CHEMICAL APPLICATIONS FOR ULTRASONIC WAVES*

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THE APPLICATIONS for sound waves in chemistry may be divided into three classifications, (a) processing applications, (b) analysis and control and (c) fundamental studies of structure and the kinetics of chemical processes. This paper is concerned primarily with the processing applications, particularly those of significance to the cosmetic chemist. The other two types of applications have been reviewed by several authors (3, 7, 16, 32, 44–46, 53).

The acoustical spectrum is divided into three regions on the basis of the hearing limits of the human ear. Sound waves with frequencies between 20 and 20,000 cycles/sec. are referred to as sonic while sound waves with frequencies above 20,000 cycles/sec. are ultrasonic and below 20 cycles/sec. are infrasonic. Confusion has existed in the past concerning the terms supersonic and ultrasonic. Supersonic should be reserved to describe those phenomena which take place with a speed greater than that of sound under some reference condition such as in air at sea level. Thus, one should speak of supersonic flight and supersonic velocities, but in contrast, ultrasonic waves and ultrasonic frequencies.

This division of the acoustical spectrum into three regions is somewhat artificial since the majority of the physical and chemical phenomena associated with sound waves bear little relationship to the hearing limits of the human ear. Many of the processing applications are not confined to ultrasonic frequencies but can be carried out successfully at sonic and in some cases even infrasonic frequencies. In such instances, ultrasonic waves may be preferred for secondary reasons. For example, personnel operating ultrasonic equipment are not annoyed by sound waves which they can not hear.

Frequent reference will be made in this paper to acoustical intensity. This term represents the amount of sound energy per second transmitted through a 1-cm.² cross section perpendicular to the direction of propagation of the sound waves. Acoustical intensity is often expressed in watts/cm.² which corresponds to joules/sec.-cm².

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Many of the processing applications are dependent on the formation of cavitation bubbles within liquids. For this reason it is worthwhile to consider the basic processes associated with cavitation before discussing the applications.

The transmission of sound waves through a liquid is attended by periodic variations of pressure. With sound waves of high intensity, these variations in pressure may be sufficient to develop tensions within the liquid provided the liquid does not rupture. In most cases, cavitation occurs within the liquid before tensions are developed. The nucleation of the cavitation bubbles, however, is a problem since the cohesive forces within the liquid are usually equivalent to tensions far greater than can be produced acoustically. Under ordinary circumstances, a liquid contains micro dust particles which have at least partially hydrophobic surfaces. If the liquid also contains a dissolved gas, micro bubbles filled with both vapor and the gas are expected to exist within the cracks or surface irregularities of these particles even though the liquid is not completely saturated with the gas. With the introduction of sound waves into the liquid, these bubbles periodically vary in size. More dissolved gas diffuses into a bubble during the rarefaction than redissolved during the compressional part of the acoustical cycle. This results in the growth of the bubbles with each cycle through rectified diffusion to a size which may be considerably larger than that of the partially hydrophobic particles. When a bubble attains a size corresponding to a resonance condition, the expansion and partial collapse of the bubble with each cycle of the sound waves become extreme. Instantaneous pressures within the cavitation bubbles and in the liquid immediately adjacent to the bubbles may reach in excess of 10³ atm. primarily because of the finite momentum of the liquid as the bubbles partially collapse. The situation is somewhat analogous to the wellknown water hammer which occurs when liquid flow is stopped abruptly within pipes. The destructive effects of the shock waves originating from these resonating cavitation bubbles are far greater than any associated with the sound waves responsible for the cavitation. Since the compression of the gases within the bubbles is at least partially adiabatic, relatively high instantaneous temperatures are believed to be realized within the bubbles (e.g., >1000°C.). Furthermore, there is evidence that larger cavitation bubbles in higher order resonance modes generate many additional small bubbles (51) which in turn grow until a resonance condition is reached. For a more detailed discussion of cavitation, the reader is referred to references 3, 7, 16 and 51.

With commercially available equipment cavitation can be produced easily at frequencies from a few hundred through two megacycles per second. In water only a fraction of a watt/cm.² is ordinarily required. At frequencies below 1 mc./sec., cavitation does not appear to be a partic-



Figure 1.—Cavitation in water produced by focused ultrasonic waves at a frequency of 600 kc./sec. from a concave barium titanate sound source. The white blur in the center represents intense cavitation at the convergence of the ultrasonic waves.

ularly frequency dependent phenomenon. Above 1 mc./sec. increasingly higher acoustical intensities are required to produce appreciable cavitation until at several megacycles per second the acoustical intensities available for practical purposes are insufficient to produce cavitation effects. Since the majority of the processing applications involve cavitation, this means that a wide range of frequencies is available for such applications.

PROCESSING APPLICATIONS

The processing applications for ultrasonic waves may be resolved into the following basis effects.

- 1. Dispersion of solids and liquids.
- 2. Coagulation and precipitation of suspensions.
- 3. Degassing of liquids.
- 4. Promotion of mass and heat transfer in gases and liquids.
- 5. Initiation and control of crystallization.
- 6. Sonochemical reactions.

Each of these will be discussed in terms of the proposed mechanisms for the effects and the present as well as potential utilization of these effects in the chemical industry. A brief review of the equipment commercially available for such applications will be presented at the end of the paper.

Dispersion of Solids and Liquids

Intense sound waves are capable of dispersing materials in both the liquid phase (41, 42) and the gas phase (25, 40). Dispersion in the liquid phase will be considered first. Two mechanisms have been proposed to explain the dispersion of solids and liquids by intense sound waves. In most instances the dispersing effects are contingent on acoustically produced cavitation within the liquid. The extreme mechanical effects associated with cavitation appear to be the primary agency by which solids as well as liquids are dispersed in a liquid phase.

In the case of a few liquid pairs (e.g., mercury and water), it has been observed that emulsions can be formed with ultrasonic waves even in the absence of cavitation. Surface waves are excited at the interfaces between the two liquids. The situation is represented in Fig. 2. As the amplitude of the transverse waves becomes greater, droplets of one liquid are thrown into the other liquid and vise versa. Cavitation, however, is the predominant agency for most emulsions.

While almost any solid or liquid can be suspended in a second liquid by means of cavitation, emulsions are by far the easiest to form. A survey of the literature as well as current experimental work in the author's laboratory indicate that the mean particle size for emulsions is often of the order of 1 micron, a value which is somewhat disappointing since it is relatively large for stable colloidal suspensions. For emulsions of such large particle size to be stable for any appreciable time, stabilizing agents usually must be added to provide protection. It is interesting to note that mineral oil suspensions in water produced ultrasonically even in the absence of stabilizing agents at concentrations of the order of 1 per cent oil have proved stable for periods of the order of one month. The ultimate or limiting concentration of one liquid phase in a second liquid phase is contingent on the nature of the sound source as well as the properties of the liquids. While only a small percentage of oil can be suspended in water in the absence of a stabilizing agent, concentrations in the excess of 75 per cent can be obtained with surface active agents present.

The literature provides insufficient data upon which to base any statement as to the rate of emulsification, particularly in terms of commercial processing. Crawford (7) reports that whistle-type transducers (to be described later) have been used in England to produce emulsions in the pharmaceutical, cosmetic and food processing industries. While ultrasonic waves offer promise as a means for preparing emulsions, overoptimism is to be discouraged since current indications are that ultrasonic emulsification is not yet competitive with more conventional techniques even for relatively small scale industrial applications.

The suspension of solids in liquids is more difficult to accomplish and



Figure 2.—Surface waves at the interface between two phases.

requires more intense sound waves. If the solid is already subdivided, dispersion through further reduction of particle size proceeds more readily. Ultrasonic waves are effective in breaking up agglomerated particles.

When intense ultrasonic waves within a liquid impinge on a gas-liquid interface, the liquid is dispersed as a fog. Sollner (40) has obtained evidence that cavitation within the liquid phase near the interface is involved in the formation of the aerosol. On the basis of unpublished research at Western Reserve University, the author believes that surface waves of the type represented in Fig. 2 at the liquid-gas interface also contribute to the formation of fog and may be more important than cavitation. While the fogs generated with ultrasonic waves are often dense optically, the droplet size is relatively large, and hence, the fogs are usually unstable. McCubbin (25) with ultrasonic waves at 2.4 mc./sec. in water found the mean droplet size to be between 1 and 10 microns. The fogs are more difficult to produce with viscous liquids. In Fig. 3 is a photograph of the fog produced when ultrasonic waves at a frequency of 600 kc./sec. are focused from within the liquid phase so as to converge at the water-air interface. No immediate industrial applications are anticipated for the ultrasonic formation of aerosols on the basis of present information.

Coagulation and Precipitation Effects

Ultrasonic waves are capable of producing appreciable increments in the rate of coagulation or precipitation of metastable suspensions in liquids (42). Such effects are observed only in the absence of cavitation with suspensions which lack adequate protection. In the presence of cavitation the dispersing effects usually are predominant. As a result, most of the work reported in the literature has been carried out at low intensities so as to avoid cavitation. The results at these low intensities have not proved sufficiently great to warrant industrial application. It should be noted, however, that cavitation can also be prevented even at moderately high



Figure 3.—Fog produced by ultrasonic waves at 600 kc./sec. focused to converge at the surface of water.

intensities by degassing the liquid and by using increased static pressure on the liquid. Experiments with much higher acoustical intensities without cavitation might yield faster rates of agglomeration and precipitation than have been reported to date.

The coagulation effects are the result of an increased probability of collision between particles in the presence of the sound waves. On the basis of various second order properties of sound waves, attempts have been made to predict the increase in the rate of collision. At least three factors are involved. In the sound field the displacement imparted to the large suspended particles is smaller and lags behind that of the small particles. This results in an increased number of collisions per unit time. When the sound waves encounter two particles located side by side, the periodic variations in the velocity of the solvent molecules are greater between the two particles than in the bulk of the solvent because of the partial constriction of flow caused by the suspended particles. On the basis of Bernoulli's principle, an apparent attractive force is expected between the two particles. A third factor is radiation pressure. In the presence of standing waves, radiation pressure caused the suspended particles to move to either the nodes or antinodes of the standing waves, depending on the acoustical properties of the suspended particles.

With aerosols the situation is more promising because the acoustical effects are considerably larger. The optimum frequency for most particle size distributions is sonic rather than ultrasonic (i.e., 10³ to 10⁴ cycles/sec.).



Figure 4.—Sonic precipitator for mists.

For a given particle size distribution, however, the frequency must be maintained within relatively narrow limits for large effects to be obtained. Several pilot plant sonic precipitators (8, 27) have been constructed with air driven sirens as the sound sources. Figure 4 is a diagram of a unit designed for the precipitation of sulfuric acid mists. In the standing wave field the droplets increase to a size of the order of 10 microns. A cyclone precipitator is then used to complete the precipitation. With sirens operating at a frequency in the range 1000 to 4000 cycles/sec. and driven by a 10 horsepower compressor, units of this type have been reported to be capable of handling several thousand cubic feet of mist ladden air per minute (27). Sonic precipitators of similar type also have been used for carbon and other solid particles.

Such precipitators have several disadvantages compared to conventional electrostatic precipitators. These include large power consumption, costly maintenance, corrosion problems in the sirens and erratic performance with changes in the particle size distribution in the influent. These are some of the reasons why sonic precipitators have not yet found wide use. Sonic precipitators should be considered, however, for systems where other methods of precipitation are not satisfactory, e.g., materials which constitute an explosion hazzard if precipitated electrostatically or which will not acquire the desired electrical charge in an electrostatic precipitator.



Figure 5.—Degassing of water with low intensity ultrasonic waves at a frequency of 800 kc./sec.

Degassing of Liquids

The formation of cavitation bubbles within a liquid is contingent on the presence of dissolved gases within the liquid. The growth of the cavitation bubbles leads to the degassing of the liquid. Evidence of this degassing effect can be seen in terms of the air bubbles shown in Fig. 5. The water within the vessel is being subjected to relatively low intensity ultrasonic waves (<1 watt/cm².) at a frequency of 800 kc./sec. Degassing effects are even more pronounced if the pressure of the gas above the liquid is reduced so as to help prevent the redissolution of the gas in the liquid. The degassing of liquids with sonic or ultrasonic waves on a large scale is entirely feasible. Such a technique should offer particular advantage in the case of viscous liquids which are difficult to degas. The removal of dissolved gases from molten metals (39) and molten glass (22) with ultrasonic waves has been reported. Relatively little acoustical power is required and equipment is available for continuous flow processing.

Mass and Heat Transfer Within Fluids

The rates of many physical and chemical processes involving two or more phases are limited by diffusion in the fluid phases despite extensive mechanical agitation. Usually a boundary layer persists in the fluid phases at the interfaces. In the case of a liquid phase, this boundary layer cannot be reduced to less than 10^{-3} cm. with ordinary agitation. Sound waves are capable of disrupting these boundary layers and the associated diffusion gradients in the case of both gases and liquids.

Research (52, 53) at Western Reserve University has shown that cavitation is the primary agency for the disruption of concentration gradients within liquids. A Schlieren microscope has been used to prove that ultrasonically produced cavitation reduces the effective thickness of the boundary layer at a solid-liquid interface to 10^{-4} cm. as compared with the value of 10^{-3} cm. stated above. The oscillating cavitation bubbles near the interface produces micro-agitation which disrupts the gradient. In processes which are limited by diffusion in a liquid phase despite extensive stirring, ultrasonic waves offer promise as a means for increasing the reaction rates. This is particularly important for reactions involving a liquid phase within a porous solid. Typical of the heterogeneous processes, the rates of which can be substantially increased with ultrasonic waves, are extraction processes, dialysis (31), dissolution of sparingly soluble materials, electrodeposition (52, 53) and dyeing of fabrics (5).

The effects of ultrasonic waves in promoting the cleaning of metal surfaces with organic solvents as well as the cleaning of fabrics with detergents is in part the result of improved mass transport within the liquid phase. In addition, however, cavitation helps to disperse material adsorbed on the solid surfaces. Industrial cleaning of metal surfaces with ultrasonic waves at the present time is probably the most important processing application for sound waves.

Sound waves are also capable of reducing concentration gradients within gas phases. Unfortunately information is not generally available in the literature as to the magnitude of the effects or the practicality of using sound waves for promoting mass transport in gases on a large scale.

Inasmuch as sound waves expedite mass transport within fluids, heat transfer should also be increased. The mechanisms as well as the magnitude of the effects should be the same for both cases. The use of sound waves in heat exchangers involving either gases or liquids might permit an appreciable reduction in size. The generation of the sound waves within the heat exchanger can be accomplished readily by incorporating a flow-type generating unit in the feed line to the exchanger. Such devices operate off the flow of fluid through them and will be described later in this paper.

Crystallization Effects

Ultrasonic waves have been reported to increase the probability of nucleation for the formation of crystals in a number of cases (3) including organic solutions (21) which are difficult to crystallize, e.g., sucrose solutions (2, 43). Furthermore, it has been claimed that ultrasonic waves afford control over crystal size (20) with smaller crystal size being favored in supersaturated solutions. An adequate quantitative theory has not yet been developed for the effect of ultrasonic waves on crystal nucleation. It is well known, however, that any form of mechanical motion in a liquid tends to increase to some extent the rate of nucleation. The tendency for smaller crystals to be formed can be explained in terms of the development of many centers for crystal growth simultaneously in the presence of the sound waves. The author has learned of several companies in the United States which are using ultrasonic waves on a small industrial scale to help promote and control the crystallization of organic materials.

Sonochemical Reactions

The term sonochemical reactions describes those chemical reactions which can be made to take place through the action of sound waves. All sonochemical reactions appear to be contingent on cavitation. In the absence of cavitation, ultrasonic waves even at the highest intensities currently available in the laboratory do not have sufficient energy to break ordinary chemical bonds.

Typical of the sonochemical reactions which have been studied extensively are the following:

- 1. The formation of hydrogen peroxide in water containing a dissolved gas such as a rare gas or oxygen (13, 23).
- 2. The formation of nitrogen compounds in water saturated with nitrogen gas (29).
- 3. The breakdown of various organic molecules in the liquid state to yield decomposition products which then undergo subsequent chemical reactions (48, 50).
- 4. Ultrasonically induced polymerization (1, 10, 15).
- 5. Ultrasonic degradation of polymers (19, 26, 36-38, 49).

Two types of mechanisms involving cavitation have been proposed to explain sonochemical reactions. The first is contingent on the fact that the compression of gas within the cavitation bubbles during the part of the cycle involving collapse is at least partially adiabatic. Very high instantaneous temperatures then are to be expected within the bubbles (13, 47). These high temperatures (e.g., 1000°C.) in turn cause the dissociation of the various components within the cavitation bubbles. In aqueous solutions, water is dissociated to yield hydrogen and hydroxyl radicals. The over-all sonochemical reaction is then the result of subsequent reactions of the dissociation products. For example, according to this mechanism the sonochemical formation of hydrogen peroxide in water during cavitation represents the recombination of the hydroxyl radicals.

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If nitrogen gas is present, the reaction of the nitrogen with the hydroxyl radicals results in the formation of nitrites and nitrates.

The second proposed mechanism involves electrification phenomena which have been postulated by various workers (11, 12, 14, 23) to be associated with the development cavitation bubbles. Electrical discharges are presumed to occur within a cavitation bubble because of charge differences between various parts of the bubble such as the atmosphere within the bubble and the surface of the bubble. Sonochemical reactions are attributed to the dissociation of various components of the cavitation bubbles as result of these discharges.

Unfortunately the primary mechanism for sonochemical reactions has not yet been completely resolved. Recent work (9) with isotopic techniques for the study of the sonochemical formation of hydrogen peroxide supports the thermal dissociation mechanism far better than any electrification mechanism.

Sonochemical reactions in general are characterized by poor yields in terms of the amount of acoustical energy required for the reactions. Furthermore, the majority of the reactions are only of minor industrial significance even if good yields were obtained. Such reactions as the formation of hydrogen peroxide, however, must be considered when studying the effects of sound waves on biological systems—for example, in the sterilization of water.

The most extensively studied sonochemical reaction is the formation of free iodine in aqueous solutions containing potassium iodide and saturated with carbon tetrachloride (13, 47, 48, 50). Starch is usually added to establish the presence of the I₂. A deep blue color develops within a few seconds after the solution has been introduced into a moderately intense sound field (e.g., 5 watts/cm.²). During cavitation, the carbon tetrachloride is dissociated to yield Cl_2 which in turn reacts with the iodide ions to form I₂. A small fraction of the I₂ is also the result of the oxidation of the iodide ions by sonochemically produced hydrogen peroxide.

One type of sonochemical reaction which may prove of industrial significance is the initiation of polymerization with ultrasonic waves (1, 15). Free radicals formed during cavitation are capable of initiating free radical polymerization (23). The information in the literature is not sufficient to provide a basis for evaluating the full promise of this type of sonochemical effect.

Ultrasonic waves are also capable of degrading polymers dissolved in solution. The monomer is not produced. According to some investigators (24, 26, 36), cavitation is not required for polymer degradation with ultrasonic waves. These workers attribute the degradation to fractional and shear effects inherent in the sound field. In most instances, however, supporters of this theory have not taken adequate precautions to prevent cavitation in their experimental work and have made mathematical assumptions in their theoretical treatments which do not appear to be justified. The majority of the workers (19, 30, 33, 49) believe that cavitation is required for ultrasonic degradation. Recent measurements in the author's laboratory (33) indicate that degradation does not occur with solutions of polymers such as polystyrene in the absence of cavitation even at an intensity of 1000 watts/cm.², a value some 30 fold higher than used by previous workers. The mechanical effects associated with resonating cavitation bubbles are far greater than those associated with the sound waves which give rise to the cavitation. The extreme rates of shear near the surface of the cavitation bubbles probably lead to the rupture of the polymer molecules.

The graph in Fig. 6 indicates (33) the extent of the degradation of polystyrene dissolved in toluene as a function of acoustical intensity and frequency under the conditions stated in the legend. The relative viscosities of the polymer solutions are represented on the left ordinate while the viscosity-average molecular weights are represented on the right. The initial molecular weight was 3.3×10^6 . The threshold intensity for degradation in Fig. 6 correlates with the threshold for cavitation.

While the rate of degradation increases with increasing ultrasonic intensity, the ultimate degree of degradation is not a function of intensity (19, 28, 30, 35) provided there is cavitation. This is in accord with cavitation theory (16, 28, 35). A molecular weight of approximately 30,000 has been reported





to be the limiting value for polystyrene solutions (36). Similar results have been found for other polymers. If the molecular weight distribution of the polymer before ultrasonic degradation is relatively wide, distribution for the degraded polymer is considerably narrower.

No extensive industrial use of ultrasonic waves for the degradation of polymers is anticipated since most chemists are interested in increasing rather than decreasing the molecular weight of polymers.

In addition to the mechanical degradation associated with cavitation, intense ultrasonic waves can cause thermal degradation. The absorption of the sound energy within a liquid results in the progressive heating of the system. As a result, it is important to provide a means for cooling the liquid in order to prevent pyrolysis. The absorption coefficient for sound waves increases as the square of the frequency in most cases; hence, processing applications involving viscous liquids should be carried out preferably at relatively low frequencies to minimize thermal problems.

Of the various processing applications mentioned above, the most promising with respect to cosmetic chemistry appear to be the production of colloidal suspensions (particularly emulsions), the degassing of liquids and the expediting of mass and heat transfer in fluids. While all of these applications can be accomplished relatively easily, engineering data are generally not available.

Ultrasonic Equipment for Processing Applications

For the most part, the choice of frequencies for processing applications is not critical since cavitation occurs over a wide range of frequencies. When cavitation is to be produced throughout a relatively large tank, low ultrasonic frequencies (e.g., 20 kc./sec.) are used because the sound energy can be distributed more uniformly throughout the tank. Often very high intensities are required in a restricted region as is the case with continuous flow processing systems. In such instances, higher ultrasonic frequencies in the range 10⁵ and 10⁶ cycles/sec. are favored since ultrasonic waves of shorter wavelengths are more readily focused.

Several excellent reviews (3, 6, 7, 16, 17) on ultrasonic equipment for industrial applications have been published in recent years. Only a brief résumé of ultrasonic generators will be presented in this article. Samsel (34) has also considered a number of the factors involved in the choice of generating devices for various applications.

The majority of the processing applications involve the propagation of ultrasonic waves through liquids. Three types of ultrasonic generators have been used extensively for this purpose: (a) hydrodynamic devices, (b) piezoelectric transducers and (c) magnetostrictive transducers. The term transducer refers to any device which changes one form of energy to another, e.g., alternating electrical energy to sound waves. The hydro-



Figure 7.-Hydrodynamic generator.

dynamic and magnetostrictive generators are best suited to sonic and low ultrasonic frequencies (5000-50,000 cycles/sec.). Piezoelectric transducers are practical for frequencies as low as 10,000 cycles/sec. but have found most extensive use in the range 100 to 1000 kc./sec. for processing applications.

Hydrodynamic Devices

Hydrodynamic generators convert the mechanical energy associated with liquid flow to acoustical energy. One of the simplest types for producing moderately intense ultrasonic waves in liquid is the resonant wedge whistle of Janovski and Pohlman (18) as shown in Fig. 7. A jet of liquid impinges in a wedge-shaped resonator. Intense sound waves are then propagated into the liquid from this resonator and cavitation results. Units of this type are commercially available. This type of sound source is inexpensive both in terms of the initial cost and operation. Crawford (7) reports that such liquid phase whistles operating at 30 kc./sec. have been used for the dispersion of water and oil in the manufacture of hair cream. Several other types of hydrodynamic oscillators (4) have been developed to convert hydrodynamic flow to oscillatory motion and may become feasible for the generator of acoustical waves at sonic and low ultrasonic frequencies for processing applications with a minimum of cost.

Piezoelectric Transducers

If a single crystal of a material with an anisotropic lattice is placed in an electrical field, the crystal will change its dimensions. This effect, known as the inverse piezoelectric effect, is utilized as a means for converting electrical energy to acoustical energy. Periodic variations in the dimensions are produced through the use of an alternating electrical field. Sound waves are then propagated into any medium in contact with the vibrating surfaces of the transducer. The electrical power to drive these transducers is obtained from an electronic radio-frequency generator.

Prior to World War II, α -quartz was used almost exclusively for the generation of intense ultrasonic waves by the piezoelectric effect. A diagram of a transducer of this type is shown in Fig. 8. The alternating electrical field is applied by means of a metal conducting coating on the two plane surfaces of the circular quartz plate. The frequency of the



Figure 8.—Piezoelectric transducer assembly.

sound waves is the same as that of the alternating electrical field but the frequency must be adjusted to correspond to a resonance mode of the quartz plate if intense ultrasonic waves are to be generated. With the unit in Fig. 8, the majority of the ultrasonic energy is propagated into the liquid rather than the air on the reverse side of the quartz plate. Transducers of the type described above are of limited value in processing applications because α -quartz is expensive, is generally available only in simple geometric shapes of relatively small size and requires high voltage for operation.

Since World War II, the ferroelectric materials have been used extensively in place of guartz. Ferroelectric materials such as barium titanate can be produced in a variety of shapes since they are polycrystalline yet behave very similar to the single crystal of an ordinary piezoelectric material. In addition the ferroelectric materials cost less than α -quartz and require far lower a.-c. voltages to drive them. Several types of barium titanate transducers are shown in Fig. 9. Transducer A can be mounted in place of the quartz plate in Fig. 8. The spherically concave transducer B focuses the sound energy to substantially a point while the transducers C and D have a line focus. Through this focusing action, ultrasonic intensities (e.g., 10² and 10³ watts/cm.²) far higher than previously available can be used for processing applications. The hollow cylindrical type can be obtained mounted within the wall of a stainless steel pipe with flanges for connection into a continuous flow processing system. Barium titanate is also available in several other forms within stainless steel jackets suitable for submergence in processing tanks.



Figure 9.—Ferroelectric transducers. A—circular plate, B—spherically concave bowl, C—hollow cylinder, D—trough type. Electrical leads to metallic coatings on parallel surfaces.

Magnetostriction Transducers

Figure 10 is a diagram of a magnetostriction transducer. In the presence of a magnetic field with an alternating component, certain metals such as nickel will be periodically elongated and contracted. If one end of the bar is connected to a diaphragm in contact with a liquid, sound energy will be transmitted into the liquid. The frequency of the sound waves is the same as that of the alternating component of the magnetic field but should be adjusted to correspond to a mechanical resonance frequency of the bar if high intensity sound waves are to be generated. The metal bar is laminated to reduce eddy currents. The magnetic fields are provided through the current through the coils in Fig. 10. Since magnetostriction generators are used at sonic and relatively low ultrasonic frequencies, the alternating current may be obtained from a relatively inexpensive high-frequency motor-driven generator rather than an electronic generator as is usually the case with piezoelectric transducers.

In general equipment is available for processing applications through the pilot plant stage and in many instances on a large industrial scale.

CONCLUSIONS

Cosmetic chemistry appears to be a particularly promising field for processing applications involving ultrasonic waves. In general the scale of these processing applications is expected to be relatively small compared to those in other chemical industries. Furthermore, the cost associated with ultrasonic processing should be only a small fraction of the relatively high cost of the final product. While the author is optimistic about poten-



FIGURE 10.-Magnetostrictive transducer.

tial processing applications, the engineering know-how must be obtained before these applications can become realities.

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