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THE AIR-JET GENERATOR AS A MEANS FOR SETTING UP WAVES IN A LIQUID MEDIUM

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1. Transmission of Acoustic Energy from the Air-Jet Generator to a Liquid Medium.

The acoustic air-jet generator is an effective means of setting up waves of great intensity and high frequency in air. A most attractive proposition would be to try whether the generator might be used for the production of waves in a liquid medium. Now, however, a very minute fraction only of the acoustic power which impinges upon the surface of a liquid like water enters the liquid. One might, nevertheless, hope for a not inconsiderable intensity in the liquid owing to the comparatively excessive amount of acoustic energy available in the acoustic generator in question. The locality where the density of the acoustic energy is greatest is undoubtedly the oscillator and so it was concluded that the liquid medium should be coupled as closely as possible to the air in the oscillator. This is the idea underlying the device shown in fig. 1. The apparatus shown is an acoustic generator with a particularly shaped oscillator *O* consisting of a small disk through which is carried a conaxial bore with a sharpened edge. The bore forms the oscillator proper. Above the same the container for the liquid medium, a glass tube *T*, is arranged. The air in the oscillator and the liquid in the container are separated from each other by a thin membrane *M* only, constituting the bottom of the oscillator. The membrane is pressed down against the plane surface of the rear side of the oscillator body by the disk D_3 into which the tube *T* is cemented, D_3 being clamped to the holder D_2 of the oscillator by the screws *SS*. A thin rubber packing is found necessary between *M* and D_3. The setting of the oscillator relatively to the nozzle *N* of the jet is effected by means of the nut *A* turning on a thread cut in the surface of the jet pipe *P*. On this nut a disk D_1 is secured carrying three bolts B coupling D_2 to the nut. The displacement of the latter member and so of the oscillator may be read on a scale engraved in the surface of the pipe P. In fig. 2 a photograph of the apparatus has been reproduced.

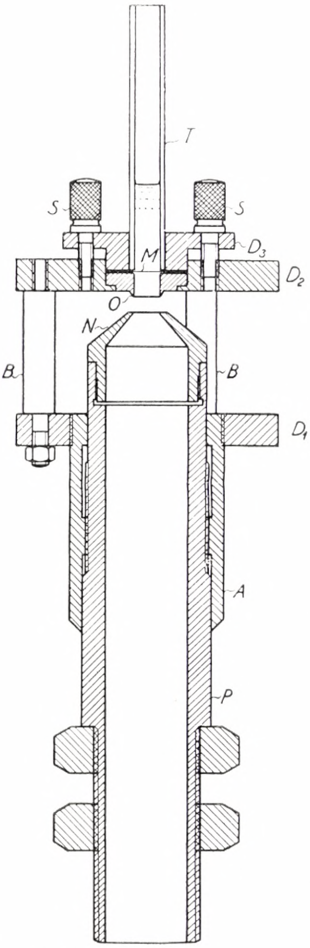

Fig. 1. Apparatus for transmitting Acoustic Energy from an Air-Jet Generator to a Liquid Medium.

A great many experiments on the membrane were carried out at an early stage. As materials for the membrane thin sheets of steel, phosphor-bronze, celluloid and rubber were tested (together with mica which, however, soon proved too weak). Again, a number of oscillators of various diameters (4, 5, 6, 7, 8 mm) and depths were tried, the depth being in all cases equal to the diameter. With the first apparatus the oscillator was of the purely cylindrical form indicated in fig. 1. Later on it turned out that a considerably larger amount of power could be transmitted if an oscillator of the type shown in fig. 3 were employed. The cylindrical part of the oscillator has here been given an extension directly under the membrane. At the same time the container T for the liquid is made considerably wider which often means a great advantage in the applications.

Some details from the work of development may here be stated. With a jet of 6 mm a membrane of phosphor-bronze of a thickness of 0.10—0.15 mm proved appropriate. Thinner membranes gave a higher intensity in the liquid but were apt to break down too soon. Hence it was found necessary to find a compromise between intensity and durability. In any case the membrane has only a limited life-time, varying from some minutes to some hours. Ways in which the membrane is ruptured are illustrated in fig. 4. Generally the rupture takes place

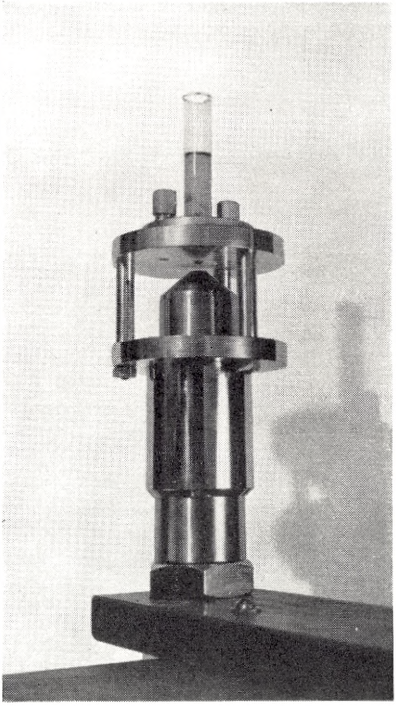

Fig. 2. Apparatus for transmitting Acoustic Energy from an Air-Jet Generator to a Liquid Medium.

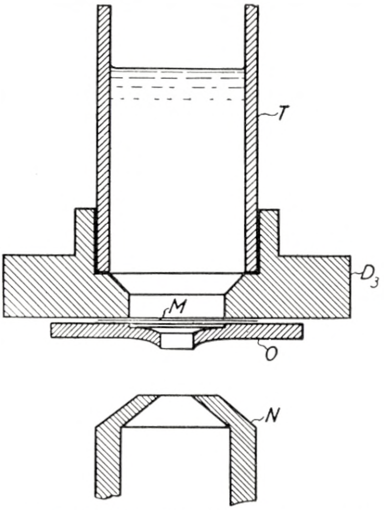

Fig. 3. Oscillator with Radial Extension at the Bottom.

about the centre of the membrane. With purely cylindrical oscillators such as that shown in fig. 1 the membrane was apt to burst along the edge. The life-time was, however, in this case greatly increased by the introduction of packings of thin paper or rubber on both sides of the membrane and by a slight rounding of the edges of the oscillator O and the disk D_3, fig. 1. It should be noted that care must be taken to keep the uppermost packing well inside the edge of D_3 because otherwise the edge of the packing is "atomized" and the particles dispersed in the liquid which in many applications may prove fatal.

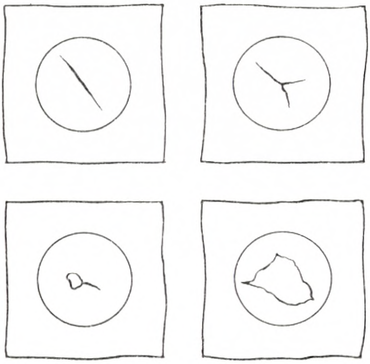

Fig. 4. Modes of Rupture of the Membrane.

Further developments will be described in connection with the various uses made of the generator.

2. Estimate of the Power transmitted to the Liquid Medium.

We shall try to form an idea of the acoustic power transmitted from the oscillator to the liquid medium which we shall assume to be constituted by water. In so doing we shall visualize the mode of operation of the air-jet generator in the following way. The actual total radiation W watt from the generator originates from a train of waves running down to the bottom of the oscillator where it is reflected totally. The oscillations of the air in the oscillator are the result of the interference of the incoming and the reflected wave. Arriving at the orifice of the oscillator the latter wave is emitted into the surroundings and constitutes the actual radiation. From this simplified picture it follows that the membrane between the air in the oscillator and the liquid medium is hit by a wave train the intensity I_a of which is

$$(1) \qquad I_a = \frac{W}{\frac{\pi}{4} d^2} \text{ Watt/cm}^2,$$

d being the diameter of the oscillator and—it is here assumed—of the free surface of the membrane.

The fraction T of this intensity transmitted to the liquid is influenced by the membrane. Let us, however, neglect the same and suppose that the wave train impinged directly on a plane surface of the water. Then T is determined solely by the specific acoustic resistances r_a and r_l of the two media, air and liquid (water). The specific resistance of a medium is, as will be known, the product of the density ϱ g/cm³ of the medium and the velocity c cm/sec of sound in the medium. For air at 20° C and a pressure of 1 kg/cm² and for water the resistances are

$$r_a = 40 \text{ g/(cm}^2 \cdot \text{sec) and } r_l = 142000 \text{ g/(cm}^2 \cdot \text{sec)}$$

respectively. Now it has been found that the average temperature in the oscillator does not differ much from that obtaining in the container from which the jet is fed, i. e. as a rule not much from the temperature of the surroundings, while the average pressure in the oscillator will be about $0.75\, p_0$ where p_0 is the absolute pressure in the said container[1]. Hence, if p_0 is measured in kg/cm² the specific acoustic resistance of the air in the oscillator may be expressed as

$$r_a = 30 \cdot p_0 \text{ g/(cm}^2 \cdot \text{sec) } (p_0 \text{ in kg/cm}^2).$$

The fraction T of the wave energy transmitted to the water is determined by

$$(2) \qquad T = \frac{4\, r_a r_l}{(r_a + r_l)^2} \sim \frac{4\, r_a}{r_l} = \frac{120\, p_0}{r_l}.$$

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[1] Comp. The Air-Jet Generator, Ingeniørvidenskabelige Skrifter 1939, No. 4, København 1939. This monograph is referred to in the sequel by A. J. G.

Generally the air-jet generator is operated at an excess pressure of about 3 kg/cm², i. e. with a value of p_0 equal to approximately 4 kg/cm². To this pressure corresponds

$$T = 3.38 \cdot 10^{-3},$$

i. e. 0.338 p.c. only of the acoustic energy is transmitted to the water.

In the fundamental investigations on the air-jet generator reported in A. J. G. it was found that the total radiation from a generator of diameter and depth d cm and operated at an excess pressure p kg/cm² is determined by

$$W/d^2 = 295 \sqrt{p - 0.93} \text{ Watt/cm}^2. \tag{3}$$

From (3) and (1) it follows that the intensity of the wave in the oscillator is

$$I_a = \frac{4}{\pi} \cdot 295 \cdot \sqrt{p - 0.93} = 375 \sqrt{p - 0.93} \text{ Watt/cm}^2 \, (p \text{ in kg/cm}^2) \tag{4}$$

independent of the width of the oscillator and so of the frequency of the waves. With $p = 3$ kg/cm²

$$I_a = 540 \text{ Watt/cm}^2.$$

Multiplying this with the value of T found above we derive for the intensity of the transmitted wave-train just beyond the membrane under the conditions stated

$$I_l = 540 \cdot 3.38 \cdot 10^{-3} = 1.825 \text{ Watt/cm}^2.$$

We shall compare this with the intensity produced by a piezo-quartz generator. For a quartz disk of a thickness of 0.9 cm and an effective radiating surface of 11.2 cm² operated at resonance in water with a voltage 10 kV r.m.s. H. Tscherning calculated a total radiation of 31 Watt and thus an intensity

$$I_l = \frac{31}{11.2} = 2.77 \text{ Watt/cm}^2$$

provided the quartz disk is furnished with a reflector[1]. The resonance frequency was $N = 307.5$ kHz. Hence the intensity produced in water by any air-jet generator (independent of the frequency) operated at an excess pressure of 3 kg/cm² should be $\frac{1.825}{2.77} \cdot 100 = 66$ p.c. of that produced by the piezo-quartz generator in question. The intensities of the two generators would thus seem to be of the same order of size and so perhaps the effects produced with the quartz generator might with some reason be anticipated with the air-jet generator. This conjecture is, however, not quite safe, for the effects might depend on the accelerations in the wave-trains rather than on the intensities. Hence we shall compare the accelerations in the two cases considered above.

In a wave-train of sinusoidal waves of displacement-amplitude a the amplitude of acceleration g is given by

$$g = a\omega^2 \text{ cm/sec}^2, \tag{5}$$

ω being the cyclic frequency of the wave. Further the intensity is determined by

$$I = \frac{1}{2}\varrho v^2 \cdot c = \frac{1}{2}\varrho a^2 \omega^2 \cdot c \,(\text{erg/sec})/\text{cm}^2, \tag{6}$$

v being the velocity amplitude of the wave and ϱ the density of the medium. Comparing two waves of different intensities I_1 and I_2 and of different frequencies N_1 and N_2 it follows from (5) and (6) that

$$\frac{g_1}{g_2} = \frac{\omega_1}{\omega_2}\sqrt{\frac{I_1}{I_2}} = \frac{N_1}{N_2}\sqrt{\frac{I_1}{I_2}}. \tag{7}$$

The frequency of an air-jet generator depends somewhat on its setting, i. e. on the distance from the nozzle to the oscillator and decreases when this distance increases. It is generally operated with its maximum frequency N_1 and the latter is determined by

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[1] H. Tscherning: Les générateurs d'ultra-sons de laboratoire et leurs applications. Revue Générale de l'Electricité, août 1947, t. LVI, p. 319—327. Paris 1947.

$$N_1 = \frac{5860}{d} \text{ Hz.} \tag{8}$$

In the case of an oscillator of diameter $d = 0.3$ cm $N_1 = 19530 \sim 20000$ Hz. We have seen that the intensity I_1 in the waves transmitted to water was 1.825 Watt/cm². In the case of the quartz generator the frequency was $N_2 = 307500$ Hz and the intensity produced in water was $I_2 = 2.77$ Watt/cm² if the generator is operated with 10 kV r.m.s. Introducing the values here stated in (7) we get

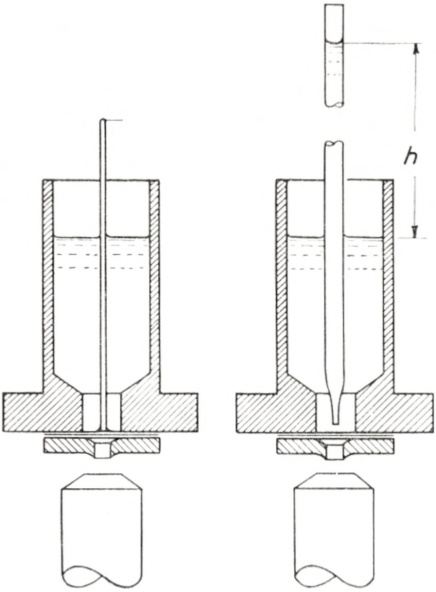
$$g_1/g_2 = 0.053.$$

Thus the acceleration set up with the air-jet generator is 5.3 p.c. only of that which is produced by the quartz generator. It would be half of that thus 2.6 p.c. in the case of a 10000 Hz air-jet generator ($d = 0.6$ cm).

The deductions here given have, as stated, been based on the assumption that the effect on the transmission of the membrane separating the two media may be neglected. Actually there is an influence as appears from the fact that the thinner the membrane the higher the wave-intensity produced in the liquid. On the other hand the reduction of the intensity is very far from what it would be if the liquid was separated from the air in the oscillator by a wall of phosphor-bronze or steel through which the waves were transmitted only as compression waves. The factor T of transmission from air to steel would with an absolute pressure of 3 kg/cm² in the air be about $0.126 \cdot 10^{-3}$, the specific resistance of steel being $3.9 \cdot 10^6$ g/(cm² · sec). Again the factor of transmission from steel to water is about 0.138 and so the factor of transmission from the air in the oscillator to the water would be $0.126 \cdot 0.138 \cdot 10^{-3} = 0.0175 \cdot 10^{-3}$ or 0.52 p.c. only of the value derived for direct transmission. It is safe to say, that the picture of the transmission neglecting the membrane altogether comes by far closer to the truth than that based on a perfectly stiff plate. On the actual part played by the membrane some light will be shed by experiments described in the sequel.

3. Motion of the Membrane.

The problem of measuring the intensity of the waves in the liquid medium of the generator has been severally tackled. So far the attempts have not been successful. This is presumably not to be wondered at in view of the extremely limited extension of the field in question. The attempts have, nevertheless, thrown light on the process of transmission and particularly on the motion of the membrane. This fact may justify some words about this part of the research work.



Figs. 5 a—b. The Needle Experiment and the Pressure Pipe Experiment.

Two experiments in particular should be reported: 1° the needle experiment and 2° the pressure pipe experiment, figs. 5 a—b. Both of the two experiments were carried out with an oscillator of width 3 mm and depth 3 mm having an extension of 6 mm about as indicated. The membrane was made of 0.1 mm phosphor-bronze. The frequency of the aerial vibrations was 12000 Hz. In the former experiment a steel needle of a diameter of 0.5 mm and a length of 25 mm was at one end soldered to the centre of the membrane as indicated in fig. 5 a. A short and fine glass fibre was cemented to the other end. The latter was illuminated with light from a narrow slit and the bright image of the slit formed by the fibre was observed in a microscope. When the generator was operated the amplitude of the vibration of the central part of the membrane, when loaded with the needle, could be measured. It was found to be 0.0006 cm if the container was filled with water and 0.0009 cm when empty. Now, the intensity I_l corresponding to a displacement amplitude a_0 in a train of waves of the cyclic frequency ω $(= 2\pi N)$ is

$$(1) \qquad I_l = \frac{1}{2} \varrho a_0^2 \omega^2 c \cdot 10^{-7} \text{ Watt/cm}^2.$$

Introducing $a_0 = 0.0006$ cm, $\omega = 2\pi \cdot 12000$ rad/sec and $c = 146000$ cm/sec, i. e. the velocity of waves in water, we derive for the generator in question

$$I_l = 15.0 \text{ Watt/cm}^2.$$

In paragraph 2 the intensity which should be expected in the case of a direct transmission from the air in the oscillator to the liquid in the container, i. e. without a membrane—was found to be

$$I_l = 1.825 \text{ Watt/cm}^2$$

independent of the frequency. It is impossible to conceive that the transmission of energy should be much larger with the membrane (which was not tuned to the oscillator) than without the same. The explanation of the apparent contradiction is probably that indicated in fig. 6. Here M is the membrane separating the two media A and W. If the vibrations of all the zones of the membrane were in the same phase an energy transmission of the order of size calculated above would result. Actually the membrane oscillates more or less as indicated or, as an effect of the impact of the aerial waves, annular waves are formed on the membrane running from the centre out to the circumference where they are reflected back to the centre and so on. The result is obviously that of the membrane vibrating between the two shapes shown. This means a greatly diminished transmission of compression waves seeing, that the main effect of the deformation of the membrane will be a radial "rippling" of the water (without any appreciable compression or dilatation of the medium). Some transmission of wave energy of course remains but by far not that directly judged from the amplitude of the central part of the membrane.

This conception of the conditions immediately above the membrane was borne out by the second of the two experiments referred to above, fig. 5 b. In this experiment a glass tube drawn below to a narrow capillary point was approached to the centre of the membrane moved by means of a slide with micrometer screw (not shown in the figure). When the point was quite close to the membrane water would rise in the tube to a height h of up to about 50 cm. The effect is readily understood. During the upwards motion of the central part of the membrane the water is pushed towards the aperture of the tube and will penetrate into the same. When the membrane is retreating the space evacuated by the membrane will fill not with the water sent up into the tube but with water from the surroundings of the membrane. If v_0 is the velocity amplitude of the vibrations of the membrane the water in the tube will most likely rise to a head h determined by

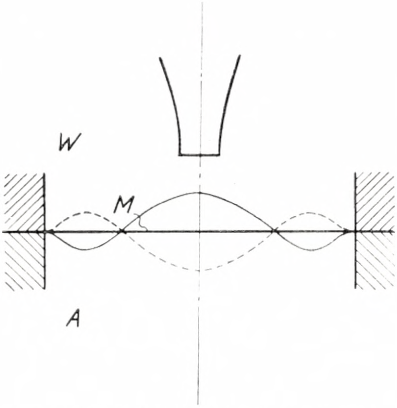


Fig. 6. Motion of the Membrane.

$$v_0 = \sqrt{2\,gh}. \tag{2}$$

Seeing that $v_0 = \omega a_0$, a_0 being the amplitude of the displacement of the centre of the membrane, we may calculate a_0 from the observed head. Putting $h = 50$ cm and $\omega = 2\pi \cdot 12000$ rad/sec we find $v_0 = 313$ cm/sec and

$$a_0 = 50 \cdot 10^{-4} \text{ cm}.$$

This amplitude is about 8 times as large as that, $6 \cdot 10^{-4}$ cm, found with the membrane loaded with the needle. Now the mass of the needle is approximately twice that of the membrane, viz. 38.3 mg as against 22.2 mg. So the reduction of the amplitude is perhaps not too surprising.

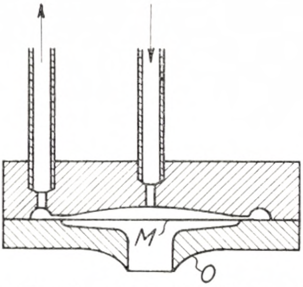


Fig. 7. The Acoustic Membrane Pump.

Guided by the conception here set forth the acoustic pump indicated in fig. 7 was suggested and substantiated by one of the authors (LARRIS). Above the membrane a flat rather narrow chamber was arranged as shown. Above the centre of the membrane the inlet pipe of the pump opens into the chamber while the outlet has connection with a circular channel round the chamber. Obviously the radial wave train running from the centre towards the circumference will push the liquid in the chamber outwards thus driving it out of the pump while fresh liquid will be taken in at the centre. This pump was successfully employed in an arrangement for continuous production of emulsions, an application of the generator to be described below.

4. Attempts at Measuring the Wave Intensity in the Liquid.

The experiments described in paragraph 3 left us without any definite information as to the intensity of the waves set up in the liquid. As stated several attempts have been made to measure this intensity. A few of them will here be reported.

In the first instance the authors tried to weigh the radiation pressure. A cylinder made of lead was hung from a balance as shown in fig. 8. When the waves were put on an upward pressure could readily be measured depending on the distance from the membrane to the cylinder. The method was, however, soon abandoned for two reasons. What is desired is to find the intensity close to the membrane where the various effects are generally most conspicuous. Now if the cylinder is introduced here the field is greatly changed by the presence of the cylinder and further the intensity is no longer measured. A special experiment established this fact beyond any doubt. If a rod with a plane end was carried down to just above the vibrating membrane the rod was drawn with great force towards the membrane. The effect observed is well known from the classical experiment with a plane sheet of pasteboard or metal being attracted to a nozzle in a plane wall from which a jet is emitted when the sheet is brought up close to the front of the nozzle so that a narrow gap is formed between the front and the sheet. The attraction is a direct consequence of the Bernoulli hydrodynamic theorem. Above the centre of the vibrating membrane an alternating flow of liquid is produced as found in paragraph 3, and this flow will of course have quite the same effect as the jet on a sheet approched to the membrane. The forces acting on the lead cylinder in our

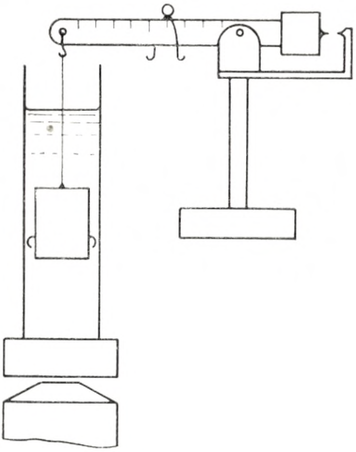


Fig. 8. Apparatus for Measuring the Wave Intensity in the Liquid.

case are thus not solely, and probably only to a very small degree, due to the radiation pressure.

A subsequent attempt was based on a crystal microphone fig. 9. The receiver was made up of three tiny plates of Rochelle salt $C_1 C_2 C_3$ with electrodes of tin foil, the three crystals being electrically connected in parallel. The crystals were cemented by shellack to the plane end of short rod of glass R. The rod with the crystals was mounted in a glass tube T with a plane bottom serving as the receiver membrane. Against the latter the crystal plates were lightly pressed by a spring between the rear end of the glass rod and a stopple closing the glass tube. The two terminals of the microphone were generally connected to a moving coil pointer instrument with dry rectifier for up to 2 mA and with an internal resistance of 70 ohm. Full deflection could be obtained without any amplification.

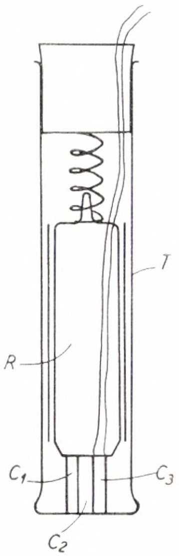


Fig. 9. Rochelle Salt Microphone.

The experiment recorded in fig. 10 was carried out with the microphone now described, the leads of the microphone being, however, in this case carried to an amplifier with a pointer instrument. The diagram shows how the reading on this instrument varied with the distance a between the nozzle and the oscillator when the position of the microphone was kept constant in the container with the liquid. The figures written on the various curves indicate the excess pressures in kg/cm^2 at which the generator was operated. The curves should be compared to curves representing the variation with a of the radiation into air from a normal air-jet generator. The latter curves are chiefly of the same character as the curves in fig. 10 (comp. A. J. G. figs. III. 15 and 16). This fact greatly supports the assumption that the microphone readings may be considered as correct relative values for the wave intensity under the prevailing conditions. The wave field with the microphone introduced into the container is, however, not the same as without. This is not always an objection of great consequence for in several cases the microphone may be left in position during operation seeing that it constitutes part of the whole apparatus. Undoubtedly at the present juncture the crystal microphone represents the soundest proposition for the relative measurement of the wave field intensity.

A third attempt at solving the problem is finally indicated in fig. 11. During operation the temperature will rise considerably in the liquid. This is, however, not solely due to absorption of

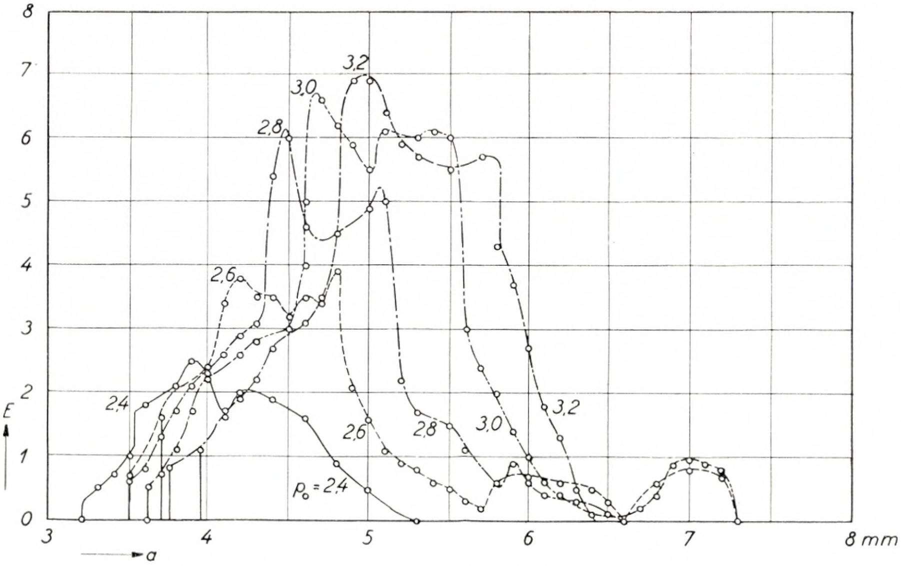


Fig. 10. Investigation on the Wave Intensity in the Liquid.

the wave energy but also to a transmission of heat from the oscillator through the membrane. True, the average temperature in the oscillator is approximately equal to the temperature of the surroundings, provided the jet is fed with air of this temperature. Close to the membrane an excess temperature, however, obtains. (Comp. A. J. G. figs. V. 35 and 36 a). In order to eliminate the effect of the heat transmission the arrangement shown in fig. 11 was suggested by one of the authors (Larris). The figure shows a thermocouple with two joints one of which is embedded in a rubber body while the other is free. The system is introduced into the liquid wave field. When no waves are put on the two joints will assume the same temperature, viz. that of the liquid, irrespectively of the temperature level and so no deflection is observed on the galvanometer to which the two leads of the thermocouple are connected. During operation an absorption of wave energy will ensue in the rubber and give rise to a temperature difference in the two joints which may be taken as a measure of the wave intensity. The absorption is of course due to elastic hysteresis in the rubber. The apparatus here suggested would have one great advantage, viz. that of not deforming the field appreciably, for the rubber covering may be made quite tiny. The sensibility of the indicator is, however, unfortunately rather too small. Probably it might be raised by the application of a material with a higher elastic hysteresis than rubber, if such a material can be found. Another proposition would be to replace the rubber covered joint with a spiral indicator as described in A. J. G. (Comp. Chapt. II. 10) though this device may also prove too insensitive for the purpose in question.

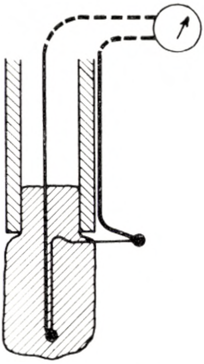


Fig. 11. The Rubber Indicator.

It will be gathered that so far the problem of measuring the wave intensity in the liquid wave field has not found its final solution, at any rate not the problem of an absolute measurement of the field. The intensity is generally estimated from the rapidity of some or other of the effects of the field. We proceed to describe some of these effects.

5. Production of Emulsions by Sound Waves.

This effect of the sound waves was first observed by Wood and Loomis and described together with numerous other effects in a classical paper[1]. The effect may readily be demonstrated with the apparatus here considered. The container is filled with water to a height of 3 cm above the membrane. Waves are put on and a drop of oil or some other liquid, which does not mix with water, is introduced into the water say by means of a pipette or a piece of wire. Almost instantly a milky cloud of minute oil drops suspended in water is formed round the drop and in the course of a few seconds it will fill out the whole container. The greater the intensity of the waves or the closer to the mem-

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[1] R. W. Wood and A. L. Loomis. Physical and biological effects of high frequency sound waves of great intensity. Phil. mag. (7), 4, 417—436. 1927, Nr. 22.

brane the oil drop the more rapid the process. It would seem that oils of low viscosity are emulsified more readily than heavier oils. Oils with a refraction index appreciably different from that of water are best suited for the demonstration seeing that the emulsions produced appear whiter and thus form greater contrast.

Instead of emulsions of oils in water, emulsions of water in oil may be formed, and as readily. We shall not here enter upon any discussion of the mechanism of the formation of emulsions by means of sound waves[1]. We shall confine ourselves to a brief report on some observations on emulsions of oil in water.

In the first instance the concentration of the emulsion was determined by means of a hydrostatic balance (Mohr's balance). Let the densities of water, oil, and the emulsion be ϱ_1, ϱ_2 and ϱ_3 respectively, then the concentration C in question, i. e. the ratio of the volume v_2 of the oil to that, v_3, of the emulsion is readily seen to be

$$(1) \qquad C = \frac{v_2}{v_3} = \frac{\varrho_3 - \varrho_1}{\varrho_2 - \varrho_1} = \frac{\varrho_3/\varrho_1 - 1}{\varrho_2/\varrho_1 - 1}.$$

Hence, if ϱ_2 and ϱ_3 are measured in terms of the density ϱ_1 of the water employed the concentration is derivable. From observations on emulsions produced from various oils exposed to the same wave field for various intervals of time the following general facts were found.

1. The concentration will rise to a certain value, the maximum concentration, after which a continued exposition has no longer any effect. For various oils about the same values of 0.5—1.5 p.c. were found.

2. After the production the concentration will decrease gradually at a slower and slower rate reaching a value of about 0.5 p.c. in the course of some days. Hereafter the emulsion is stable for months or years.

The precipitation of the oil immediately or shortly after the production of an emulsion takes place on the surface of the vessel or on the free surface of the water, the larger oil drops

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[1] The reader may be referred to the excellent manual: EGON HIEDEMANN. Grundlagen und Ergebnisse der Ultraschallforschung. Verlag Walter de Gruyter & Co, Berlin 1939.

being first precipitated. The precipitation on solid surfaces represent a source of error in the determination of the specific density of the emulsion by a hydrostatic balance, seeing that the body submerged in the emulsion is apt to catch oil drops with the effect that the effective volume of the body is changed.

The fact that the concentration *during the production* of the emulsion by sound waves cannot be raised beyond a certain limit undoubtedly finds its explanation—at least in part—in the well-known Bjerknes effect, i. e. the mutual attraction of particles suspended in a liquid moving relatively to the particles in a direction perpendicular to the line of connection between the particles. Such a relative motion is set up by the waves and will thus tend to counteract the formation of drops. When as many drops are produced per sec. by the process of dispersion as will unite per sec. under the influence of the Bjerknes attraction the concentration has reached a maximum. The latter attraction—of a purely hydrodynamic nature—may, however, not alone determine this maximum. If the drops have a uniform electric charge they will repulse each other, i. e. the charge will counteract the Bjerknes attraction and tend to raise the maximum concentration and perhaps to stabilize the emulsion. This consideration raises the question of a possible electric charge on the drops. To throw light on this question the following experiment was made.

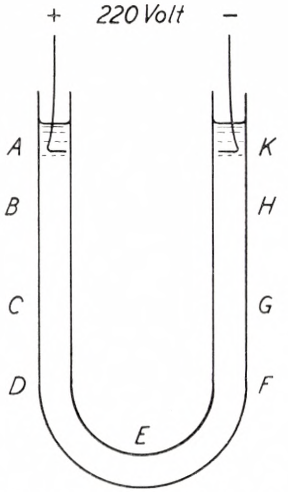


Fig. 12. Experiment on the Electric Charge of the Drops in an Oil Emulsion.

In a U-shaped glass tube, fig. 12, two platinum electrodes were introduced as indicated, the distance between the two being 20 cm measured along the tube. Into the latter was poured an acoustically produced emulsion of a mineral oil in distilled water till the surfaces were raised above the electrodes. A d.c. voltage of 220 V was put on the electrodes. After some minutes the liquid below the negative electrode down to the place H had become clear, while the liquid from H to the surroundings of the positive electrode had not changed. Immediately round A a cloud of a somewhat denser emulsion had, however, been formed. This emulsion was not stable as appeared from the fact that oil was precipitated on the liquid surface above *A* in the shape of visible oil drops. If the electric field is kept on for several days or weeks the boundary surface between the emulsion and the clear water continues to move in the direction of the positive electrode till all oil has been removed and the liquid has become clear all over the tube.

Quite obviously the oil drops in the emulsion are negatively charged. The velocity of the drops in the electric field indicated above was measured. In order to secure well defined experimental conditions the experiment was carried out as follows. The U-tube was filled with distilled water up to the levels *C*, *G*. Then the emulsion was poured simultaneously and very slowly into the two branches of the tube. In this way rather sharp boundary surfaces between water and emulsion were secured at such distances from the electrodes that the electric fields might be considered homogeneous. When the field was put on both of the two boundaries moved at the same rate, the velocity observed being 0.005 cm/sec at a field intensity of 11 V/cm.

The acoustic production of oil emulsions described above has attracted attention particularly within medical circles and given rise to several tests. Some of these may here be indicated.

Lepra may be treated by injection into the veins of an oil product known under the commercial name of "Antileprol" (Bayer). The oil is translucent and comparatively non-viscous. It should be injected in the shape of an emulsion with the smallest possible drops. It turned out that emulsions of the necessary fineness could be produced readily enough by the acoustic generator. The concentration—of 0.5—1 p.c.—did not, however, suffice and so this mode of production had to be abandoned.

Another oil product "Jodumbrin" (Medicinalco) is used in X-ray examinations on the spine system to replace the spinal-liquid in order to obtain the necessary contrast. Again an emulsion of the oil was required for injection and again the attempt failed on the ground of a too low concentration of the emulsion. It would seem that the acoustic method would in many cases prove suited for the production of useful emulsions in the medicine if some means of increasing the concentration without reducing the fineness could be found out.

More promising perhaps were certain attempts at producing emulsions of tar in water for the treatment of certain skin diseases. Generally an alcoholic solution of the tar is used but seeing that sometimes the alcohol gives rise to inconveniences for the patient it was suggested that the solution should be replaced by an aqueous emulsion of tar. For the preparation of the required quantities of this emulsion the acoustic pump shown in fig. 7 was utilized, two central inlets being furnished, one for the water, the other for the tar. The pump acted continnuously and would produce the emulsion at a reasonable rate. It is reported that the effect of the emulsion was rather satisfactory although perhaps also in this case a higher concentration of the emulsion would seem desirable.

6. Effects on Suspensions of solid Substances in Liquids.

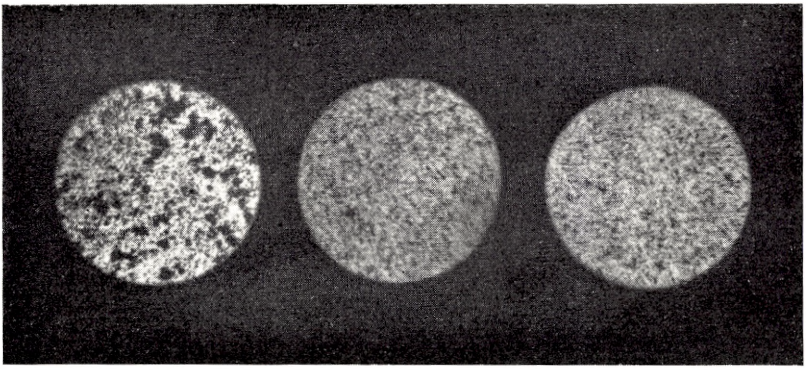
Under the influence of sufficiently vigorous sound waves suspensions of solid substances in a liquid are apt to become more homogeneous, conglomerates of finer particles being broken down or the particles themselves disintegrated. Several observations of this well-known effect have in the course of time been made with the acoustic generator in question. Some instances will here be reported.

Samples of cesspool mud were observed under a microscope and proved to consist partly of rather large thread shaped particles resembling plant roots. After being treated with waves of about 10 kHz for some minutes these particles had been disintegrated and short thread pieces only were left.

In another test water from a cement factory with suspensions of cement particles was examined. Here the unmistakable effect of the waves was to disintegrate larger conglomerates.

On the initiative of Dr. S. Stamer experiments were carried out on the production of suspensions in water of the substance 9:10 dimethyl—1:2 bencanthracen. A concentration of 1 p.c. only was required but a very fine suspension was essential, the product being destined for injection into the veins in the treatment of Leukaemia. Before being exposed to sound waves the suspension consists mainly of conglomerates of a diameter of 20 to 30 μ made up of particles of an average diameter of 2 μ. The colour of the suspension was yellow like sulphur. After being exposed to sound waves of frequency 10 kHz for 2 minutes the large conglomerates had disappeared. After 5 minutes a change of colour into a lighter yellow was manifest.

High frequency sound waves have been widely used for the production of fine grained photographic "emulsions". This application, too, of the acoustic generator here discussed was tested with the distinctly positive result illustrated in figs. 13 a—c. In the case considered a silver-bromide collodium product 6—III was exposed to waves. Fig. 13 a shows the commercial product when not treated, fig. 13 b and c the product when exposed to waves of the frequencies 15 and 35 kHz respectively for 5 minutes.



Figs. 13 a—c. Disintegration Effect of the Waves in Photographic Suspensions a) before Treatment, b) and c) after Treatment for 5 Minutes with Waves of Frequencies 15 and 35 kHz respectively.

The effect of the waves is unmistakable; apparently it is the same with waves of 15 and 35 kHz. The tests were carried out on the initiative of "Grafisk Institut", Copenhagen.

Recently suspensions of diphtheria bacteria in salt water were treated with sound waves. The suspension not treated consisted of conglomerates of bacteria, the aspect was milky. After treatment the liquid had become almost clear and the conglomerates had been broken down and there was something to indicate that the bacteria proper had been disintegrated. The experiments here referred to were suggested and partially carried out by Dr. Lautrop of the Serum Institute of Copenhagen.

In connection with the experiment now described a modified device for the exposition of the various substances to the sound waves may be mentioned. The substance, say the suspension of bacteria, is not exposed directly to the waves in the vessel above the membrane, but the waves are transmitted through a very thin rubber membrane to a second vessel in which the substance is contained. Fig. 14 shows this arrangement which was used not only in the experiment on bacteria but also in various other tests. Its obvious advantage is, of course, that the vessel for the substance in question can be filled and emptied independently of the acoustic apparatus and that the container for the substance may readily be sterilized before filling.

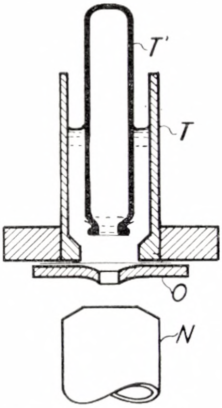


Fig. 14. Modified Arrangement for Experiments on various Effects of the Sound Waves.

Mention should further, under this heading, be made of one of the most conspicuous effects of the sound waves; viz. that of haemolysis of blood. The effect, with the apparatus here described and with frequencies above 10 kHz, is almost instantaneous. The blood corpuscles emptied of their content of red substance always exhibit a regular globular shape independent of the shape of the original blood cell. Attempts have been made to follow the process of haemolysis under the microscope, waves being transmitted to the sample under observation. So far these attempts have failed, owing to experimental difficulties.

7. Biological Effects.

Biological effects have also been made the subject of investigations with the acoustic generator, thus for instance the effect on the growth of living tissues where a clear cut influence could in certain cases be established. A rather complete investigation was carried out on the respiration of potatoes by D. Müller in collaboration with A. Meldgaard. Reference should here be made to: Die Naturwissenschaften, 30 p. 292 (1944) where the results were published in full. Here we may confine ourselves to the graph in fig. 15. The arrows on the uppermost curve indicate the junctures at which the sample in question is exposed to sound waves of a frequency of 4 kHz for 10 minutes. The increase of the respiration after each treatment is absolutely mani-

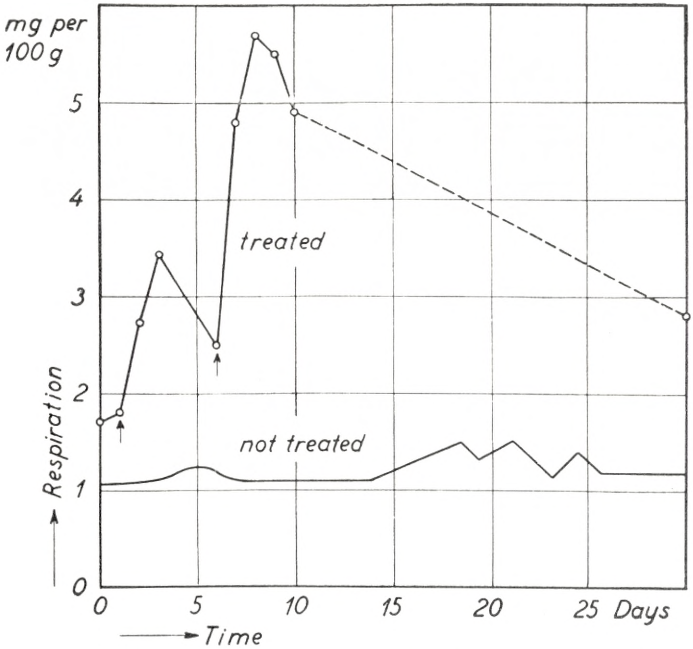


Fig. 15. Effect of Acoustic Waves on the Respiration of Potatoes (D. Müller and A. Meldgaard).

fest. The maximum of respiration appears 2 to 3 days after each treatment. The effect of successive treatments is obviously accumulative.

8. Conclusion.

Tests other than those indicated above have been carried out with the acoustic generator forming the subject matter of the present paper. The instances of the effects obtainable with the generator will, however, suffice to show that the air-jet generator is not only a most effective device for the production of high frequency sound waves in air but, in the shape described above, also a means for the setting up of such waves in a liquid and a means comparable to the quartz generator. It has been the main purpose of the paper to establish this fact and not to make the various illustrative effects the subject of more elaborate investigations. Such investigations have, however, often been carried out elsewhere, seeing that most of the effects considered have long ago been studied with the quartz generator. The interest attaching to the development of the air-jet generator for waves in a liquid lies in the fact that the latter generator is an extremely simple and inexpensive means for the production of these waves. The device described above may in most applications be operated from a cylinder with compressed air thus requiring no comepressor plant. Its manipulation is the simplest possible.

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