R_x = measured resistance of the heating element, Ω
R_p = resistance between the two slide-wire contacts in the a.c. potentiometric circuit, Ω
T_o = temperature of saturated nitrogen at atm. pressure, °F.
T_{se} = average surface temperature, based on electrical resistance, °F.
T_{sea} = average surface temperature, based on electrical resistance, converted to area average, °F.
ϵ = average porosity of the flow control element, %
μ_f = viscosity of nitrogen, lb./(ft.$^{-1}$/hr.$^{-1}$)

LITERATURE CITED

1. Wayner, P. C., Jr., and S. G. Bankoff, *A.I.Ch.E. Journal*, **11**, No. 1, 59 (1965).
2. Wayner, P. C., Jr., Ph.D. thesis, Northwestern University, Evanston, Illinois (1963).
3. Pai, V. K., M.S. thesis, Northwestern University, Evanston, Illinois (1963).

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Liquid Atomization in a High Intensity Sound Field

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High intensity sound was investigated as a means for liquid breakup. Sonic generators provided energy to atomize liquid introduced near the sound source. Droplet size was measured at several conditions of air and liquid flow for sound intensities ranging up to 160 decibels.

Atomization was good at low liquid flows but became rather coarse as flow rate increased. The droplet size distributions were not uniform. No improvement in breakup could be attributed directly to the sonic compressions and rarefactions beyond that normally produced by the tearing action of air in conventional two-fluid atomizers at comparable air/liquid ratios.

The purpose of this study was to determine if sound energy with its characteristic condensations and rarefactions could be made to disturb liquid sheets and streams and thereby improve atomization. One possible result would be nearly uniform droplets.

Rayleigh, Haenlein, and Weber observed uniform droplets from liquid jets (*1, 2*). A liquid jet becomes disturbed upon leaving the orifice. If this disturbance remains unchanged, a constant time lapse will occur from the beginning of the disturbance to formation of a drop. Therefore, the distance to droplet formation may be changed by varying the liquid velocity. Secondary dis-

TABLE 1. OPERATING CONDITIONS FOR HARTMANN ATOMIZER

	Figure 3 Droplet size distribution curve A	B	C	D
Liquid feed	Annular sheet			
Sound frequency (kcycles)	42	18	*	42
Water flow (gal./hr.)	50			20
Water pressure (lb./sq. in.)	50			12
Air flow (lb./hr.)	15.4			
Air pressure (lb./sq. in.)	50			
Sauter mean diameter (μ)	158	139	124	21

* No resonant cavity.

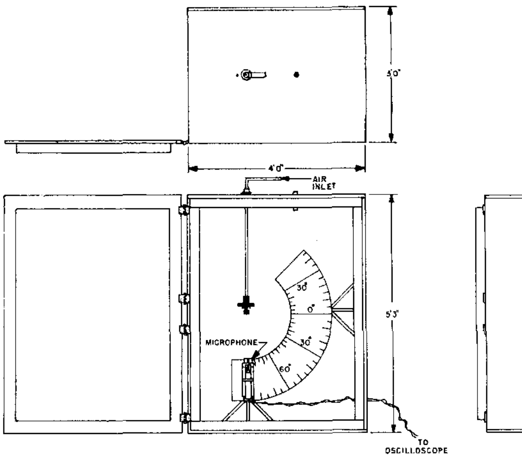

Fig. 1. Anechoic chamber and microphone for measuring sound.

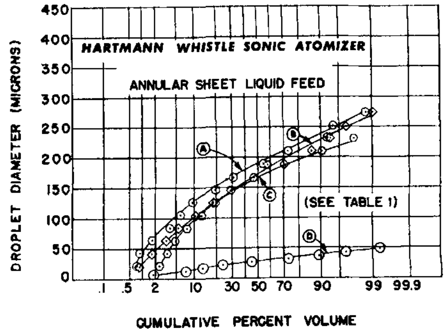

Fig. 3. Droplet size distribution data for Hartmann whistle sonic atomizer operated at several different sound frequencies.

turbances, such as gentle puffs of air applied to the stream near the orifice, will reduce the distance to droplet formation. It did not seem unreasonable that disturbances from sonic energy could periodically disrupt liquid streams and produce droplets of uniform size.

Liquid sheets also exhibit a sequence of physical phenomena in producing droplets (3). Sheet instability and interaction with the atmosphere result in rapidly growing waves. Upon attaining a critical wave amplitude, the sheet ruptures and forms ligaments. Because of surface tension, the ligaments break up into droplets. It is conceivable that the imposition of sonic energy could affect the initial wave action and thereby control droplet size.

EXPERIMENTAL EQUIPMENT

Operating pressures and flow rates for air and water were measured by pressure gauges and flow meters. A sound sensing system composed of a 20 to 90,000 cycles/sec. flat-response microphone and an oscilloscope permitted viewing and measuring sound wave characteristics. The microphone was accurately positioned around the sound generator by using a calibrated protractor mounting. These were enclosed in the anechoic chamber shown in Figure 1.

Droplet size was determined by immersion sampling and automatic scanning of photomicrographs of the collected droplets. Droplets were collected by spraying dyed water into a cell containing a hydrocarbon solvent (*4*). Because of the solvent's low density and immiscibility with water, the droplets sank to the bottom of the cell and remained suspended as nearly perfect spheres. These were photographed at 50X magnification and the negatives scanned in an automatic droplet analyzer (*5*). The droplet size spectrum and Sauter-mean diameter were then computed.

PROCEDURE AND RESULTS

A sonic atomizer is composed of two main systems: the sound generator and the device for introducing liquid to the zone of high-intensity sound. This study utilized Hartmann whistle and stem-and-cavity types of sound generators because of their compact size and simplicity. Compressed air was employed as the energizing gas, and liquid was supplied in the form of streams or annular sheets.

The Hartmann whistle sonic atomizer used in this study is depicted in Figure 2. By varying cavity depth and distance between cavity edge and air orifice, it was possible to modulate the sound frequency and intensity and observe their effect upon droplet size. To gain maximum benefit from the radiating energy, liquid was introduced around the sound source as a symmetric annular sheet.

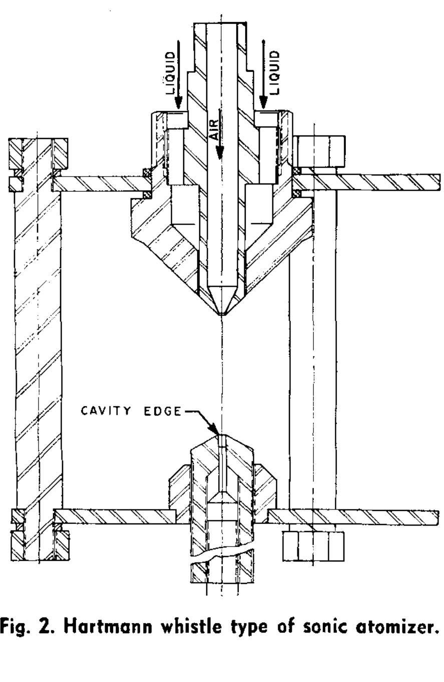

Fig. 2. Hartmann whistle type of sonic atomizer.

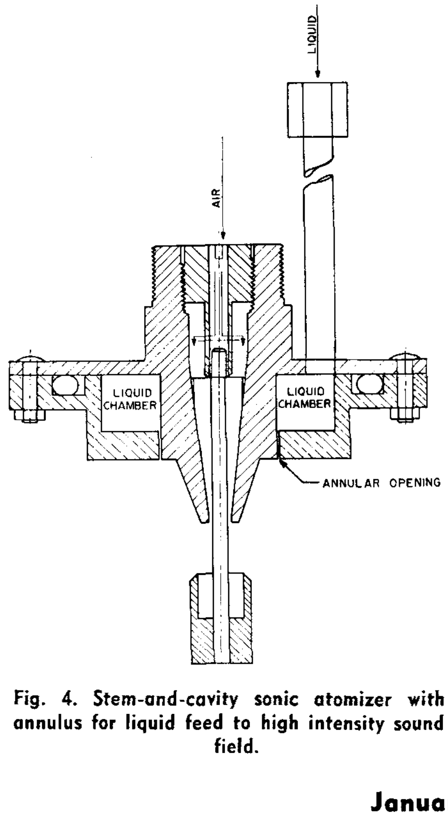

Fig. 4. Stem-and-cavity sonic atomizer with annulus for liquid feed to high intensity sound field.

TABLE 2. OPERATING CONDITIONS FOR STEM-AND-CAVITY ATOMIZERS

	Figure 6 Droplet size distribution curve A	B	C
Liquid feed	Annular sheet		Streams
Water flow (gal./hr.)	123	185	10
Water pressure (lb./sq. in.)	20	40	30
Air flow (lb./hr.)	66	35	58
Air pressure (lb./sq. in.)	90	40	70
Sauter mean diameter (μ)	282	256	173

The frequency of sound generated by the Hartmann whistle is determined by the same factors as for a closed-end tube (6):

$$f = \frac{c}{4(L + 0.3\,d)}$$

where f = sound frequency, c = sound velocity, L = cavity depth, and d = cavity diameter.

Maximum sound intensity was achieved by properly adjusting the air supply and cavity edge position. The microphone was placed 10 in. from the sound cavity on a line perpendicular to the atomizer axis. With 50 lb./sq. in. air, 135 decibels were recorded. Decibel reference is 0.0002 dynes/sq. cm.

Droplet size was measured for 50 gal./hr. water flow rate while operating the sound generator at two different cavity depths resulting in frequencies of 42 and 18 kcycles. Sauter-mean diameters of 158 and 139 μ, respectively, were calculated. The generator was also operated at zero cavity depth where no definite sound frequency prevailed. Here, the 124-μ Sauter diameter indicated unexpectedly fine atomization. Other investigators have also found similar results (7). The droplet size distribution curves in Figure 3 show maximum droplets of at least 225 μ at all frequencies for 50 gal./hr. operation (Table 1).

Another test at 42 kcycles., but with liquid flow rate reduced to 20 gal./hr., indicated much finer atomization, as also shown in Figure 3. The Sauter diameter was 21 μ. A reduced droplet size range also resulted.

To determine whether a critical distance existed between the sonic source and liquid to obtain maximum atomizing energy from the sound, liquid streams were introduced at various positions in proximity to the sound source. No location could be found where a noticeable improvement in the quality of atomization was observed. Atomization occurred at the zone where the liquid impinged upon air deflected from the cavity.

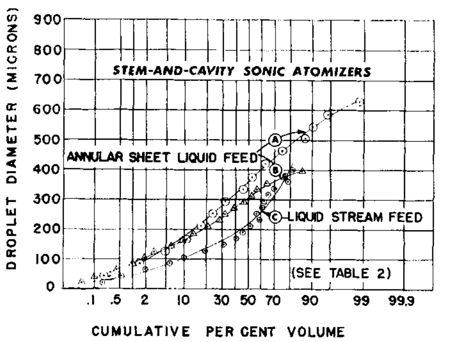

Fig. 6. Droplet size distribution data for stem-and-cavity sonic atomizers.

Although the Hartmann type of sonic atomizer was useful for studying variables affecting sound generation and liquid atomization, this design had practical limitations. For example, the cavity supports interfered with the spray, impairing spray pattern. Also, finer atomization at high liquid flow rates and more uniform droplets were desired.

The stem-and-cavity sonic atomizer, designed with a centrally located stem supporting the cavity, eliminated obstructions in the spray. Moreover, other investigators had found that this generator produced high-intensity sound at lower air pressures (8, 9). A sound level of 152 decibels, measured 2 in. from the cavity, indicated the intense sound field to which the liquid was subjected in the authors' tests.

Two methods were used to supply liquid to the sound field: an annular sheet and liquid streams flowing parallel to the nozzle axis from holes concentrically located around the sound source (Figures 4 and 5).

While operating with the concentric liquid sheet, droplet samples were taken at water flow rates of 123 and 185 gal./hr. and air pressures of 90 and 40 lb./sq. in., respectively. The resulting droplet size curves are shown in Figure 6. The same figure reveals that the liquid streams also produced a broad droplet size spectrum, even though a much lower liquid flow rate of 10 gal./hr. was used. Operating conditions for these droplet measurements are listed in Table 2.

These unsuccessful attempts to produce uniform atomization suggested the desirability of other design approaches. One idea was to focus sound upon liquid

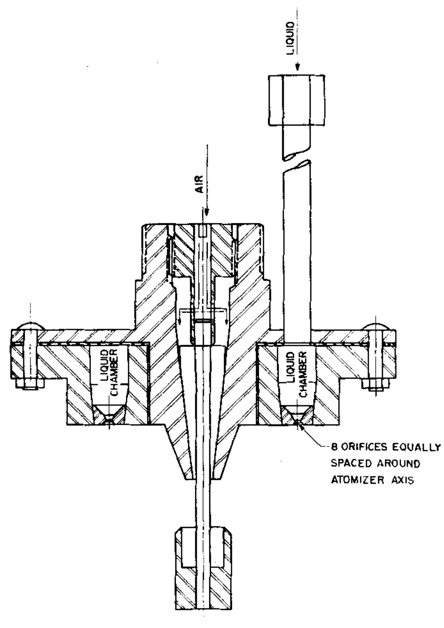

Fig. 5. Stem-and-cavity sonic atomizer having orifices for liquid feed to high intensity sound field.

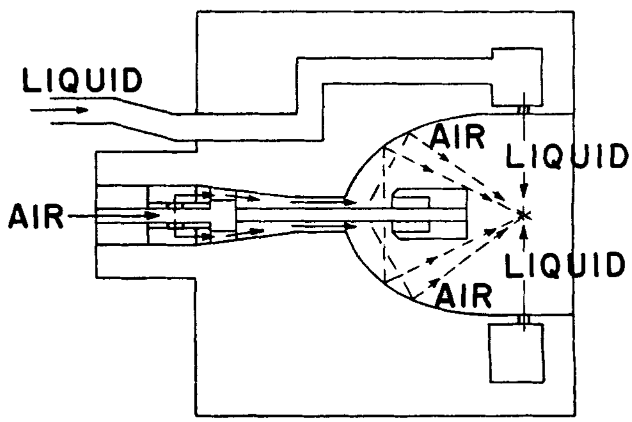

Fig. 7. Sonic atomizer with elliptical reflector.

streams, thereby increasing its intensity and perhaps improving atomization.

Figure 7 shows this modification. Air jetting into the cavity set up a sound field that radiated from the edge of the cavity. An elliptical reflector directed the sound and air to a focal point below the cavity. Liquid was also directed to the focal point through orifices in the reflector.

To determine whether improved directivity had actually been achieved, readings were again taken with the traversing microphone. Compared with results for the same sonic generator without reflector, focusing increased the intensity in front of the reflector by 10 decibels and at the side decreased it by 15 decibels.

Although droplet size was not measured quantitatively, the appearance of the spray did not indicate significant improvement in quality of atomization. This model was also used in spray drying coffee solutions. Dry product particles ranged from fines to large agglomerates, indicating that a broad range of droplets existed in the spray.

To further explore the effect of sound on atomization with these devices, the cavity was replaced with a deflector designed to direct air to the reflector in a similar manner without generating intense sound. Figure 8 shows this modification. No difference was observed between the sprays produced with and without sonic radiation.

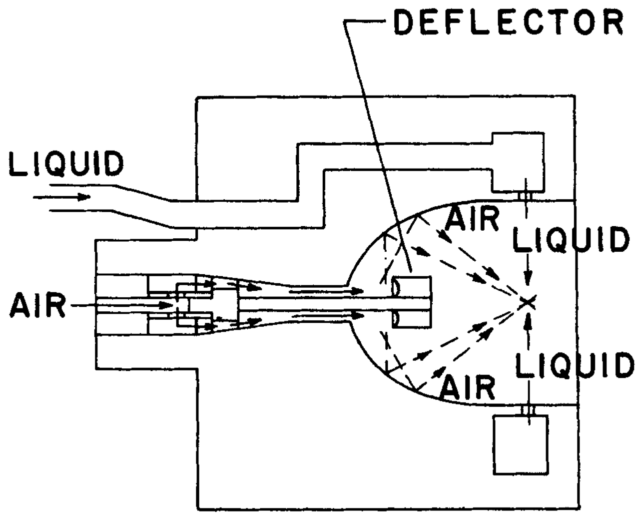

Fig. 8. Atomizer design with resonant cavity replaced by curved deflector.

DISCUSSION

The role of sound in liquid atomization is complex and difficult to isolate from the accompanying pneumatic effects. Nevertheless, some observations are possible by considering the energy relationships in sonic devices.

To illustrate, the power input was estimated for the stem-and-cavity atomizer operated with 90 lb./sq. in. air at a flow rate of 123 gal./hr. As stated earlier, this device generated a 152 decibel sound level 2 in. from the cavity. Based on the decibel reference of 0.0002 dynes/sq. cm., this was equivalent to a sonic pressure of 7,960 dynes/sq. cm. and a total radiated power of 49 w. (36 ft.-lb./sec.).

The total pneumatic power input, on the other hand, exceeded 1000 ft.-lb./sec. This was calculated from the air flow and pressure, with isothermal expansion assumed. Only 3.5% of this input was converted to sonic energy. However, this is in line with statements of other investigators who mention 5% as a typical maximum efficiency for whistle generators of this type.

The sonic, pneumatic, and hydraulic power inputs for the above test are shown in Table 3 together with the energy required to overcome surface tension during droplet formation. The latter is very small, resulting in an overall efficiency of only 0.012%. This is typical of pneumatic atomization in which the utilization of energy is much less effective than in pressure nozzles where energy is transmitted as an intrinsic quality of the sprayed liquid (*10*).

Sonic radiation is similar to pressurized air in the sense that it must impinge upon and interact with a liquid stream to produce fine droplets. Although the efficiency of this mechanism is difficult to assess, it has been shown that the sonic input is far less than the available pneumatic energy. Moreover, because of geometrical considerations, only a portion of the total sound energy can be applied to the liquid. The efficiency of sonic energy conversion would therefore have to be substantially greater than that associated with pneumatic atomization to cause a noticeable improvement.

Table 3. Energy Supplied Stem-and-Cavity Atomizer for 123 gal./hr. Water and 90 lb./sq. in. Air (Figure 6A)

Energy source	Estimated power (ft.-lb./sec.)
Sonic	36
Pneumatic (excl. sonic)	1,000
Hydraulic	13
Power required for droplet formation	0.13
Overall efficiency = 0.012%	

CONCLUSIONS

The sonic atomizers in this study did not provide exceptional spray characteristics. There was no evidence that sound from the Hartmann whistle or stem-and-cavity generators significantly affected droplet size or uniformity. Addition of a sonic reflector and removal of the resonant cavity had little effect.

Air appeared to be the predominant atomizing medium. Relationships between air/liquid mass ratio and droplet size were analyzed for both sonic and air atomizing nozzles. Both types produced finer droplets as the air/liquid ratio was increased. From the standpoint of air consumption, no advantage was detected for the sonic atomizer models used in this study.

LITERATURE CITED

1. Giffen, E., and A. Muraszew, "The Atomisation of Liquid Fuels," p. 20, Chapman and Hall, Ltd., London (1953).
2. Marshall, W. R., Jr., "Atomization and Spray Drying," p. 4, American Institute of Chemical Engineers, New York (1954).
3. Dombrowski, N., and W. R. Johns, *Chem. Eng. Sci.*, **18**, 203 (1963).
4. Tate, R. W., *A.I.Ch.E. Journal*, **7**, 574 (1961).
5. Adler, C. R., A. M. Mark, W. R. Marshall, Jr., and R. J. Parent, *Chem. Eng. Progr.*, **50**, 14 (1954).
6. Carlin, B., "Ultrasonics," p. 128, McGraw-Hill, New York (1960).
7. Allen, J. M., S. Chapman, C. F. Speich, A. A. Putnam, J. W. Bloemer, and E. Ungar, "The Behavior of Boron Oxide Particles in High-Temperature Air Streams," p. 6, Arnold Engineering Development Center, AiResearch and Development Command, Tullahoma, Tennessee, Second Quarterly Report (1957).
8. Crawford, A. E., "Ultrasonic Engineering," p. 120, Academic Press, New York (1955).
9. LeLandais, M., *Ultrasonic News*, **7**, Winter (1960).
10. Gretzinger, J., and W. R. Marshall, Jr., *A.I.Ch.E. Journal*, **7**, 312 (1961).

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