

Ultrasonic Cleaning

- What is it?
 - Use of high-frequency sound waves in the range between 40 and 200 kHz (above the upper range of human hearing, or about 18 kHz) to remove a variety of contaminants from parts immersed in aqueous media. (1)
 - Can clean metals, glass, ceramics, etc. (1)
 - Can be used with a variety of cleaning agents (1)
- How do they clean?
 - Cavitation
 - Acoustic streaming
- Advantages
 - Less time is needed to clean components (1)
 - More efficient than conventional methods in removal of contaminants. See Figure 6.4 (1)
 - Components have a greater lifespan than those cleaned by other methods. The improved surface finish reduces wear and damaging friction (1)
 - Cost of materials is reduced since fewer parts have to be rejected through inefficient or damaging cleaning (1)
 - Because of inherently small size of the cavitation jet and relatively high energy, ultrasonic cleaning has ability to reach into small crevices and remove surface soils effectively (3)
 - Although high capital costs, reduced solvent expenses can often pay for a system in a short period of time (4)

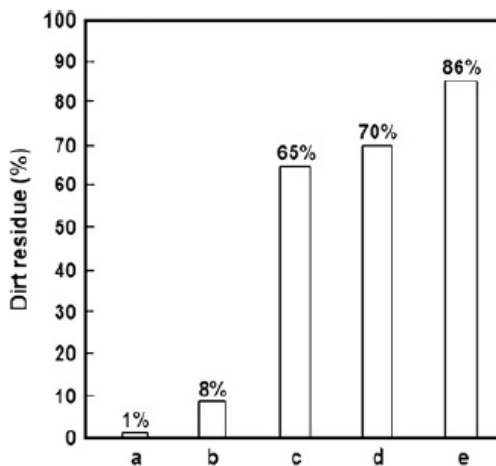


FIGURE 6.4 The efficiency of cleaning by ultrasonics is compared with the efficiency of cleaning by more conventional methods. (a) Ultrasonics. (b) Brush cleaning by hand. (c) Steam degreasing. (d) Forcible motion in fluid. (e) Spraying [17].

- Others in EPA article
- Disadvantages
 - Cavitation Erosion
 - Loss of surface material due to microscopic bubble implosion (1)
 - However, the simultaneous processes of surface cleaning and of surface erosion allow the optimization of parametric settings to maximize the cleaning efficiency, while minimizing the level of erosion damage (1)

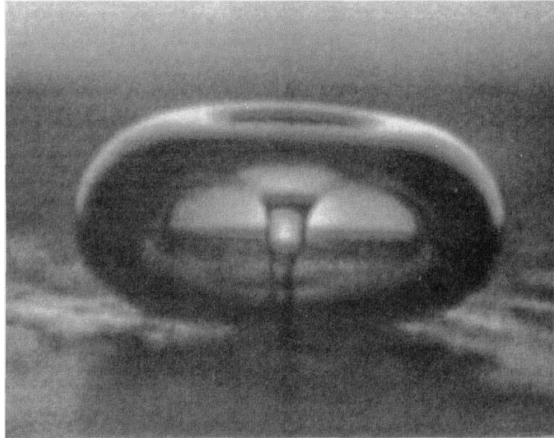
- Testing must be performed to obtain optimum combination of cleaning solution concentration and cavitation level (4)
 - Dependent upon many controllable factors
- Used in many applications
 - Microelectronics, hard-disk drives, medical devices, biomedical, automotive components, optics, jewelry cleaning (1)
- Multiple frequency choices available
 - 20–40 kHz
 - Heavy-duty cleaning - engine blocks, heavy metal parts, and for removal of heavy greasy soils (1)
 - 40–70 kHz
 - General cleaning - machine parts, optics, and other components (1)
 - This frequency range is very good at removing small particles (1)

Ultrasonic Cleaning Principles

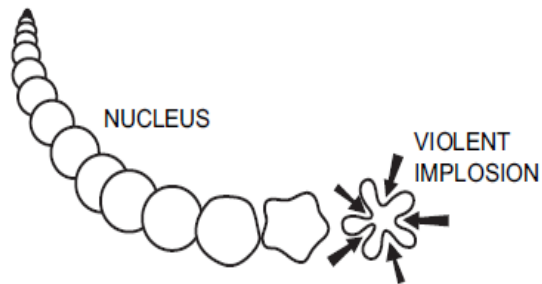
- Cavitation
 - Process
 - Cavitation action preferentially takes place at discontinuities on surface and radiates outward from them (1)
 - Scratches, pinholes, pre-existent pits, contaminant particles (1)
 - Nucleation
 - Micron size bubbles form and grow due to alternating positive and negative pressure waves in solution (3)
 - Transient cavities (vacuum bubbles, vapor voids) are produced (1)
 - Constructive combination of acoustic waves results in a decrease in pressure, creating a localized bubble (1)
 - Bubble consists almost entirely of solvent vapors in properly degassed solutions (1)
 - Growth
 - Vacuum nucleus continues to grow as liquid molecules are extended against and beyond the liquids natural elasticity/bonding/attraction forces (1)
 - Bubbles continue to grow until they reach resonant size (3)
 - Implosion
 - Just prior to implosion, there is a large amount of energy stored in the bubble itself (3)
 - Ultrasonic pressure wave goes through compression cycle, the localized pressure drops, and the bubble collapses (1)
 - The implosion event, when it occurs near a hard surface, changes the bubble into a microscopic jet about one tenth of the bubble size (3)
 - The jet travels at speeds up to 400 km/h toward surface (3)
 - Occurs on the order of microseconds (1)
 - Pressure of about 35-70 MPa (1)
 - Localized temperatures of 5000 degrees C (1)
 - *At 20 kHz frequency (1)

- Jets remove particles from surfaces and convey cleaning chemicals to organic and inorganic chemical contamination on surface (1)
 - Combination of pressure, temperature, and velocity allows the jet to free contaminants from their bonds with substrate (3)

- Diagrams



- Fig. 1 Imploding cavity in a liquid irradiated with ultrasound captured in a high-speed flash photomicrograph. Courtesy of National Center for Physical Acoustics, University of Mississippi (3)



- FIGURE 6.16 Growth and collapse (implosion) of a cavitation bubble.
- (1)

- Function of frequency
 - At low ultrasonic frequencies, cavitation is very strong and dominates the cleaning process when compared with acoustic streaming (1)
 - See Figure 6.17 – cavitation strength vs. frequency (1)

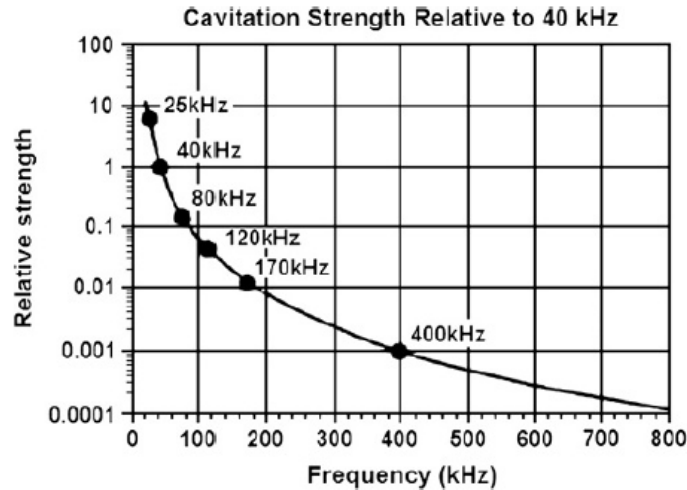


FIGURE 6.17 Cavitation strength as a function of frequency.

- The higher the frequency, the smaller the cavitation bubble size (1)

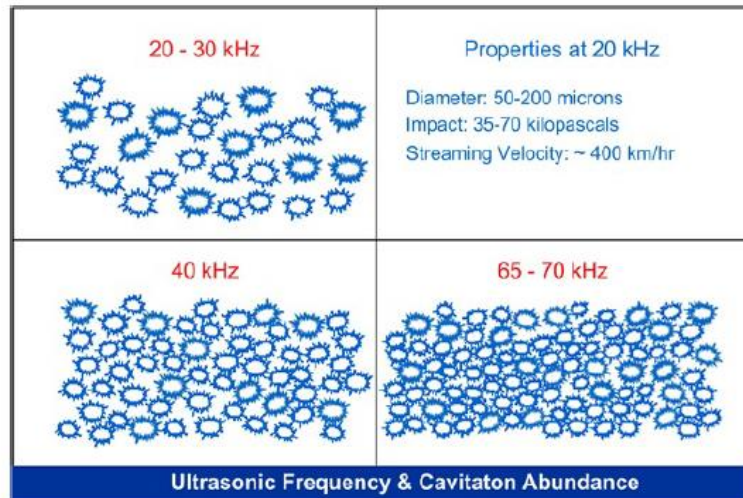


FIGURE 6.18 Cavitation abundance varies with frequency.

(1)

- Cavitation affected by several variables
 - Frequency, time, chemistry and concentration, load size, contamination level, power density, detergent or solvent type, part geometry, basket/rack configuration, cavitation uniformity, bath temperature, part material, contamination type, bath filtration (1)
- Energy required
 - Minimum energy is dependent upon natural molecular forces and natural elasticity of the liquid medium in order to grow the cavities (1)
 - For water
 - Min amount of energy needed to be above cavitation threshold were found to be about 0.3 and 0.5 W/cm² (per transducer radiating surface) for 20 and 40 kHz (1)
- In depth force calculations?
- Acoustic Streaming
 - Process

- Bulk movement of the liquid occurs (1)
- Contaminates that get removed from the surface are carried away by acoustic streaming (1)
- Can penetrate through boundary layer of motionless liquid that surrounds all tank surfaces (1)
 - At low ultrasonic frequencies, acoustic streaming is randomized and not highly directional (1)
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- Function of frequency
 - At high ultrasonic frequencies, cavitation bubbles are very small, and acoustic streaming velocities can be very high (1)

Ultrasonic Cleaning System

- Basic Components
 - A bank of ultrasonic transducers mounted to a radiating diaphragm, an electrical generator, and a tank filled with aqueous solution. (3)
 - An ultrasonic cleaner is simply a metal tank (stainless steel; Figure 6.10A) that has piezoceramic transducers bonded to the bottom (Figure 6.10B) or side. The transducers are coupled to an ultrasonic generator.

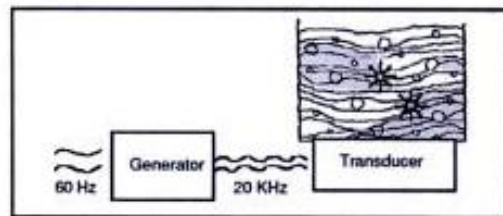


Figure 6. Ultrasonic cleaning tank.



FIGURE 6.10 Ultrasonic tank.
Courtesy of Crest Ultrasonics.

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- Transducers
 - Purpose
 - Convert alternating electrical energy to vibratory mechanical energy to produce the positive and negative pressure waves in the aqueous medium (1)
 - The transducers vibrate at their resonant frequency due to a high-frequency electronic generator source; induce amplified vibration of the diaphragm (1)
 - Range in frequency from 20 to 80 kHz (3)

(1)

- This amplified vibration is the source of positive and negative pressure waves that propagate through the solution in the tank (1)
 - When transmitted through water, these pressure waves create the cavitation process. (1)
 - The resonant frequency of the transducer determines the size and magnitude of the resonant bubbles. (3)
 - The lower frequency produces larger bubbles with more energy. (1)
 - The higher the frequency, the less aggressive is cavitation and the smaller are the implosions (1)
- Piezoelectric vs. Magnetostrictive
 - Piezoelectric transducers
 - Convert alternating electrical energy directly to mechanical energy through the use of the piezoelectric effect (1)
 - Certain materials change dimension when an electrical charge is applied to them. (1)
 - When excited by a high-frequency electronic generator, the transducer vibrates at resonant frequency (1)
 - Problems
 - The performance of a piezoelectric unit deteriorates over time.
 - The crystal tends to depolarize itself over time and with use, which causes a substantial reduction in the strain characteristics of the crystal (3)
 - Less vibratory energy is produced, and a decrease in cavitation is noticed in the tank (3)
 - Piezoelectric transducers are often mounted to the tank with an epoxy adhesive, which is subject to fatigue at the high frequencies and high heat generated by the transducer and solution (3)
 - The epoxy bond eventually loosens, rendering the transducer useless. (3)
 - The capacitance of the crystal also changes over time and with use, (3)
 - Affecting the resonant frequency and causing the generator to be out of tune with the crystal resonant circuit. (3)
 - Energy transfer of a piezoelectric transducer is another factor. (3)
 - Because the energy is absorbed by the parts that are immersed in an ultrasonic bath, there must be a substantial amount of energy in the tank to support cavitation. (3)
 - If this is not the case, the tank will be “load-sensitive” and cavitation will be limited, degrading cleaning performance. (3)
 - Due to the low mass of the piezoelectric transducers, manufacturers must use thin diaphragms in their tanks. (3)
 - A thick plate simply will not flex (and therefore cause a pressure wave) given the relatively low energy output of the piezoelectric transducer. (3)
 - There are several problems with using a thin diaphragm. A thin diaphragm driven at a certain frequency tends to oscillate at the upper harmonic frequencies as well, which creates smaller implosions. (3)

- Another problem is that cavitation erosion, a common occurrence in ultrasonic cleaners, can wear through a thin-wall diaphragm. Once the diaphragm is penetrated, the solution will damage the transducers and wiring (3)
- Magnetostrictive transducers
- known for their ruggedness and durability in industrial applications
- When current flows through the coil it creates a magnetic field, and nickel has a unique property of expanding or contracting when it is exposed to the magnetic field.
 - This is analogous to deformation of a piezoelectric crystal when it is subjected to voltage.
 - When an alternating current is sent through the magnetostrictive coil, the stack vibrates at the frequency of the current.
- Advantages over Piezoelectric
 - The nickel stack of the magnetostrictive transducer is silver brazed directly to the resonating stainless steel diaphragm.
 - The silver braze creates a solid metallic joint between the transducer and the diaphragm that will never loosen.
 - The silver braze also efficiently couples the transducer and the diaphragm together, eliminating the damping effect that an epoxy bond creates.
 - The use of nickel in the transducers means there will be no degradation of the transducers over time; nickel maintains its magnetostrictive properties on a constant level throughout the lifetime of the unit.
 - Magnetostrictive transducers also provide more mass, which is a major factor in the transmission of energy into the solution in the ultrasonic tank.
 - Zero-space magnetostrictive transducers have more mass than piezoelectric transducers, so they drive more power into the tank, and this makes them less load-sensitive than piezoelectric systems.
 - A radiating diaphragm that uses zero-space magnetostrictive transducers is usually 5 mm (in.) or greater in thickness, eliminating any chance for cavitation erosion wearthrough. Heavy nickel stacks can drive a plate of this thickness and still get excellent pressure wave transmission into the aqueous solution.
- In summary, the advantages of zero-space magnetostrictive transducers are:
 - They are silver brazed for permanent bonding with no damping effect
 - They provide consistent performance throughout the life of the unit with no degradation of transducers
 - Their high mass results in high energy in the tank and less load sensitivity
 - Their thick diaphragm prevents erosion wearthrough
- Problems
 - The magnetostrictive transducer is not as efficient as a piezoelectric transducer.

- For a given voltage or current displacement, the piezoelectric transducer will exhibit more deflection than the magnetostrictive transducer.
- Ultrasonic Generator
- <http://www.americanpiezo.com/standard-products/ultrasonic-cleaning-transducers.html>
- - Energizes the transducers. The generator transforms the electrical energy from the power source into a suitable form for efficiently energizing the transducers at the desired frequencies.
 - The ultrasonic generator converts a standard electrical frequency of 60 Hz into the high frequencies required in ultrasonic transmission, generally in the range of 20 to 80 kHz.
 - Designed to power a specific number of transducers.
 - Each transducer requires a minimum amount of voltage to activate, usually about 75% of the maximum voltage of the transducer.
 - A typical generator usually has controls for varying the amount of power to the transducers (power intensity control), and a built-in frequency sweep that will vary the frequency sweep rate (sweep frequency rate control) over the operation range of the transducer.
 - Fixed vs. swept frequency
 - When using a fixed-frequency transducer nodes and antinodes are formed (standing waves) in the fluid, which produce variations of cavitation energy with position. These standing wave patterns can be modified by reflection of the pressure waves from surfaces in the tank.
 - This variation in cavitation with position can be overcome somewhat using swept-frequency generation.
 - A typical system uses 40 ± 2 kHz.
 - This technology eliminates the standing waves and hot spots in the tank that are characteristic of older, fixed-frequency generators.
 - Autofollow circuitry is designed to maintain the center frequency when the ultrasonic tank is subject to varying load conditions.
 - When parts are placed in the tank or when the water level changes, the load on the generator changes. With autofollow circuitry, the generator matches electrically with the mechanical load, providing optimum output at all times to the ultrasonic tank.
 - If frequency sweeping is not used or there are large variations of cavitation energy with position, the parts should be moved from one region to another in the tank during cleaning.
 - Conversion Diagram

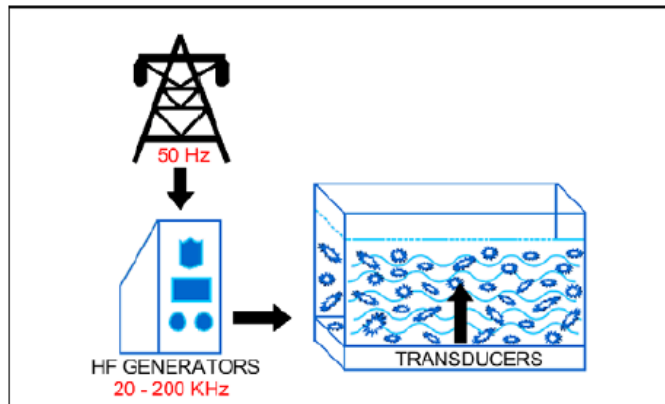


FIGURE 6.1 Ultrasonic cleaning system (from www.crest-ultrasonics.com).

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- Tank
 - Purpose
 - Contain solution, isolate cavitation process, serve as transducer mount and diaphragm
 - Geometry Effects
 - Generally rectangular and can be manufactured in just about any size.
 - The size of the ultrasonic tank (Figure 6.10) is dependent upon the parts being cleaned.
 - Transducers are usually placed in the bottom or on the sides, or sometimes both when watt density (watts per gallon) is a concern.
 - The transducers can be welded directly into the tank, or watertight immersible units can be placed directly into the aqueous solution.
 - Construction
 - A tank should be sturdy in construction, ranging from 11 to 14 gauge in thickness.
 - Larger, heavy-duty industrial tanks should be 11 to 12 gauge and should contain the proper stiffeners for support due to the weight of the solution.
 - Tanks are normally made of 316L stainless steel.
 - However, some tanks are made of special alloys or polymers.
 - The tank surface may be electropolished for reduced surface roughness or physical vapor deposition (PVD) coated with TiN to preserve against erosion.
- Basket
 - In some existing systems, there is a large inventory of stainless steel baskets for handling the parts throughout the cleaning system.
 - If possible, it is best to use these baskets due to the relatively high cost of replacement.
 - In ultrasonic cleaning, the mesh size or hole configuration of the basket is very important.
 - Mesh sizes greater than 200 mesh or less than 10 mesh work best.
- Tank Assembly
 - Electrical energy at the ultrasonic frequency is supplied to the transducer by the ultrasonic generator. This electrical energy is applied to piezoelectric/magnetostrictive element(s) in the transducer, which vibrate. These vibrations are amplified by the resonant masses of the transducer and directed into the liquid through the radiating plate.
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 - Active vs. still tank

- A tank is considered active if it is fitted with transducers and can be activated to produce cavitation
- It is considered a still tank if it has not (yet) been activated to produce cavitation or has not been fitted with ultrasonic transducers.
 - A still tank can be activated by insertion of an immersible transducer into the bath.
 - The more common method of inducing cavitation in a cleaning tank is to fasten transducers to the outer surface of the bottom or sides (or both) of the tank
- Constructing new vs. changing existing system
 - If a current system exists, such as a vapor degreaser or soak tank, several things need to be considered.
 - It may be practical, and possibly most economical, to retrofit the existing unit from one that uses solvent an organic solvent to one that uses an aqueous cleaner.
 - Ultrasonic transducers can be added to an existing tank by cutting a hole in the tank and welding the transducer(s) in, or by simply dropping a watertight immersible unit into the tank.
 - The latter method will take up some room in the tank, but it requires less labor.
 - Additional work may have to be done to the tank, such as removing the cooling coils from the vapor degreaser, adding additional fittings for a filtration system, and so on.

Variables in Ultrasonic Cleaning

- Optimization of cleaning process (All correlated with cavitation?)
 - An effective cleaning process must first be developed (1)
 - amplitude and frequency of pressure wave (energy density, standing wave pattern) (2)
 - nature of the transducer fluid (density, viscosity, surface tension, vapor pressure) (2)
 - surfaces in the transducer medium that must transmit the pressure waves (2)
 - flow and filtering of the cleaner fluid (2)
 - temperature of fluid (2)
 - gas content of the fluid (2)
 - energy of cavitation implosion (temperature, pulse height of ultrasonic wave) (2)
 - cavitation density changes with position in tank (2)
 - cavitation density changes with time (2)
 - shape of the pressure pulse (2)
 - nature of ultrasonic cycle train (quiet time, degas time, cycles per train) (2)
 - geometry of the system and associated fixtures. (2)
- Cavitation optimization
 - At lower frequencies, cavitation erosion will eventually erode through the bottom of the tank over a long period of time (1)
 - More prominent with lower frequencies (1)
 - Higher frequencies will also cause erosion but it will take a relatively long time to see the effects (1)

- By adjusting power and frequency to an optimum level, erosion damage to the part and tank can be avoided (1)
- Higher frequencies result in a more even power distribution, smaller cavitation bubbles, and can remove smaller particles (1)
 - Don't want to go too small though because jets won't be strong enough to clean in a short amount of time
- Solution
 - The intensity with which cavitation takes place depends on the properties of the fluid.
 - Best to use a water-based detergent in the ultrasonic cleaning process (3)
 - Water is an excellent solvent, nontoxic, nonflammable, and environmentally friendly (3)
 - However, it can be difficult and expensive to dispose of soiled water. (3)
 - Detergents can therefore be added to lower the surface tension and provide the necessary wetting action to loosen the bond of a contaminant to a substrate. (3)
 - Also, the cavitation energy in a water-based solution is more intense than in an organic solvent. (3)
 - The energy required to form a cavitation bubble in a liquid is proportional to the surface tension and the vapor pressure.
 - Thus the higher the surface tension of the fluid, the greater the energy required to form a bubble, and the greater the energy released on collapse of the bubble.
 - Water, for instance, with its surface tension of about 70 dynes/cm, is difficult to cavitate. However, with a surfactant, the surface energy can be lowered to 30 dynes/cm and cavitation is easier.
- Temperature
 - Solution temperature has a profound effect on ultrasonic cleaning effectiveness.
 - The temperature of the transducer/cleaning media is important, not only to degas the fluids but to enhance cleaning and maximize cavitation.
 - Higher temperatures will result in higher cavitation intensity and better cleaning
 - However, if the temperature too closely approaches the boiling point of the solution, the liquid will boil in the negative pressure areas of the sound waves, reducing or eliminating cavitation.
 - Water cavitates most effectively at about 70 °C (160 °F); a caustic/water solution, on the other hand, cleans most effectively at about 82 °C (180 °F) because of the increased effectiveness of the chemicals at the higher temperature.
 - Solvents should be used at temperatures at least 6 °C (10 °F) below their boiling points (Ref 2).
- Power Density
 - The transducers(s), typically operate at 18–120 kHz, and at an energy density of about 100 W/gallon of fluid. The ultrasonic cleaner size can be from 5 gallons for a small cleaner up to very large systems using many transducers.
- Testing and other guidelines
 - Ultrasonic erosion or deformation of aluminum foil or an aluminum metallized glass surface can be used to determine the cavitation power that a surface is exposed to in the ultrasonic solution.
 - A general rule is that ultrasonic cavitation should generate ten holes in a 1x2 inch area on aluminum foil of 1mm thickness in 10 s.

- The cavitation intensity can be studied by observing the cavitation damage on a series of aluminum foils with increasing thickness.
- The damage changes from hole-generation to dimpling to pitting to no damage, with foil thickness.
- The cavitation intensity of an ultrasonic cleaner should be plotted as a function of position with fixtures and substrates in position since reflections from surfaces can change the cavitation energy distribution.
- The cavitation pattern should be checked periodically, particularly if the fixturing is changed.
- Fixturing is very important in ultrasonic cleaning to insure that all surfaces are cleaned.
 - In general, the total area of parts, in cm², should not exceed the volume of the tank, in cm³.
 - Parts should be separated and suspended with the surface to be cleaned parallel to the stress wave propagation direction.
 - The parts must not trap gases which prevent wetting of the surface by the cavitating fluid.
 - Metal or glass holding fixtures of small mass and an open structure should be used. Energy-absorbing materials such as polyethylene or fluoropolymers should not be used in fixturing since they absorb the ultrasonic energy.

References

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- (2) Surface Engineering, Ultrasonic Cleaning, Vol. 5, ASM Handbook
- (3) Handbook of Deposition Technologies for Films and Coatings, Ch. 3 – Surface Preparation for Film and Coating Deposition Processes
- (4) Guide to Cleaner Technologies – Cleaning and Degreasing Process Changes, Ultrasonic Cleaning, United States Environmental Protection Agency, Office of Research and Development, Washington, DC, February 2004