Drying

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Sonic Drying

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This paper deals with the application of airborne sonic energy in the drying process. Particular emphasis is placed on the development of the Hartmann-type sound generator for this application. The mechanism of the drying of solids is shown to be a complicated process influenced by many factors. How a sound field can influence these factors and increase the rate of drying is discussed. A description of a typical sonic dryer is given in conjunction with actual applications.

SONIC drying finds its application where moisture is to be removed from materials without increasing their temperature. Sonic drying competes with other methods such as air drying or drying in a vacuum. Sonic drying offers the advantage of (1) speeding up the process and (2) decreasing the final mositure content. These advantages must be balanced against the cost of additional equipment needed for sonic drying.

Sonic whistles have been found to be suitable sound generators for this application. The greater part of the cost is the investment in the air supply and in the sonic whistles. The operating cost of the air supply may not be insignificant. Hence, the economics of applying sonic drying depends on the ability to install sonic whistles of improved design.

I. SOUND GENERATOR

During the past decade, a good deal of effort has been devoted to developing the Hartmann-type sound generator for industrial applications. The broad scope of the generator's applications range from its use as a device to frighten birds, which are a hazard at airfields, to its use as a detector for gas chromatography.[1] However, most of the successful applications have been in drying, defoaming, spraying, and dust precipitation. It is the purpose of this paper to discuss the generator in conjunction with sonic drying.

The configuration of the Hartmann sound generator was based on an ultrasonic whistle developed by Galton[2] during the 1880's. This device, a schematic of which is shown in Fig. 1(a), consisted of a cylindrical cavity positioned in opposition to an annular orifice from which issued a relatively high-velocity gas stream. This is analogous to a closed organ pipe, which is excited into resonance by a flow of air. Galton's generator was primarily a low-powered signaling device to test the high-ferquency range of the hearing of animals.

In 1919, Hartmann published a report[3] describing a more powerful sound generator wherein the gas jet exits at supersonic velocities. His device, shown in Fig. 1(b), incorporated a conical converging nozzle to replace the annular orifice of the Galton whistle. When the resonator cavity is placed in opposition to the jet in what is called a zone of pressure instability, the air in the cavity is caused to oscillate. The frequency of these oscillations assumed to correspond to the fundamental mode of the cavity is given by $F=C/\lambda=C/4(L+0.3d)$. C is the velocity of sound in the driving gas, L is the cavity depth, and d its diameter; the acoustic wavelength is λ. This relationship is only approximate; the

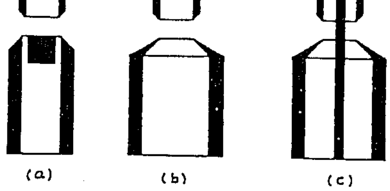
(a) (b) (c)

FIG. 1. Schematic representation of Galton, Hartmann, and Yellot–Savory sound generators.

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[1] Chem. & Eng. News 39, 49 (26 June 1961).

[2] F. Galton, Nature 27, 491 (1883).

[3] J. Hartmann, "On a New Method for the Generation of Sound Waves," Phys. Rev. 20, 719 (1922); see also, J. Hartmann, "The Acoustic Air-Jet Generator," Ingenioervidenskab. Skrifter Ser. B No. 4 (1939).

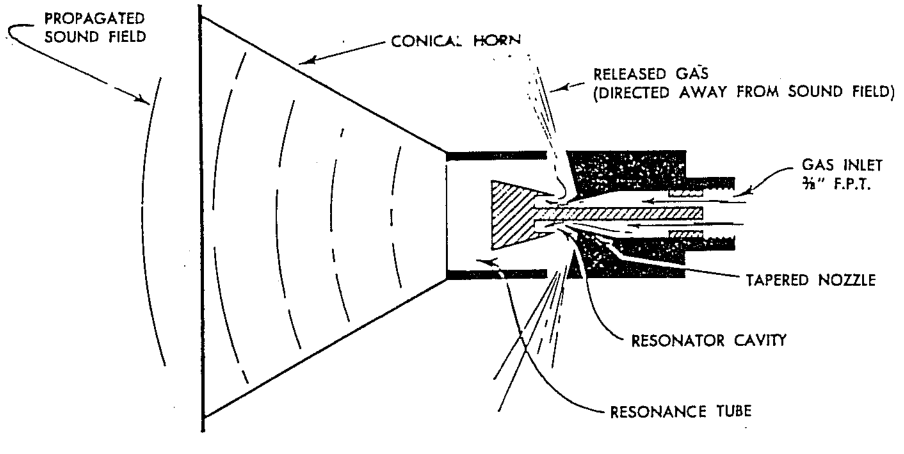

FIG. 2. Schematic representation of the Branson pneumatic sound generator.

exact value is also a function of the gas pressure and the distance between the nozzle and cavity.

The basic Hartmann generator and an improved version by Boucher[4] still proved to have limitations for industrial use because of their high air consumption and relatively low intensities.

Shortly after World War II, Yellot and Savory,[5] in the USA, and Hartmann and Trudso,[6] in Denmark, developed a generator [Fig. 1(c)] wherein a rod is centrally positioned along the axis of the gas jet. This feature not only allowed for a more compact design, but also increased the generator's output and efficiency.

Now, an improved generator has been developed that appears to be the most powerful Hartmann-type sound generator to date. This was accomplished by optimizing the relationships of such critical dimensions as the nozzle diameter, rod diameter, resonator depth and diameter, and the distance between nozzle and resonator.

II. SOUND REFLECTOR

Simple ray-theory-designed reflectors could not be efficiently utilized because of the turbulent effect of the high-velocity air flow. A novel feature of the new generator's reflector is its ability to separate the air flow from the sound field. This not only allows for higher sound intensities because of the absence of air turbulence, but also allows the generator to be used where air contamination of the treated media is not acceptable. A schematic representation of this sound generator is shown in Fig. 2.

Figure 3 shows the relationship of sound-intensity level and frequency as a function of air pressure for one set of design parameters. With an air pressure of 30 psig, a maximum sound-pressure level of 163 dB (*re* 0.0002 μbar) was obtained. This was measured axially in the free field at a distance of 12 in. from the lip of the resonator.

The developed sound generator described was used as the sound source in sonic-drying studies. There have been several investigations in the past that involved the application of acoustic energy for the purpose of drying. Much of this work is no longer technically significant because it has been outdated by the development of sound generators with outputs well beyond the ranges reported. However, for those who might want to examine this past work, a list of references is included.[7–9]

III. MECHANISM OF SONIC DRYING

Sonic energy has been found to be a highly useful aid in increasing the efficiency of various methods of drying. It is important to note that, although sonic energy can by itself dry moisture-laden materials, the economic factors concerning the practical application of this technique require that, in conjunction with this energy, standard drying methods be used. It becomes apparent that a dryer that can continuously expose new surfaces of material to a high-intensity sound field would be a good choice to accomplish this. Although the first attempts to dry with the aid of ultrasonics were made over 25 years ago, the question as to why ultrasonic energy can dry materials has not been fully answered to data. A clearer understanding of the problem can best be obtained by first examining the mechanism of drying as it would normally occur, and then relating the effects of airborne sound on this process. Moisture can be held in many different ways; the discussion that follows is primarily concerned with moisture that has been physically adsorbed.

IV. TWO ZONES OF DRYING

For all solids, the drying cycle is usually divided into two separate zones. These zones are illustrated by

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[4] E. Brun and R. M. G. Boucher, J. Acoust. Soc. Am. 29, 573 (1957).

[5] J. I. Yellot and L. E. Savory, U. S. Pat. 2,519,619 (1950).

[6] J. Hartmann and E. Trudso "Synchronization of Air Jet Generators with an Appendix on the Stem Generator," Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. 26, No. 26 (1951).

[7] Y. Y. Borisov and N. M. Gynkina, Akust. Zh. 8, 129 (1962) [English transl.: Soviet Phys.—Acoust. 8, 95 (1962)].

[8] P. Greguss, "The Mechanism and Possible Applications of Drying by Ultrasonic Irradiation," Ultrasonics 1, 83 (1963).

[9] R. M. G. Boucher, Ultrasonic News 3, 8 (Jan.–Mar. 1959).

drying-rate curves as shown in Fig. 4. The curves indicate that drying is a complicated process that is controlled by several different mechanisms. Section AB in both curves represents the constant-rate period of drying and BCD represents the falling rate. Point B denotes the critical moisture content when the constant-rate period is completed.

Solids will dry at a constant rate when they are completely covered with mositure and when evaporation takes place only at the surface. During this period, the drying rate is independent of the solid material but depends on (a) the rate of diffusion through the surface film of water vapor into the carrier air, (b) the moisture content and relative velocity of the drying air, and (c) the surface temperature of the material.

Where the means used for moisture removal during this constant-rate period is a hot gas (as in the case of most rotary dryers), the drying rate is expressed as follows:

$$dw/dt = hA\Delta T/L, \qquad (1)$$

where dw/dt is the drying rate in pounds of water per hour, h is the heat-transfer coefficient (BTU/h·sq ft·°F), A is the area of heat transfer and evaporation in square feet, L is the latent heat of evaporation at the surface temperature of the particle (BTU/lb), and $\Delta T = T_A - T_S$, where T_A is the air temperature in °F, T_S is the temperature of the particle at the surface of evaporation.

Alternatively, in terms of mass transfer, the drying rate may be expressed as

$$dw/dt = KA(\Delta P/H), \qquad (2)$$

where K is the mass-transfer coefficient (lb/h·sq ft), $\Delta P = P_S - P_A$, where P_S is the vapor pressure of the water at T_S, P_A is the partial pressure of the water vapor in air (atm), and H is the gas pressure of the surrounding air (atm).

During this constant-drying-rate period, we can correlate the effects of airborne sound with the rate of moisture removal.

From Eq. (1), we see that the drying rate is directly proportional to the heat-transfer coefficient or in Eq. (2) directly proportional to the mass-transfer coefficient. The prime effect of air velocity is to influence these coefficients.[10]

The following equation expresses the heat-transfer coefficient for a rotary dryer:

$$h = bG^n/D, \qquad (3)$$

where b is the proportionality constant, G is the air mass velocity $lb \cdot h \cdot$sq ft, n is the exponent of G determined by dryer configuration, and D is the drum diameter. The exponent n has a normal range of 0.46 to 0.67 (Ref. 11).

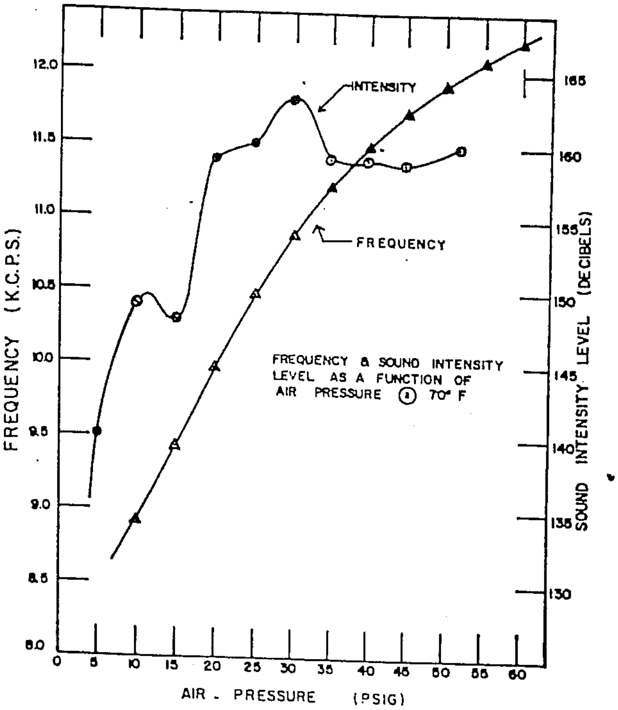

FIG. 3. Sound-intensity level and frequency as a function of air pressure.

The velocity amplitude of air subjected to an intensity level of 165 dB at 10 kc/sec is 22 000 ft/min. This is an oscillating-velocity effect occurring two times per cycle or 20 000 times per second. In comparison, the range of air velocities used in rotary dryers only varies from approximately 50 to 2250 ft/min. It would be impossible to use much higher air velocities because of dusting problems. Using a value for n of 0.50, in Eq. 3 the heat-transfer coefficient, and, therefore, the drying rate with the aid of 10-kc/sec sonics, would be 3.1

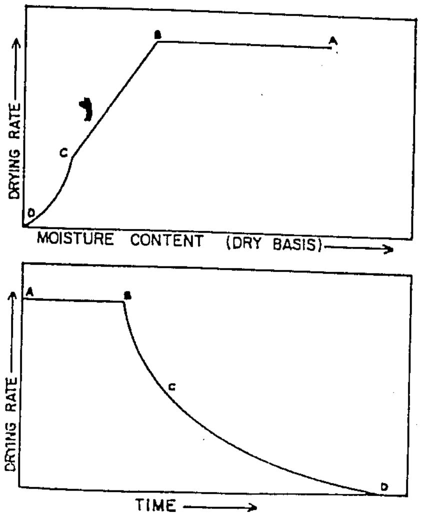

FIG. 4. Drying-rate curves.

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[10] S. J. Friedman and W. R. Marshall, Chem. Eng. Progr. 45, 573 (1949).

[11] P. Y. McCormick, Chem. Eng. Progr. 58, 57 (1962).

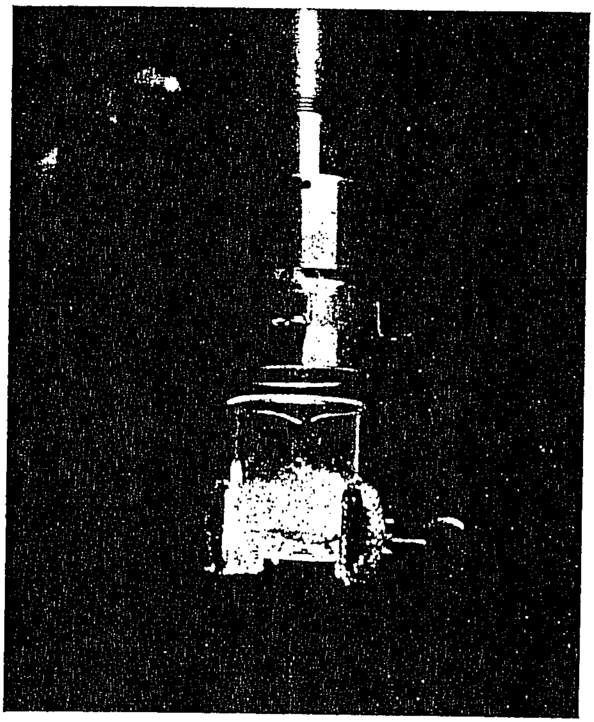

FIG. 5. Melting steel wool with sound waves.

times higher than with a stable air velocity of 2250 ft/min during the constant-rate period of drying.

From Eq. (2), we see that the drying rate is also inversely proportional to the gas pressure surrounding the liquid boundary. In a sonic standing-wave system, an intensity level of 165 dB produces a sound pressure that varies approximately 11% above and below atmospheric. It is during the negative phase of this pressure change that moisture is more readily removed. This is a rectifying process wherein the moisture once removed does not reenter during the positive pressure portion of the sound wave.

The constant-rate period of drying is over when the surface of the material is no longer completely covered with moisture. The falling-rate period of drying that ensues is usually divided into two zones: the zone of unsaturated surface drying (BC in Fig. 4) and the zone where internal liquid flow controls the drying rate (CD in Fig. 4). During the first portion of the falling-rate period, dry portions of the material are exposed to the air, thereby causing a decrease in the rate of evaporation per unit of surface. The drying rate is now being constantly decreased, dropping linearly with the moisture content. Here again, as in the constant-rate period of drying, the rate at which moisture is removed is determined by the same relationships of Eqs. (1) and (2). The only difference is that the area of evaporation is no longer constant. The second zone is reached when the rate of internal-moisture transfer is less than the rate at which moisture can be removed from the surface. During this liquid-flow zone of the drying rate curve, an increase in air velocity will not change the drying rate. However, the drying rate may be increased by increasing the internal temperature of the material, by reducing the external pressure, or by decreasing the size of the granules.

High-intensity sonic energy, when propagated into a material with a relatively high coefficient of acoustic absorption, will raise the internal temperature of the material. In fact, with a concentrated beam of sonic energy, one is actually able to ignite many materials. A vivid demonstration of this is shown in Fig. 5, where the sound generator, driven by air at 70°F, is held over a beaker containing steel wool. After a few seconds of exposure, the steel wool ignites and is transformed into a molten blob. The time required for this to take place is proportional to sound-intensity level. In a sonic dryer, one would not have to worry about igniting the material because the sound energy is not concentrated nor is the material confined as it is in a small beaker.

As described previously, reduced pressure that aids in drying is also obtained in a sound field. The effect of a reduced pressure is given by Eq. (2). The falling-rate period does not lend itself to precise mathematical formulas because of transient conditions and the nonhomogeneous nature of most materials. However, experimental tests have shown that the use of sonics appreciably reduces the drying time during this period for most materials.

V. DESIGN OF A DRYER

With the preceding theories kept in mind, a rotary-type dryer with a sound source was designed to dry materials at a maximum rate of 100 lb/h. The feed rate that the dryer can handle is determined by the characteristics of the material to be dried. Initial moisture content, density, the physical form in which moisture is bound, particle size, etc., influence the rate of drying.

The dryer, as shown in Fig. 6, has a drying chamber 8 in. in diameter by 4 ft in length. The chamber is constructed from a clear acrylic tube for visual observation and has eight lifting flights to tumble the material. A variable-speed motor controls the drum rotation from zero to 80 rpm. A hopper and feed screw are used to convey the material into the drying chamber. A variable-speed motor is used to control the material input up to a rate of 120 lb/h. As in the case of a

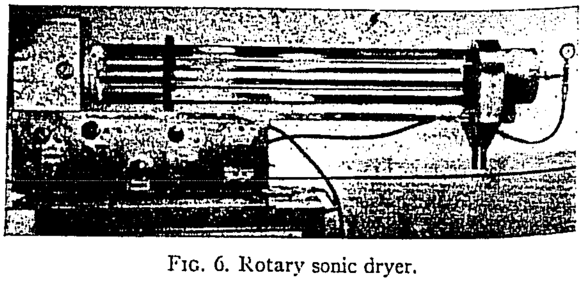

FIG. 6. Rotary sonic dryer.

standard rotary dryer, a heated flow of gas can be supplied to carry off released mositure and to bring the material up to a desired temperature. A thermostatically controlled electric heater is used to provide desired gas-inlet temperatures between ambient and 300°F. To permit the material to spiral its way down the chamber, a slope-adjusting mechanism is provided.

The sound source previously described is mounted at the outlet end of the dryer. The sound is propagated into the chamber and a standing wave is produced because of reflections from the opposite end of the tube. A sound-pressure level of 169 dB at 10.9 kc/sec is obtained at the pressure antinodes in the chamber. The gas used to power the sound source is diverted away from the chamber. Dried material drops down the outlet tube when it reaches the end of the drying chamber.

A shroud is placed around the sound source to reduce the noise to a tolerable and safe level. The driving gas, which may have picked up some dust from the chamber, then flows through a confined outlet into a cyclone or a bag collector.

The retention time of the material in the chamber and its exposure to the sound field is a most critical factor, which must be carefully controlled. The retention time as given by Friedman and Marshall is as follows[12]:

$$\theta=(0.23L/SN^{0.9}D)\pm(0.6BLG/F) \qquad (4)$$

$$B=5(D_p)^{-0.5}, \qquad (5)$$

where θ is the retention time (min), L is the dryer length (ft), S is the slope of the dryer (ft/ft), N is the rate of rotation (rpm), D is the drum diameter (ft), G is the air mass velocity (lb/h·sq ft), F is the feed rate to dryer (lb dry material/h), B is a constant depending upon the material being handled, and D is the weight average particle size of the material being handled (μ). The plus sign refers to countercurrent gas flow and the negative to parallel flow. The dryer described is a parallel-flow type. Equations (4) and (5) can be used to determine the size of a specific dryer. Knowing the approximate drying time of a material, it can also be used as a guide to make adjustments on an existing dryer to obtain the proper retention time.

Another important point to consider is the amount of material in the dryer after equilibrium of input and output has been obtained. Rotary dryers usually run with 3% to 16% of their volume filled with material. Experience has shown that attenuation with most materials is not serious enough to prohibit using loading factors up to 16%.

VI. APPLICATION

Recent tests run at the University of Connecticut's Pharmacology Department by Lawrence Rasero under the direction of Dr. Donald Skauen have demonstrated the dryer's applicability in rapidly drying thermolabile materials. Of the heat-sensitive materials treated, such as papain and ascorbic acid, none showed any form of degradation. Skauen has stated that ascorbic acid with an initial moisture content of 8% can be dried, utilizing sonics, to an essentially anhydrous state within 15 min. This is more rapid than conventional thermal methods of drying. In addition, drying is accomplished without destruction of the acid. Oven-drying of a similar hydrous acid caused a loss of as much as 25% of the ascorbic acid.

During the past year, many drying tests have been conducted on a variety of other materials. It has been determined that in all cases sonic energy has appreciably accelerated the rate of drying. A synopsis of the drying reports on some interesting materials treated with sonic energy is shown in Table I.

TABLE I. Synopsis of sonic-drying tests.

Material	Initial % moisture	Desired final % moisture	Retention time reqd. (min)	Sonics feed rate (lb/h)	No sonics feed rate (lb/h)
Wood flour	5.5	1.53	3.0	90	37
Orange crystals	3.5	1.8	15.0	38	8
Grated cheese	16.8	5.9	16.2	35	25
Powdered coal	19.2	2.0	5.0	110	48
Antacid powder	15.1	6.0	15.0	27	15
Gelatin beads	12.9	3.7	20.0	22	12
Enzyme crystals	9.8	6.4	120.0	5	2
Rubber crumb	44.0	6.0	90.0	7	4
Carbon-black pellets	48.7	1.0	25.0	18	12
Polystyrene powder	0.5	0.1	30.0	14	6
Aluminum oxide	0.5	0.2	5.0	56	32
Metallic soap of fatty acid	27.0	0.4	60.0	10	4
Rice grains	27.6	14.5	11.0	40	18

From the very promising results obtained on pilot plant and small-scale production applications, it appears that scaling up of the sonic dryer is quite practical. A dryer having a chamber volume of approximately six times the size of the present 1.4-cu ft size is now being designed. This unit will be capable of a maximum drying rate of about 500 lb/h. An equivalent-size nonsonic rotary dryer would have a drying rate of only 300 lb/h.

With the development of large-scale sonic dryers, it is this writer's opinion that there will be a wide acceptance of this technique. It is expected that the pharmaceutical, food, and chemical industries will be the prime users of this equipment.

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[12] S. J. Friedman and W. R. Marshall, Chem. Eng. Progr. 45, 482, 573, (1949).