearance of vapor bubbles that collapse, generating large differential point of pressure and temperature. In Figure 3, a pictorial representation of the action of cavitation in the dispersion of saturated bath layer and in the mechanical removal of the contaminant.

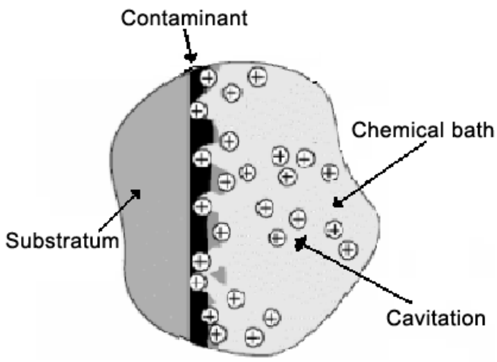

Figure 3 - Inhibition of the saturated layer and mechanical removal of the contaminant by cavitation.

Erosion

Among the myriad of contaminants, we have the chemically inerts, which are the most difficult's to remove due to the requirement of using vigorous mechanical action. For these applications, the ultrasonic cleaning systems are particularly suitable because of the erosion generated by cavitation, avoiding direct contact of the object to be cleaned with brushes or other external physical agents. See Fig.4.

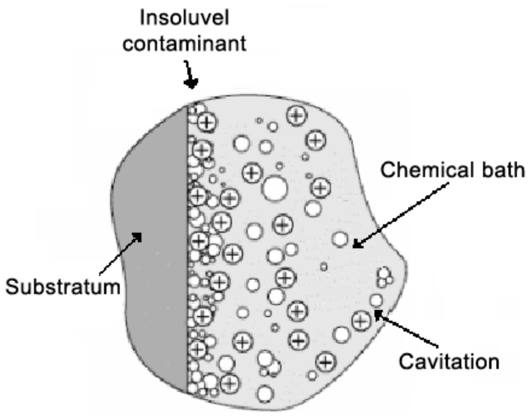

Figure 4 - Substrate with inert contaminants to the chemical bath being removed by cavitation.

In addition to cavitation, another phenomenon of propagation of intense ultrasonic fields has been explored, the momentum transfer, which becomes important at frequencies above 1 MHz. In those systems these contaminants are removed by the shear force generated by a noise jet (See Fig.5). It is also this phenomenon the principle of ultrasonic nebulizers.

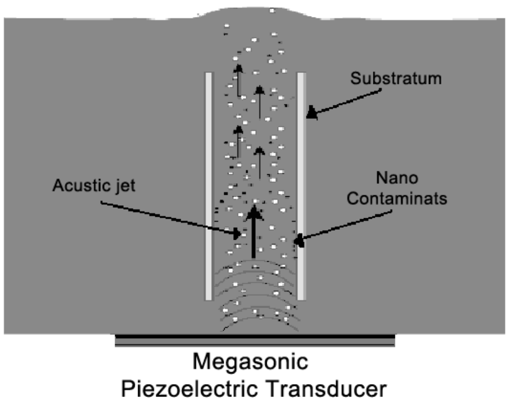

Figure 5 - Removal of contaminants of the substrate via erosion generated by the acoustic jet.

Removal of layered contaminants and air bubbles

In his propagation, the ultrasonic wave generates the expansion and contraction of air bubbles that may be trapped in holes and cavities, often preventing a thorough cleaning of the object by hindering the access of the chemical bath. These cycles leads to fatigue of layered contaminants and facilitates the removal of bubbles trapped by surface tension (during the expansion, volume increases, and consequently, the buoyant force that removes the bubble), see Figure 6. The phenomena of cavitation and the momentum transfer will be detailed and explained later.

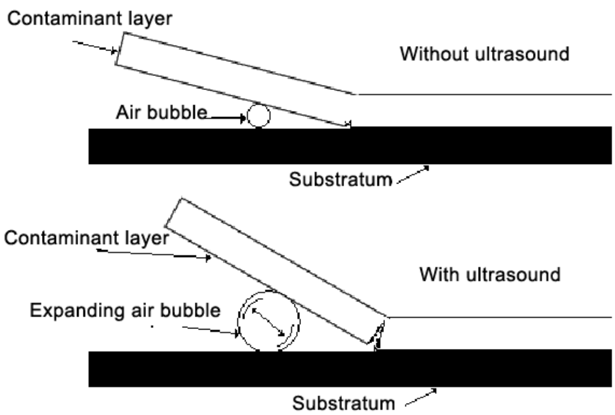

Figura 6 - Descamação de contaminantes folheados com a expansão de bolhas de ar.

ACOUSTIC SOURCES FOR ULTRASONIC CLEANING SYSTEMS

There are two kinds of acoustic sources which are used in ultrasonic cleaning systems, piezoelectric and magnetostrictive. The piezoelectrics rely on the ability of certain materials to deform when exposed to an electric field, mainly ceramics of Lead Zirconate Titanate (PZT), the magnetostrictives rely on the ability of certain materials to deform when exposed to a magnetic field, mainly, special nickel alloys. These materials constitute the active element of the ultrasonic transducers, which subjected to variables electric / magnetic fields generate acoustic fields that can easily reach 2 kW/cm2.

The magnetostrictive transducers (see Fig.7) are stronger and do not lose effectiveness over time as the piezoelectric, but in contrast, can not operate at frequencies above 20 kHz and are very expensive due to costs of alloys and type of generator (for high power / frequency and low impedance).

Figure 7 - Photo of a pair of magnetostrictive transducers. We can observe the coils wound on the core of nickel to apply the magnetic field (Blue Wave Ultrasonic).

The piezoelectric transducers, despite of the lose in efficiency with the use due to depolarization of ceramics, have several advantages that make them more attractive, such as low cost (relative) and ease of manufacturing and excitement. Supported by these strengths, these transducers have become more widespread technology, leaving to the magnetostrictive only a very small portion of the market for applications of low frequency (15 kHz). There are several types of piezoelectric transducers, the most common one is the type Langevin (TPL), which basically consists of a pair of ceramics and a pair of metal masses joined by a screw as shown in Fig.8.

Figure 8 - Example of a Langevin type of piezoelectric transducer (Crest Ultrasonics).

Besides the Langevin types, we also have the "unimorphs" and the tubulars. The "unimorphs", widely used in low-cost equipment, consist of a ceramic disc attached to a metal membrane (see Figure 9) certainly being the simplest and cheapest transducers. The tubulars (see Figure 10), are used in larger machines and require a higher technology to manufacture both, the transducer itself and the generator for electrical excitation.

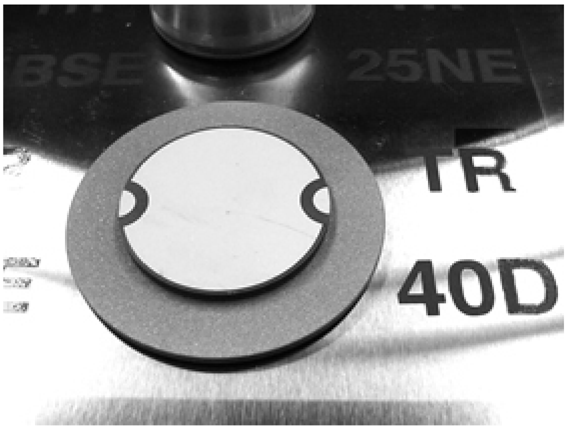

Figure 9 - Example of a piezoelectric transducer type "unimorph" (CTA, Brazil).

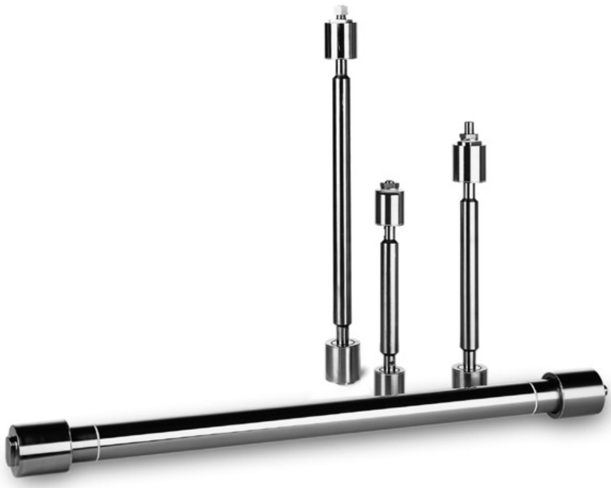

Figure 10 - Examples of tubular piezoelectric transducer manufactured in titanium (Martin WalterUltraschalltechnik).

State of the art of the Ultrasonic Cleaning Systems

The particle size distribution that a given Ultrasonic Cleaning System can effectively remove from a substrate, part or object, is a function of the frequency of the ultrasonic field. In order to extend the size distribution of particles and also reduce the negative effects of the formation of stationary waves in cleaning tanks, began the development, from the 50s, of systems capable of operate at multiple frequencies. Today, those multi-frequency systems are the "state of the art" of the industrial ultrasonic cleaning systems, and have as core, Langevin piezoelectric transducers (TPL).

Multi-frequency systems

We can divide the systems with multiple frequencies available in the market into two groups:

1-Systems with two or more sets of probes / mono-frequency generators: They are systems with two or more sets of transducers and mono-frequency generators coupled to the same cleaning tank. The first of these systems was developed in the 50s. From the decade of 70 have been developed commercial systems of 25 and 40 kHz by Branson Cleaning Equipments, Blackstone and Zenith [8,9]. The main disadvantage of this group is the need to have double number of transducers and generators. This group has only a small share of the multi-frequency market.

2-Systems with transducers and generators capable of operating at a frequency band around the main frequency and the harmonic frequencies: With the popularization of computers and the increase of environmental constraints to the use of solvents, there was a significant demand in developed countries and East Asian for ultrasonic cleaning systems that can meet the requirements of cleanliness and production speed of the microelectronic and semiconductors industry. In response to this new market demand, went ahead two American companies: Crest and CAE-Ney-Blackstone. These companies develop equipments with multiple frequencies in the range 40-170 kHz and capable of efficiently remove a wide range of particle size distribution (from a few microns to sub-microscopic particles). The equipment launched by these companies led to a second group of cleaning systems with multiple frequencies: The "group of systems with transducers and generators capable of operating in a frequency band around the main frequency and the harmonic frequencies" [10, 11]. In this group, the transducers are able to operate in harmony and are excited by generators, which in addition to multiple frequencies, can generate a scan ("sweep") around the central frequencies of each mode, collaborating in this way with the homogeneity of the power density and with the decrease of the standing waves. The frequencies at which these systems have a better performance are the fundamental (first harmonic), typically 40 kHz, and the third harmonic of about 120 kHz These systems holds the largest share of multi-frequency market.

Mono-frequential systems of 25 or 40 kHz

The 25 kHz systems are great for heavy cleaning (large amount of contaminant/particulate contaminants) and 40 kHz systems, for more delicate cleanings or the refinement of a 25 kHz cleaning. Typically these systems are associated in equipments with multistage/cleaning tanks (see Fig.1).

The traditional mono-frequency cleaning systems of 25 or 40 kHz, although for a long time has not been the state of the art, has the largest share of the ultrasonic cleaning systems market, due to the excellent cost/benefit ratio and its efficiency in performing of non-critical cleanings. These systems are widely used in the mechanical, automobilistical, aerospatial and optical industries, for the removal of metal and fatty wastes of the machining and handling processes, besides to the applications in the health area, for cleaning surgical devices. Brazil have a great demand for these systems of 25 and 40 kHz due to economic reasons and because there are limited supply of more advanced alternatives. Despite not having received major technological contributions, in order to unify their characteristics in a single bi-frequency in the range 20-50 kHz, there were developments, such as the advent of tubular transducers and generators with sweep, which improved the distribution of power density and reduced the formation of standing waves.

Expectations and Technological Perspectives for Ultrasonic Cleaning Systems

Today, most users' expectations is for devices with a better cost/benefit relationship, desires that can be fulfilled with the following innovations:

- Development of a normalized method to evaluate and standardize the quality of cleaning equipment.
- Reducing the level of acoustic noise generated by cleaning equipment..
- Compaction of the current cleaning systems while maintaining the performance and productivity.
- Development of chemicals to accelerate and facilitate the ultrasonic cleaning process.

The importance of piezoelectric ceramics for ultrasonic cleaning equipment

The piezoelectric ceramics are the "heart" of modern systems of ultrasonic cleaning. They are responsible for the conversion of electrical energy supplied by the generator in the ultrasound that will promote cavitation and cleaning. Consequently, the use of ceramics with a good quality is mandatory for get a good quality of the cleaning system.

In addition to ceramics is also important to stringent quality control in manufacturing and tuning of transducers (with electronics) using an impedanciometer or a transducers analyzer.

SUPPLEMENT: MICROSCOPIC MECHANISMS OF ULTRASONIC CLEANING

The first contact with an ultrasonic cleaning system is always intriguing. It is written in the cabinet of the machine that the operating frequency is 25 kHz or 40 kHz, both non audible frequencies, but still you can hear a hiss that resembles a frying (this hissing reaches the intensity of 90 decibels in medium and large equipments). By carefully observing the liquid, you can note the presence of filamentous formations of tiny bubbles which stir incessantly. By submerging the finger tips in ultrasonic bath, you can feel small twinges in the skin and there is an interesting release of fat that obscures the water around. Finally, can be dipped a aluminum foil in the bath to observe a mysterious disassemble of the foil within minutes. All this occurs with the liquid at room temperature. An ultrasonic nebulizer also tends to arouse enough curiosity, what comes to be that kind of cold vapor? How is it generated?

This supplement is dedicated to the understanding of the phenomena of cavitation and momentum transfer, responsible for the functioning of the ultrasonic cleaning systems.

Cavitation

The cavitation induced by pressure differentials became an known phenomenon in the late 19th century, when the British Navy was faced with the problem of power loss and corrosion of the propeller blades of his ever more powerful ships. Early studies of cavitation (performed in order to solve the problem of thrusters) were carried out by Lord Rayleigh, who created the model now known as "Rayleigh Cavity" [12]. In general, the phenomenon of cavitation refers to the formation of empty cavities or filled with gas / vapor in a liquid medium, and this definition includes the phenomena of boiling and effervescence. In the presence of sound (which generates a switched differential pressure) have the acoustic cavitation on which occurs not only the formation and expansion as well as collapse of the cavities [13]. Acoustic cavitation is the phenomenon exploited by ultrasonic cleaning systems.

Acoustic cavitation

In an absolutely pure liquid, free of diluted gases and inhomogeneities, the negative pressure required to induce the formation of cavities is very high, of the order of the tensile strength of the liquid, approximately -270 bar in the case of water (1 bar = 0.98 atmosphere). But, in ordinary liquids, some bars of negative pressure (easily provided by piezoelectric transducers) are sufficient to generate cavities from micro bubbles, dissolved gases and inhomogeneities [12]. When induced spreading of a mechanical wave (eg ultrasound) in a liquid medium, this is subjected to a alternating pressure differential that generates cycles of compression and expansion according to the frequency and amplitude of the wave. In expansion cycles (negative pressure differential), micro-bubbles, dissolved gases and inhomogeneities can give rise to cavities that oscillates in size, according to the frequency of compressions and rarefactions that follow, and who grow with rectified diffusion. Upon reaching a critical size where these cavities resonates with the frequency of the mechanical wave, there may be a rapid growth of the cavity volume that induces to float, to the implosion of the cavity or stabilization of the oscillations, depending on its filling (gas and/or vapor) and the parameters of the liquid and the mechanical stimulation.

The acoustic cavitation phenomenon is called "induced effervescence" when the cavities floats, "stable cavitation" when occurs the stabilization in the cavities oscillations, and "transient cavitation" when the implosion of the cavities occurs. The transient cavitation is the main phenomenon explored in the cleaning process by ultrasound. Stable cavitation cooperates with the cleaning process while stirring the liquid and with the degassing effervescence (that increases the intensity of the transient cavitation).

The transient cavitation is subdivided into gaseous and vaporous, in the gaseous the main filling of the cavities are gases which were previously dissolved in the liquid, and in the vaporous, the steam of the liquid which constitutes the bath. The implosion/collapse of gaseous cavities is less intense due to the dampening effect of the gases being transient vaporous cavitation more efficient in cleaning process. In Figure 10 we have a representation of the dynamic of the vaporous cavities presented for various ranges of mechanical wave, where the cavities appear, grows with rectified diffusion and finally collapse. The development and collapse of the cavities can occur over multiple cycles or a single cycle, depending on the parameters of the mechanical wave and of the liquid. **The lower the frequency of mechanical wave, the cavity has more time to grow in a growth cycle and where the mechanical wave is more intense, the growth rate of the cavity will be higher.**

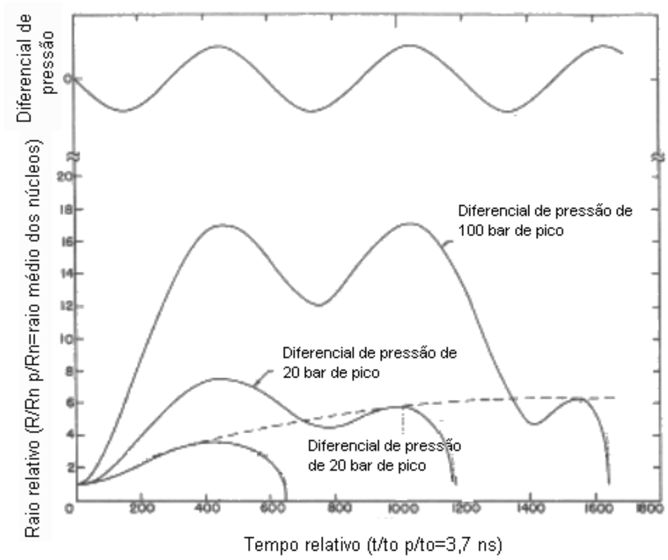

Figure 10 - Dynamics (radius as a function of time) of vaporous acoustic cavities formed in a real liquid for various ranges of ultrasound.

In Figure 11 we have a sequence of photos of the development and collapse of a vaporous cavity [15] with a similar dynamics that shown by the curve with differential pressure of 20 bars shown in Fig 10.

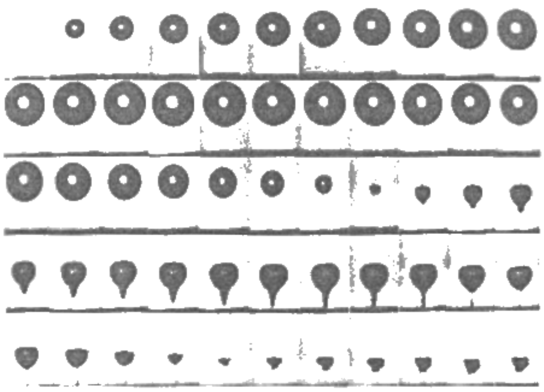

Figure 11- Pictures of the development and collapse of a vapor cavity with a similar dynamic to the showed by the curve of differential pressure of 20 bars in Figure 10.

In Figure 12 we have a picture of the moment when the cavity starts its collapse process that is not a simple reduction in the radius as predicted by the model "Rayleigh Cavity", but a non-linear phenomenon in which the cavity surface revolves.

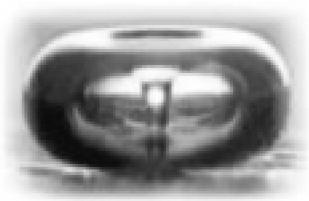

Figure 12 - Photo of the initial moment of the collapse of a cavity.

There are studies that estimate the pressure peaks and filling temperature of the cavity at the end of the process of collapse in more than 500 atmospheres and 5.000 °C [12].

Cavitation, cleaning and influence of the ultrasound frequency

The characteristic diameter of a resonant cavity, having water as liquid medium and under normal pressure and temperature, is approximately 240 µm for an excitation of 25 kHz and about 150 µm to 40 kHz. These diameters corresponds to the diameters of resonance in which the cavity will oscillate absorbing energy of the mechanical wave until collapse, and this collapse culminates in a shock wave and a high-energy jet of liquid and micro-bubbles (which will be the core of the next cavities under formation causing a chain reaction). This shock wave and the fluid jet and micro-bubbles are between 5 and 10% of the diameter of the cavity resonance (somewhere around 10 to 20 µm for frequencies in the range of 25-40 kHz) and are usually directed against nearest surface, playing the leading role of cavitation in the ultrasonic cleaning process [16].

According to the McQueen model [17], when the jet and the shock wave reaches the surface, encounter a viscous layer which is inversely proportional to the square root of the ultrasound frequency (somewhere around 2.8 µm to 40 kHz - see Figure 13) this layer protects the particles with diameters less than the thickness making them acoustically "invisible". Particles with diameters greater than the thickness of this layer are removed by viscous shear forces generated by the jet and the shock wave and the sub-microscopic particles, "invisibles" to the shear forces, are removed by the acceleration of the diffusion process of the chemically dissolved contaminants through the viscous layer, that in the absence of ultrasound would have a thickness of 30 µm, an order of magnitude higher than in the presence of ultrasound. We have, therefore, like extremes of dependence of cleaning process with the frequency the removal of particulate contaminants and coarser with lower frequencies and the removal of microscopic contaminants with higher frequencies.

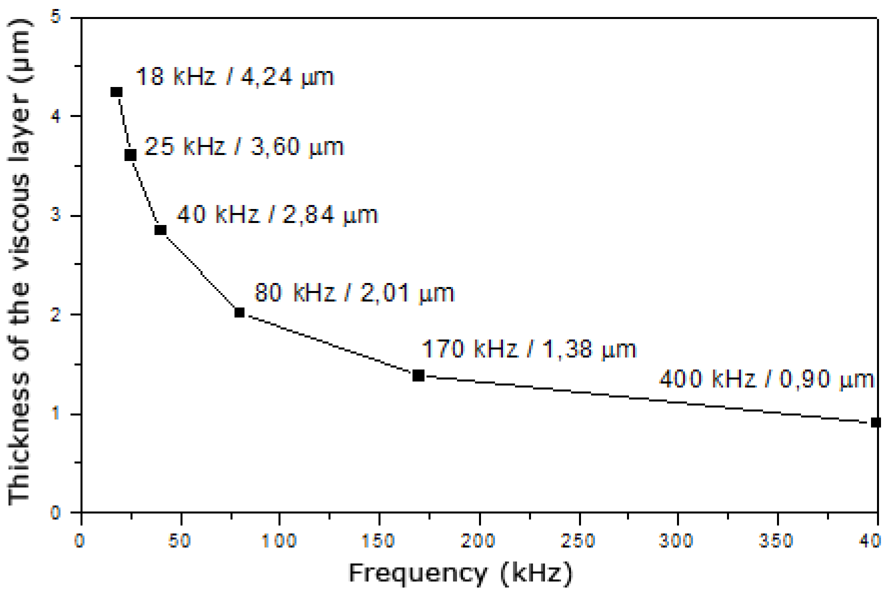

Figure 13 - Thickness of the viscous layer as a function of frequency [18]

Figure 14 shows the percentage of particles removed as a function of the particle size and the frequency of ultrasound used to induce cavitation. We can note that for the most common frequencies (25 and 40 kHz) the efficiency converges for particle sizes greater than 4 µm (the graph does not show, but for particles larger than 10 µm the performance of the ultrasound of 25 kHz exceeds that of 40 kHz), and for particle size less than 1 µm, the superiority of 40 kHz systems is significant.

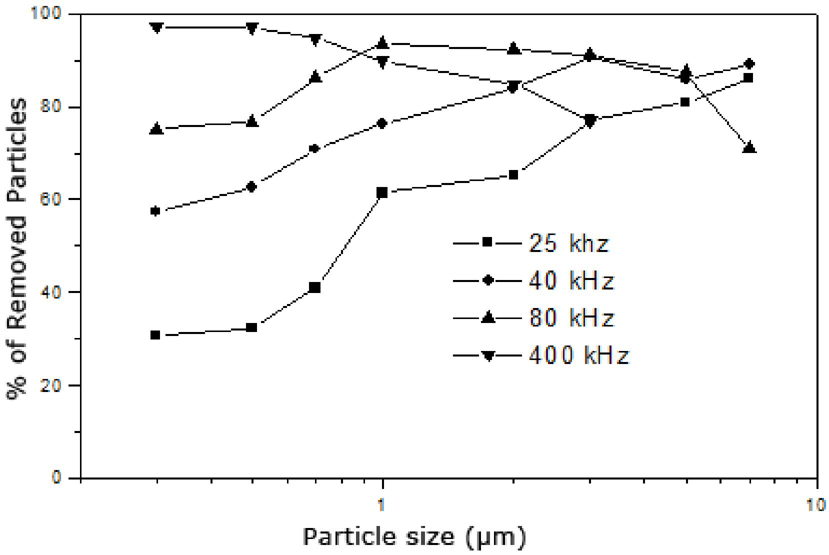

Figure 14 - Percentage of particles removed as a function of particle size and frequency of ultrasound [18].

These differences in the efficiency of mono-frequential cleaning systems as function of the frequency, justify the use of multiple cleaning tanks (see Figure 1) for medium and large systems, and the frequency selection in small equipments based on particle size distribution in the contaminant to be removed. These differences in effectiveness are the main reason for the development of multi-frequential cleaning systems.

Jet sound ("acoustic streaming")

Several phenomena associated with the non-linear acoustic such as those used by sonochemical to speed reactions (increase in heat and mass transfer, catalysis via cavitation, etc ...) are correlated with the acoustic jet, which is basically the fluid flow induced by an ultrasonic field of such intensity that cannot be modeled mathematically neglecting terms of order superior to solve the continuity equation ($\partial\rho/\partial t + \nabla \bullet \rho \mathbf{u} = 0$), propagating in a attenuating medium. Experimentally we can divide the phenomenon of jet noise in two types, a first, mainly related to the propagation of the acoustic field in an attenuating medium, and a second, related mainly to irregularities in the acoustic field and interactions with surfaces. In the first type, the fluid undergoes a force F per unit volume equal to $\rho\alpha A^2$, being ρ the density of the medium, α the attenuation coefficient of the medium and A the area of the acoustic field. In the second type, the acoustic jet and the force that the fluid is subjected depends on the boundary conditions of the propagation medium. In Figure 15 we can see the ultrasonic jets generated by an ultrasonic source of 400 kHz.

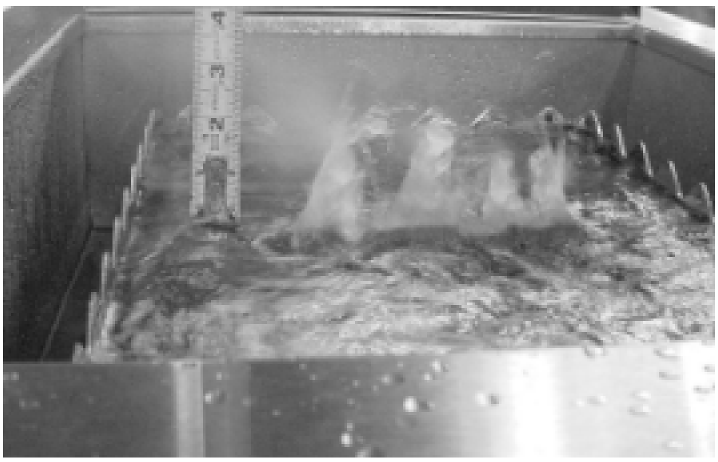

Figure 15 – Example of a "megasonic" system under operation. In this system an ultrasound source of 400 kHz generates ultrasonic jets (indicated by the white arrow) coming to jump from the surface of the liquid.

REFERENCES

[1] COTELL, C.M.; SPRAGUE, J.A.; SMIDT, F.A.; **ASM Handbook, Volume 5 / Surface Engineering**: The Materials Information Society.
[2] QUITMEYER, J.; Cleaning Challenges: Chemistry, Process, Testing, and Waste Treatment – **Cleantech Exposition 2002 Seminars**. Proceedings... CD
[3] Endereço eletrônico da **Feira da Mecânica 2004,** organizada pela Alcantara Machado Feiras de Negócios.
[4] PUSKAR, A.; **The use of High-intensity Ultrasonics**: Elsevier Scientific Publishing Company – 1982.
[5] FREDERICK, J.; **Ultrasonic Engineering:** John Wiley & Sons, Inc. - 1965.
[6] BÖSZÖRMÉNYI, I.; SEIP, C.; Ultrasonic Cleaning Fundamentals, **Cleantech Exposition 2002 Seminars**. Proceedings... CD
[7] FUCHS, J.; Ultrasonic Cleaning: Fundamental Theory and Application, **Cleantech Exposition 2002 Seminars**. Proceedings... CD
[8] PEDZIWIATR, M.P.; Ultrasonic cleaning apparatus, **United States Patent** 5,865,199, February 2, 1999.
[9] PEDZIWIATR, M.P.; Ultrasonic cleaning method in which ultrasonic energy of different frequencies is utilized simultaneously **United States Patent** 6,019,852, February 1, 2000.
[10] PUSKAS, W.L.; Apparatus and methods for cleaning and/or processing delicate parts, **United States Patent** 5,834,871, November 10, 1998.
[11] GOODSON, J.M.; Ultrasonic transducer using third harmonic frequency, **United States Patent** 6,653,760, November 25, 2003.
[12] SUSLICK, K.S.; The Chemical Effects of Ultrasound, **Scientific American** February 1989.
[13] NEPPIRAS, E.A.; Acoustic cavitation: an introduction, **Ultrasonics** January 1984.
[14] MASON, W.P.; **Physical Acoustics Principles and Methods**, Volume 1 parte B, Academic Press 1964.
[15] EDMONDS, P.E.; **Methods of Experimental Physics: Ultrasonics**, Volume 19, Academic Press 1981.
[16] NEPPIRAS, E.A.; Acoustic Cavitation, **Physics Reports** (1980) 61 159-251.
[17] MCQUEEN, D.H.; Frequency dependence of ultrasonic cleaning, **Ultrasonics**, 1986 vol 24 273-280.
[18] LAMM, E.W.; Selecting the Ultrasonic Frequency to Match the Application , **Cleantech Exposition 2002 Seminars**. Proceedings... CD.

Note: i) The contents of this application note was adapted from the dissertation "DEVELOPMENT AND CHARACTERIZATION OF BI-FREQUENTIAL POWER ULTRASONIC TRANSDUCERS FOR ULTRASONIC CLEANING SYSTEMS", by the same author presented in 2005 by UFSCar PPGCEM and web sites relevant to the subject in question. ii) The ATCP Physical Engineering is not responsible for use of the information contained herein and any associated damages.

Do you have suggestions and / or critics to improve this article?

Send to ha@atcp.com.br a / c Henrique Alves. Thank you!!