ATOMIZATION BY MAGNETOSTRICTION
INDUCED VIBRATION

By

Dennis Alan Vehe

Bachelor of Science

South Dakota State University

Brookings, South Dakota

1967

Submitted to the Faculty of the Graduate College
of the Oklahoma State University
in partial fulfillment of the requirements
for the Degree of
MASTER OF SCIENCE
May, 1969

ATOMIZATION BY MAGNETOSTRICTION INDUCED VIBRATION

Thesis Approved:

Jay G. Porterfield
Thesis Adviser

E. W. Schroeder

D. D. Durham
Dean of the Graduate College

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

CHAPTER I

INTRODUCTION

The agricultural industry now uses many types of sprayers for applying chemicals. Today, the demands are greater and the application problems are more diverse than ever. Uses have grown to include the application of insecticides, fungicides, herbicides, defoliants, growth-regulators, and plant nutrients. Thus, the efficiency, effectiveness, and safety of chemical application have grown to be extremely important agricultural problems.

According to Bainer, Kepner, and Barger (3), measures of these qualities include factors such as penetration and carrying ability of the spray, the efficiency of catch of sprays by plant surfaces, uniformity and completeness of coverage, effectiveness of individual particles after deposition, and drift.

Since particle size has a major effect on these factors, the problem of improving todays spraying systems is basically that of effectively controlling the individual droplet size produced by the drop generation process. Droplet size control is particularly important to the problem of eliminating drift. For example, a wind speed of three miles per hour will carry a 10 micron[1] particle several miles before it is deposited; whereas, a 100 micron drop will drift only 50 feet under identical conditions (5).

An ideal solution to the problem of controlling drift would be a system which could accurately generate a single, known drop size that could be continuously adjusted to suit prevailing environmental conditions.

The objective of this search is to synthesize an atomization control system that would approach this ideal solution.

---

[1] One micron = 10^{-6} meters or 1/25,400 inch.

CHAPTER II

REVIEW OF LITERATURE

The most common agricultural atomization devices in use today, the cone and fan type nozzles, utilize a process where liquid is first forced into a thin sheet. According to Roth and Porterfield (11), internal and external disturbances then cause ruptures in the sheet which enlarge rapidly to form a network of liquid filaments of varying diameter and length. Because of the variable nature of the fluid filaments, final atomization results in a wide range of drop sizes. Akesson (1) sites one such nozzle operating at 40 psi fluid pressure, as producing an average drop diameter of 136 microns with a nearly flat size distribution from 10 to 100 microns. In general, average drop size from the cone and fan type nozzles will be increased by decreasing fluid pressure, increasing surface tension, or increasing fluid density. Variation in viscosity has little effect on drop size when varied from one to ten centistokes (3).

Although not yet commonly used, jetstream atomization has recently been considered as a possible solution to controlling droplet size. According to Roth and Porterfield (10), rather than allowing a liquid sheet configuration to form and disintegrate, this method allows liquid to discharge from a circular orifice as a jetstream. Under conditions of minimum turbulance, liquid emerges as a cylindrical filament. Again, internal and external forces ultimately cause breakup into rather uniform droplets of two basic size groups. Small drops of about $0.5 \times d_o$ (d_o = Orifice diameter) are formed between larger drops that average twice the orifice diameter in size (10).

This phenomena becomes irregular and unpredictable when internal forces disrupt laminar like flow through the orifice (8). According to Roth and Porterfield (10), jetstream breakup becomes unpredictable for pressures above approximately five psi. They also calculated the drop production rate from a single jetstream to be about 3,300 drops/sec. and suggested that the use of a number of individual jetstreams would be necessary to match the drop production rate from a single fan type nozzle.

High frequency vibration has recently been used to atomize viscous fluids. One example of this approach to drop generation is the commercially available Astrospray[2] Nozzle/1700 Series. Spherical waves of pressure and rarefraction from a gas driven sonic whistle are claimed to chop liquid into regular droplets. Average drop size

---

[2] Trademark of the Heat Systems Company, Melville, L.I.

may be varied from 1 to 40 microns with the fluid flow rate varying from 0.12 to 3.5 pounds/min. (2).

Ultrasonic atomization from a solid surface, activated by a ferrite (magnetostrictive), lead zirconate or barium titanate (piezoelectric) transducer has also offered promise of a means toward atomization control. The fluid to be atomized is supplied to an ultrasonically activated solid surface. When ultrasonic impingement of sufficient force to disrupt molecular cohesion is encountered, the fluid is instantly atomized and propelled from the surface (12). Fredrick (6) states that "the drop size in the ultrasonically formed aerosol is in the range of 1 to 100 microns and is frequency dependent".

CHAPTER III

SYNTHESIS OF AN ATOMIZATION CONCEPT

Early in 1968 at the Oklahoma State University Agricultural Engineering Department's spray research laboratory, Roth and Porterfield were conducting tests to determine if high frequency oscillation applied to an orifice plate, could be used as a means of atomization control. They developed a device which they called a "variable orifice atomizing device". As shown in Figure 1, the device consisted of a piezoelectric orifice plate to which an A.C. or pulsed D.C. voltage was applied. It was claimed that the orifice diametral size-change, affected by the cyclic voltage, would cause the emerging liquid stream to atomize with the size range, frequency, and uniformity of drop production being controlled by the magnitude and frequency of the applied voltage.

Although the device was earlier observed to produce a marked effect on the atomization process, the first physical evidence delineating the nature of the effect was produced on February 21, 1968. At that time, photographs were taken of the emerging stream with the laboritory's photographic spray sampling apparatus (9).

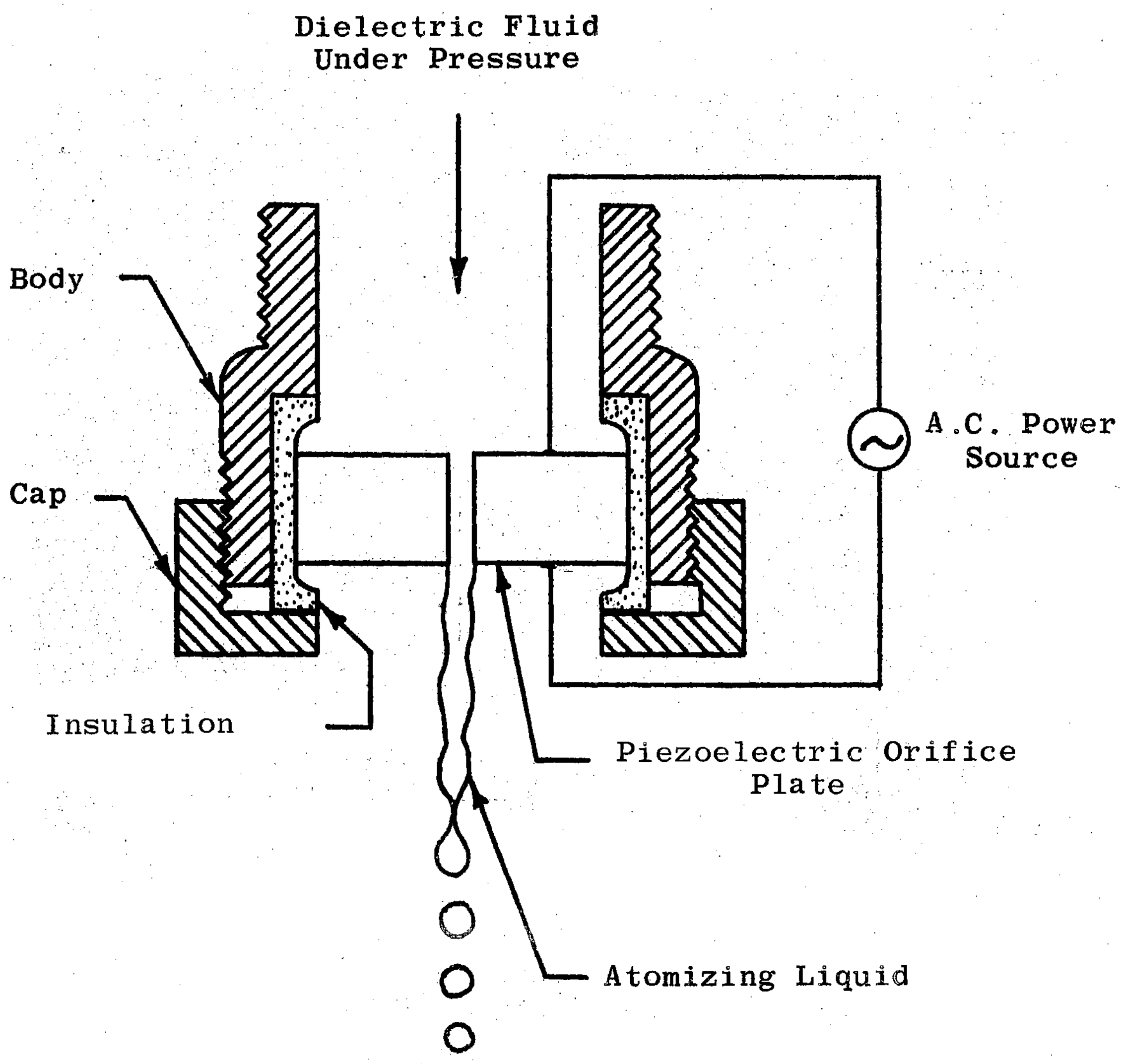

Figure 1. Piezoelectric Variable Orifice Atomizing Device

The nozzle was first operated with fuel oil at low pressure (1.5 psi). When a 500 Hertz voltage was applied to the crystal, visible impulse nodes appeared on the stream near the orifice. Figure 2-A shows a photograph displaying a single impulse node caused by the diametral size change of the crystal. When a stroboscopic light was tuned to match the 500 Hertz exciting voltage, these nodes appeared as a standing, stable wave form superimposed on the emerging stream.

With conditions held constant as in Figure 2-A, photographic samples were taken at three locations, each successively farther from the orifice. Figure 2-B shows large drops beginning to form where the nodes had appeared and a long filament forming between them. Farther downstream (Figure 2-C) the filament begins to break up and ultimately forms three droplets (Figure 2-D) of three seemingly distinct sizes. When power was increased (Figure 2-E), the arrangement of the droplets changed but the distinct sizes were still present.

Consideration of these initial findings suggested that the impulse nodes, noted in the first observation, could be moved closer together to form a smooth sinusoidal wave form superimposed on the jetstream. This was accomplished by increasing the frequency of vibration of the orifice plate to match the efflux velocity of the fluid in such a way as to produce a smooth wave form. Figure 2-F shows the resulting atomization pattern with the crystal

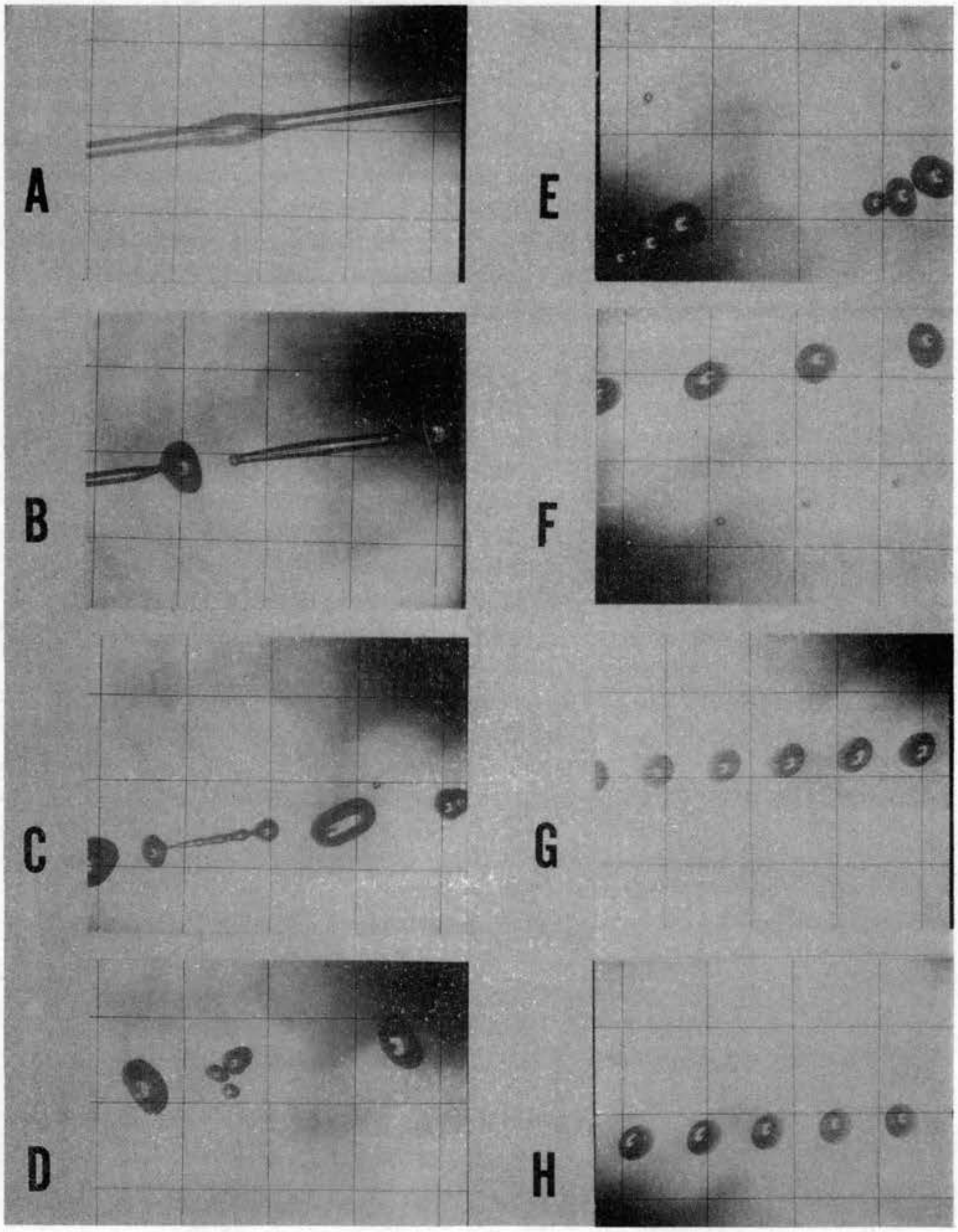

Figure 2. Drop Production From the Variable Orifice Atomizing Device

excited at 1370 Hertz. Again large drops are formed where the impulse nodes occurred, but the connecting filament was shortened and upon separation from the large drops, formed a single, small satellite drop. Further increase in frequency to 3600 Hertz, with a corresponding increase in pressure to 3.8 psi (Figure 2-G) suggested that the effect previously noted could be projected to higher pressures with matching higher frequencies. Figure 2-H shows ideal Rayleigh breakup[3] occurring when power was further increased.

The piezoelectric, variable orifice nozzle had demonstrated its ability to control the atomization process; however, several distinct disadvantages due primarily to the physical properties of the electrostriction[4] transducer were anticipated and observed during the initial testing. They were:

1. Low structural strength of the crystal
2. Difficulty in providing good electrical insulation for the crystal
3. Overheating of the crystal
4. Limitation to use with high dielectric fluids

---

[3] In the late 1800's, Lord Rayleigh predicted the necessary conditions to cause collapse of a liquid jet issuing at a low velocity.

[4] Change in length per unit length of a material with a change in electrical potential applied across the material.

It therefore became desirable to produce the orifice diametral size - change by some means that did not require the use of an electrostrictive transducer.

According to Wise (13), magnetostriction[5] transducers exhibit several comparative advantages over electrostrictive transducers. They are:

1. Ability to drive high impedance loads, such as liquids
2. Rugged construction
3. Ability to operate under difficult environmental conditions
4. Efficient operation in a frequency range (5 to 100 kc) where other transducers are relatively inefficient or difficult to construct
5. Ease of mounting
6. Good heat transfer from the metallic core

It was therefore decided that a magnetostrictive transducer would be designed to eliminate the piezoelectric crystal as the source of vibrational energy.

Initially, the most obvious method of utilizing a magnetostrictive transducer in place of the piezoelectric crystal was to pass an alternating current through a coil constructed around a magnetostrictive orifice plate as shown in Figure 3. It was hypothesized that forced

---

[5] Change in length per unit length of a material with a change in magnetic flux density in the material.

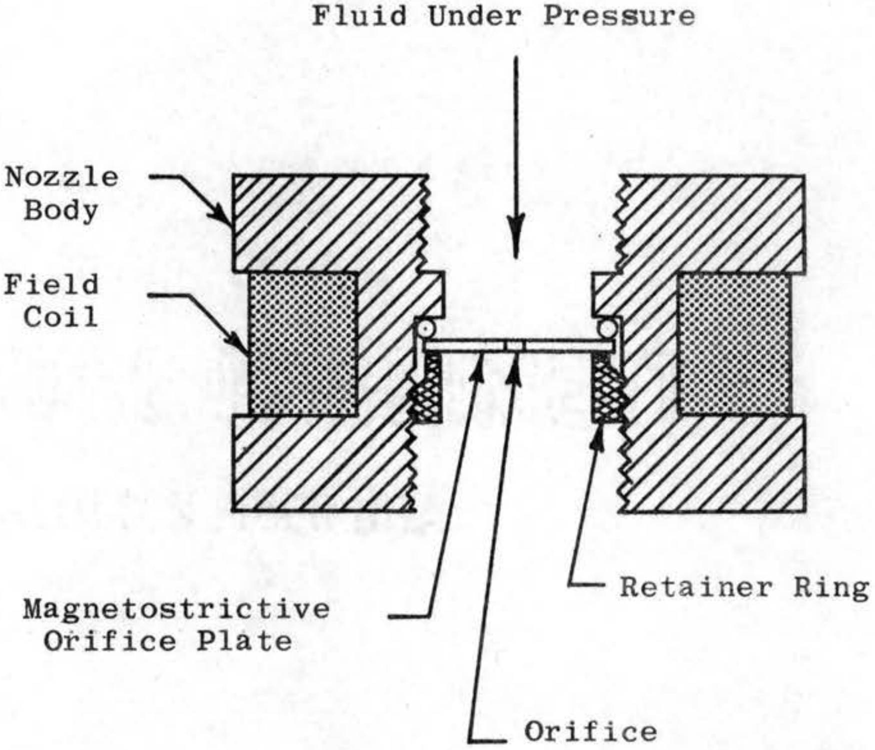

Figure 3. Magnetostrictive Variable Orifice Atomizing Device

vibration of the orifice plate would produce an atomization pattern similar to that observed with the piezoelectric variable orifice nozzle. However, when a model was built and tested, no effect was observed on the emerging stream. This was attributed to the following factors:

1. The extremely high resonant frequency of the magnetostrictive orifice plate, precluded the possibility of exciting the plate at resonance[6]
2. The mountings necessary to seal the plate absorbed a large amount of energy and over-damped the system
3. The surrounding fluid absorbed some of the vibrational energy

At this point of inquiry, an examination of alternative methods of superimposing a regular wave form on a jetstream led to the following theory: If a source of vibrational energy was placed upstream from an orifice, advancing waves of pressure and rarefraction might cause superposition of a regular wave form on the emerging stream (Figure 4). This regular wave form would in turn lead to a regular breakup process, as observed with the variable orifice nozzle, that could be controlled by varying one or more of the system parameters. Quantities considered to be pertinent system parameters include:

---

[6] According to Hund (7), the vibrational amplitude of a magnetostrictive transducer is pronounced only when the transducer is excited at its resonant frequency.

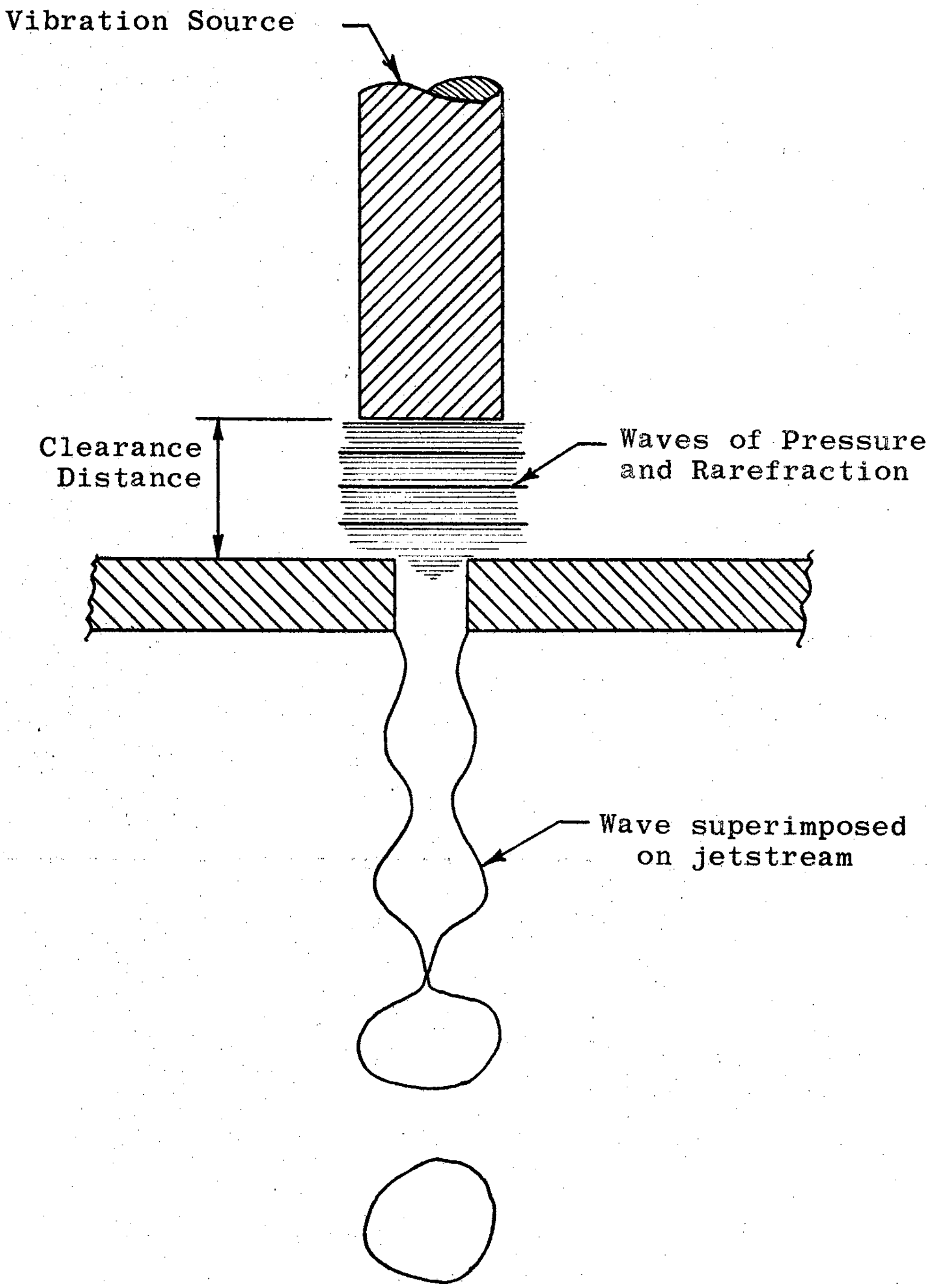

Figure 4. Vibrational Energy Source Upstream From Orifice

1. Orifice size
2. Vibrational frequency
3. Vibrational amplitude
4. Clearance distance (see Figure 4)
5. Fluid pressure
6. Fluid density
7. Fluid surface tension
8. Fluid viscosity

CHAPTER IV

DESIGN OF THE EXPERIMENTAL APPARATUS

Four qualities were considered basic to the satisfactory performance of the nozzle design. They were:

1. A magnetostrictive transducer that would efficiently provide the required vibrational energy
2. A liquid tight and mechanically efficient means of mounting the magnetostrictive transducer
3. A method for locating an orifice plate directly under the vibrational energy source
4. A means for varying the system parameters

Since it was believed that the previous attempt at building a magnetostrictive vibratory nozzle failed because of inadequate consideration of the transducer requirements, the magnetostrictive transducer was the foremost design consideration.

Design of the Magnetostrictive Transducer

The most basic design consideration in a magnetostrictive transducer is the choice of core material. Some materials displaying appreciable magnetostrictive characteristics are:

1. Pure Nickel
2. Nickel-Iron alloys such as invar and permalloy
3. Cobalt
4. Pure iron

Of these materials, nickel was found to exhibit the greatest magnetostrictive strain except where field strengths approached an impractically high level of 4,000 oersteds[7]. At these high field strengths, cobalt exhibits a greater strain (4). Nickel also exhibited relatively high strength characteristics and was found to be readily available from local sources.

According to Wise (13), the simplest form of a magnetostrictive transducer is a rod surrounded by a solenoid winding. Thus, it was decided to utilize a 1/4 inch diameter nickel rod magnetostriction transducer, where one or both of the rod ends could be used to transmit vibrational energy to the fluid.

As mentioned earlier, a magnetostrictive transducer must be excited at or near its resonant frequency to exhibit a pronounced vibrational amplitude. The resonant frequency for a rod transducer is

$$f = \frac{c}{2l}$$

---

[7] The cgs unit of magnetic intensity.

where

f = resonant frequency of the rod in Hertz.

c = velocity of sound in the core material in inches/sec.

l = rod length in inches

Since the velocity of sound in nickel is approximately 180,000 inches/sec., the rod length will fix the fundamental frequency of the transducer. A practical size limitation set the maximum rod length at five inches. Thus,

$$f = \frac{c}{2l} \approx 18{,}000 \text{ Hertz}$$

is the minimum frequency of vibration for this transducer.

The exciting winding must provide an alternating magnetic field, longitudinal with the rod, with a peak value of from 50-200 oersteds. According to Wise (13) on page 10, a value of 100 oersteds is a good nominal value for materials like nickel, permendur, and several others. This would require a winding such that

$$H = 100 = \frac{0.4\pi NI}{l}$$

where

H = magnetic field in oersteds

N = number of turns in the solenoid

I = current in amperes

l = length of the magnetic path in cm.

Thus, the choice of a wire gauge will set the number of required turns per inch in the transducer coil. An arbitrary choice of the common AWG-#18 insulated wire was made. Its current rating of five amperes and diameter of 0.05 inch set the turns per unit length at

$$\frac{N}{l} = \frac{100}{0.4\pi I} = \frac{100}{0.4\pi 5} = 16 \text{ turns/cm.} = 40 \text{ turns/inch}$$

According to Wise (13), 20 turns per inch can be accommodated in one layer, so two layers will provide the required exciting winding.

Design of the Magnetostrictive Rod Transducer Nozzle

The integration of the transducer into a feasible fluid system was next undertaken. The final magnetostrictive nozzle design as shown in Figure 5, exhibits the following components:

1. A pure nickel rod, oxide annealed[8] to a soft magnetic condition and surfaced on each end
2. A plexiglass rod and coil sheath to provide a high dielectric mount for the field coil and a guide for the nickel rod
3. Field coil of AWG#18 insulated wire wound onto the plexiglass sheath at a density of 40 turns per inch

---

[8] A cold-rolled, Nickel 200 rod was annealed by heating in air to 800°C for 1 hour and cooling at a rate of 100° per hour.

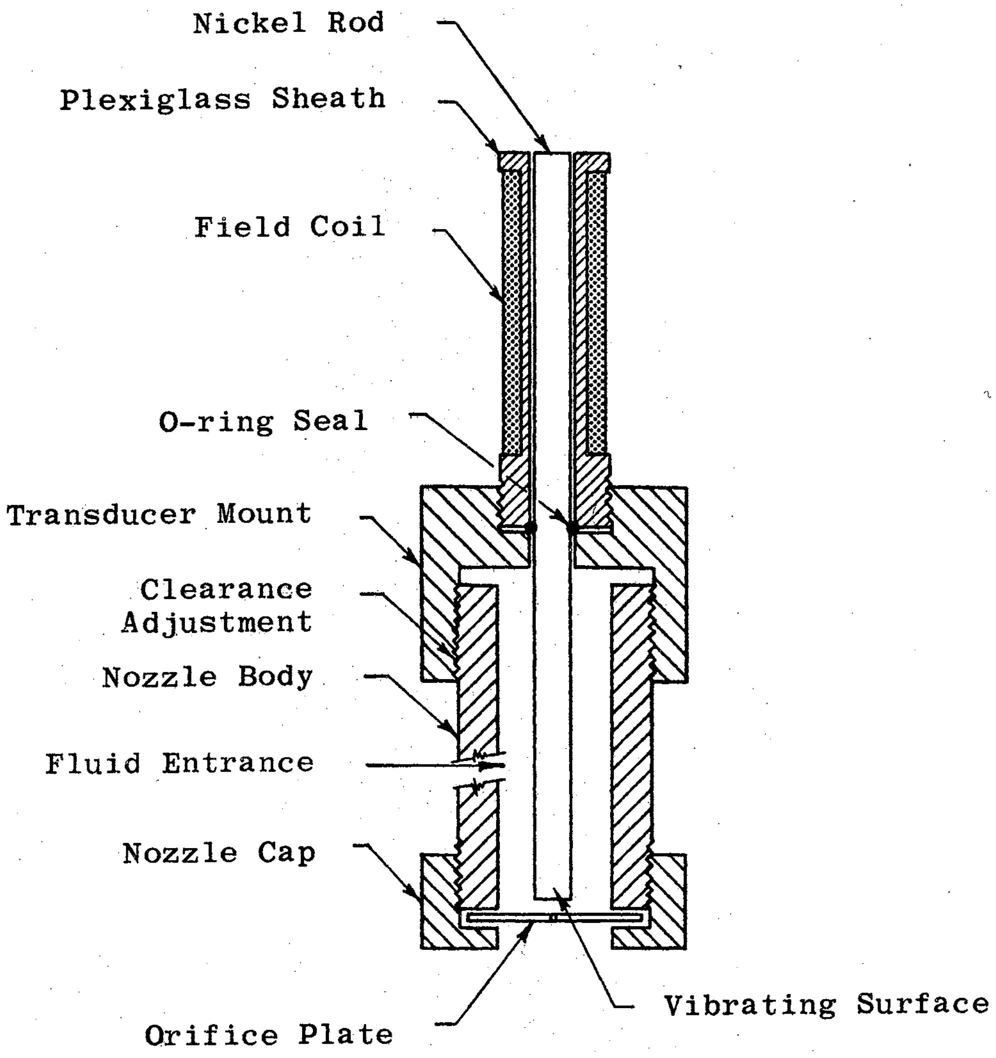

Figure 5. Magnetostrictive Rod Transducer Nozzle

4. An o-ring fluid seal and elastic mount located at the rod center
5. Main transducer mount threaded to the nozzle body
6. Threads to provide adjustment of the rod end clearance distance from the orifice plate
7. Nozzle body with a large fluid cavity to allow low velocity fluid flow to the orifice vicinity
8. Large fluid entrance (1/4" pipe) to allow low velocity fluid flow into fluid chamber
9. Nozzle cap to hold and seal the orifice plate to the nozzle body
10. Orifice plate of 0.020" brass stock with a single hole at the center
11. Rod end vibrational energy source, polished to minimize irregularities in the wave pattern

The fluid system consisted of a Binks[9] pneumatic pressure tank which forced the fluid through a screen filter before entering the nozzle. Fluid pressure was measured at the point of entry into the nozzle body.

The Electrical Power Source

A magnetostrictive transducer can be excited by two basically different means. When an alternating current

---

[9] Trademark of the Binks Manufacturing Company, Chicago, Illinois.

is passed through a coil surrounding a nickel rod, the rod becomes magnetized and contracts at the peak of each half-cycle. The rod will therefore vibrate longitudinally with a frequency double that of the magnetizing current. However, if the alternating current is superimposed over a direct current (bias current) that is greater than the alternating current amplitude, the resulting field will be unipolar and will only pulsate. Thus the rod will vibrate longitudinally at the same frequency as the exciting current. Again, the vibration is pronounced only when a natural mode of vibration is excited (7).

The most efficient operation of a magnetostrictive transducer results where the system is excited by a biased alternating current. Thus, it was decided that the transducer would be powered in this manner.

Figure 6 shows a diagram of the power supply circuitry. This is a parallel circuit with a blocking element in series with each source. The capacitor is chosen large enough to pass the alternating current and to block the direct current from flowing through the A.C. source. The inductor is chosen large enough to satisfactorily block the alternating current from flowing through the direct current source. This design allows the A.C. and D.C. sources to be nearly independent (13).

Choice of circuit components was effected largely by availability. A Hewlet-Packard Model 200 AB audio oscillator, amplified by a McIntosh Model MI 200 AB

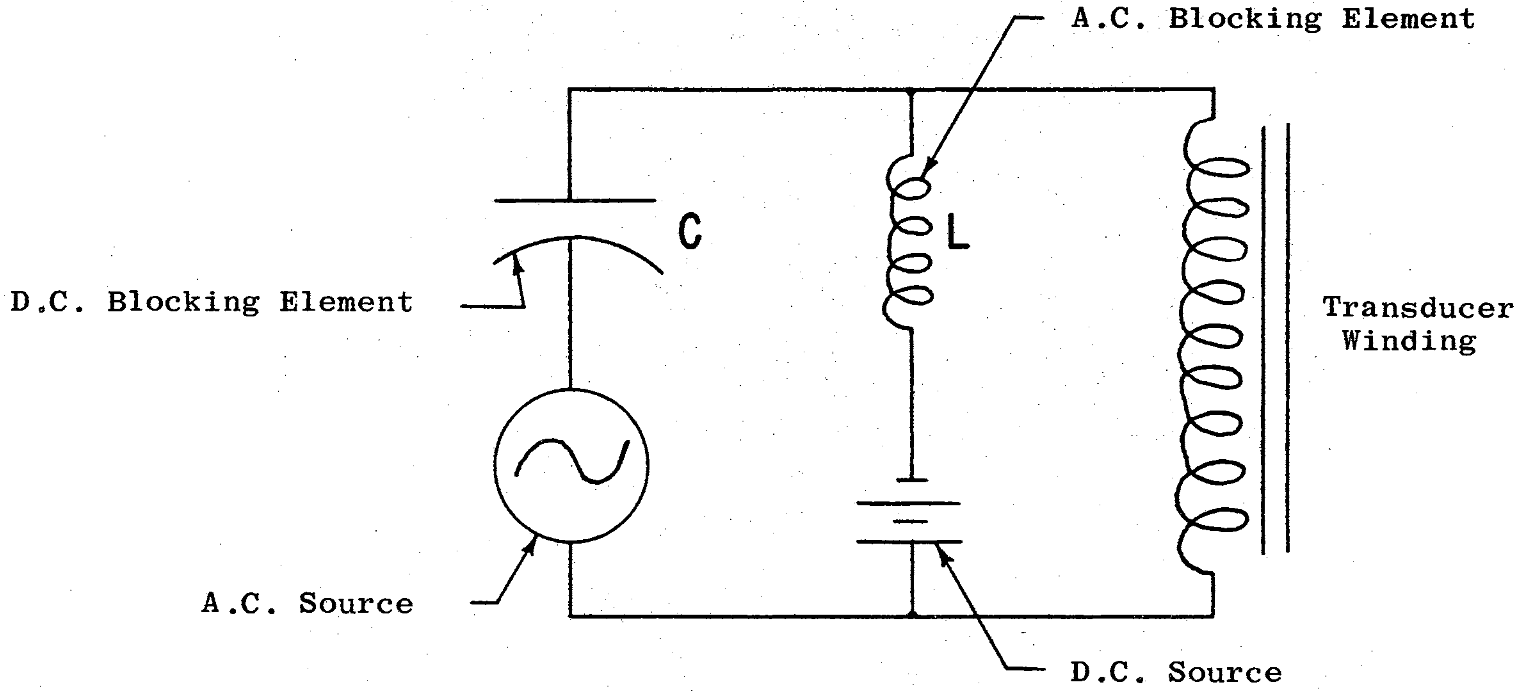

Figure 6. Power Supply Circuit Diagram

power amplifier was used as the alternating current source. This combination is capable of a 200 watt power output in a range of 20 to 20,000 Hertz. A rheostat controlled A.C. converter was used as the D.C. power source. The capacitor and inductor blocking elements were chosen as described in the next section.

Tuning the Transducer

In order to sense when the rod transducer is vibrating and to tune the rod to its maximum vibrational amplitude,[10] it is necessary to physically display the motion of the rod end. This was accomplished by placing an Astatic[11] phonograph cartridge in contact with the upper surface of the rod transducer (Figure 7). The output leads of the cartridge were fed into the upper beam input of the Tektronix[12] dual beam oscilliscope. The lower beam was connected to the transducer power input.

Figure 8 shows the resulting traces where a 4 7/8 inch nickel rod was excited at half its resonant frequency with a non-biased alternating current. The rod displayed resonance at 18,300 Hertz when excited by a frequency of 9,150 Hertz.

---

[10] Only relative amplitude will be measured as no practical means was found to measure the absolute amplitude of vibration.

[11] Trademark of the Astatic Corporation, Conneaut, Ohio.

[12] Trademark of Tektronix, Incorporated, Beaverton, Oregon.

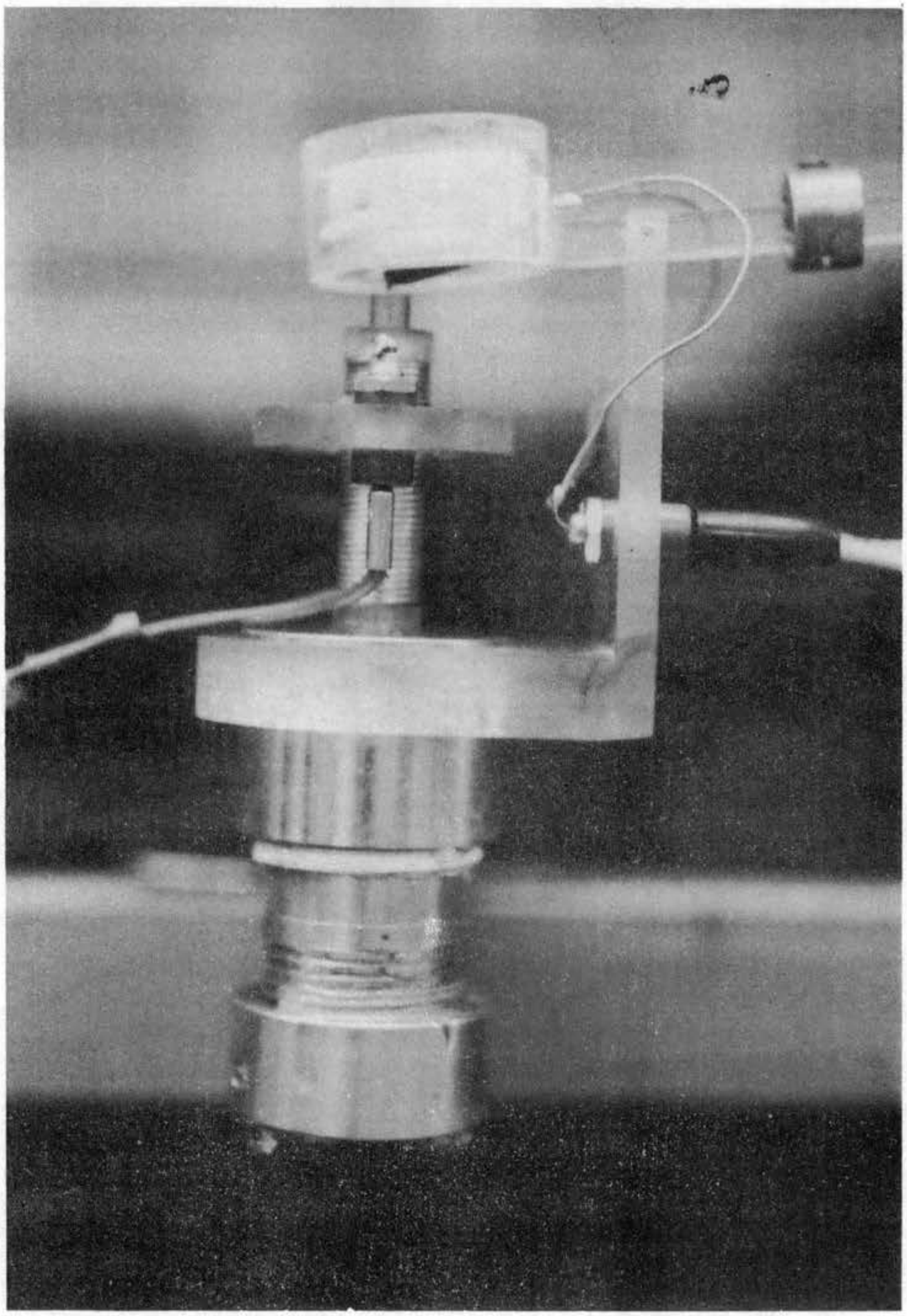

Figure 7. Magnetostrictive Rod Transducer Nozzle With Vibration Sensor

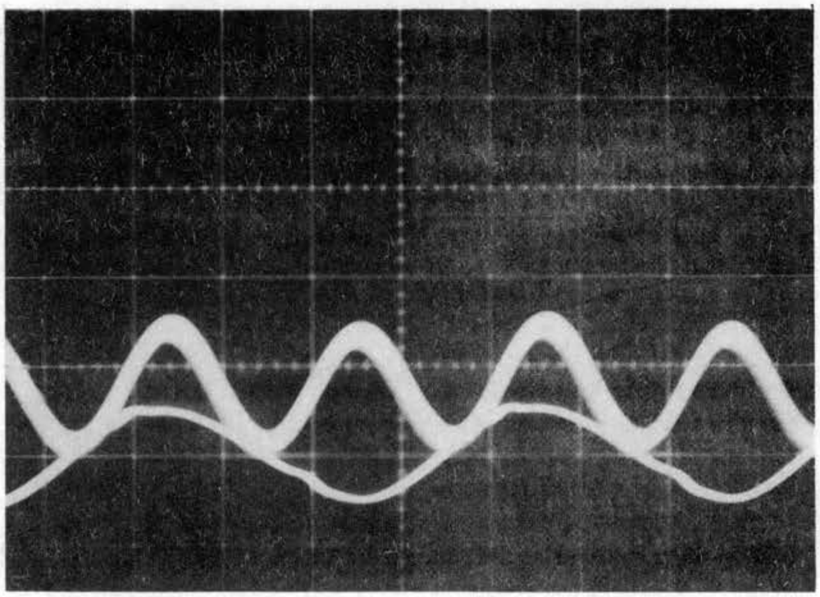

Figure 8. Oscilliscope Traces for a Magnetostrictive Rod Transducer Excited by a Non-Biased Alternating Current

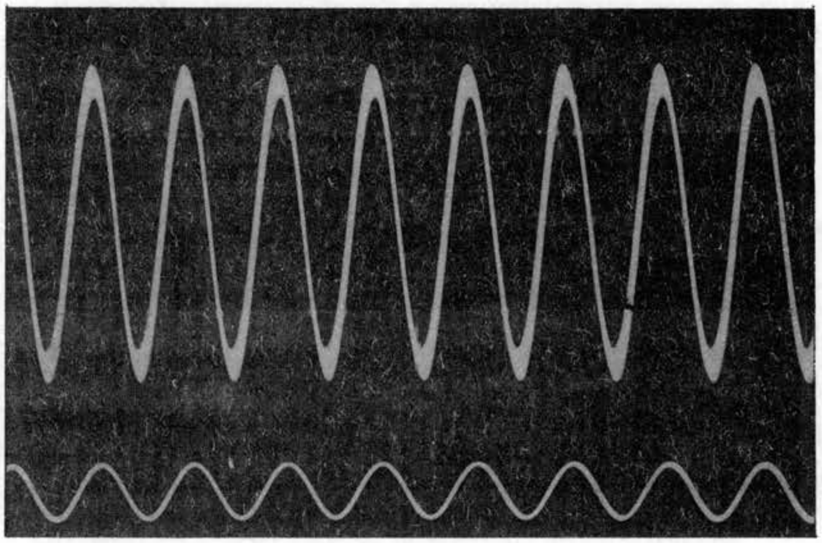

Figure 9. Oscilliscope Traces for a Magnetostrictive Rod Transducer Excited by a Biased Alternating Current

Figure 9 shows the rod in resonance at 18,300 Hertz when excited at 18,300 Hertz with a biased-alternating current. As was predicted, the amplitude of vibration was greater with the biased exciting current.

The actual tuning of the transducer was accomplished by varying the pertinent electrical quantities and observing the transducer output trace for maximum amplitude. A peak in vibrational amplitude was noted when the capactance of the D.C. blocking element reached a value of 0.47μF. The impedance of the inductor was simply chosen to be much greater than the impedance of the transducer winding and was not considered to be a critical factor. The bias current produced a peak amplitude of vibration when it reached a value of 2.5 amperes. The frequency of the exciting current must be tuned in like manner, to match the resonant frequency of the individual rod being used.

CHAPTER V

PRELIMINARY TESTING OF THE ROD MAGNETOSTRICTION TRANSDUCER NOZZLE

A theoretically suitable transducer-nozzle integration had been accomplished and was ready to be evaluated for its atomization controlling capability. For the initial testing, a 0.015 inch diameter orifice plate was installed and the rod end clearance was set at approximately 0.020 inch. The 4 7/8 inch nickel rod was tuned to its resonant frequency of 18,300 Hertz by varying the exciting frequency and observing the oscilliscope for maximum vibrational amplitude of the rod transducer end.

Tap water at 68°F was introduced under gradually increasing pressure. Checks for leaks during this initial pressure addition, proved the transducer seal and orifice plate mounting to be functional as no leaks developed.

Stroboscopic examination of the emerging stream revealed tiny ripples appearing on the stream near the orifice. When the stroboscope was tuned to 18,300 flashes/ min., the ripple appeared as a standing wave form that appeared to be similar to the phenomena observed with the piezoelectric variable orifice nozzle; however, the nodes were smaller and closer together. This was attributed to a higher ratio of frequency to efflux velocity of the fluid than was observed with the piezoelectric nozzle. Thus, an increase in fluid pressure (i.e., an increase in fluid efflux velocity) should cause the wavelength to increase to a level comparable to that observed earlier.

The predicted wavelength increase with increase in fluid pressure was verified, and at a value of 30 psi an orderly, stable atomization process resulted. Figure 10 shows the emerging stream backlighted by a stroboscopic light tuned to 1/60th the rod frequency of 18,300 cps. When the stroboscope was tuned, the emerging stream was observed as a standing pattern of evenly spaced droplets. This suggested that the system was producing a single drop per cycle of rod vibration.

To test this theory, a single flash photograph (Figure 11) was taken of the emerging stream and the flow rate was measured. If a one to one relationship between drop production and rod vibrational frequency existed, a calculation of flow rate based on this premise should match the measured flow rate.

Assuming drop production frequency to be 18,300 drops/sec. and the droplet shape to be spherical, and measuring

d_o = drop diameter = 0.0234"

f = frequency = 18,300 cycles/sec.

Q = flow rate 2.07 cm^3/sec.

then

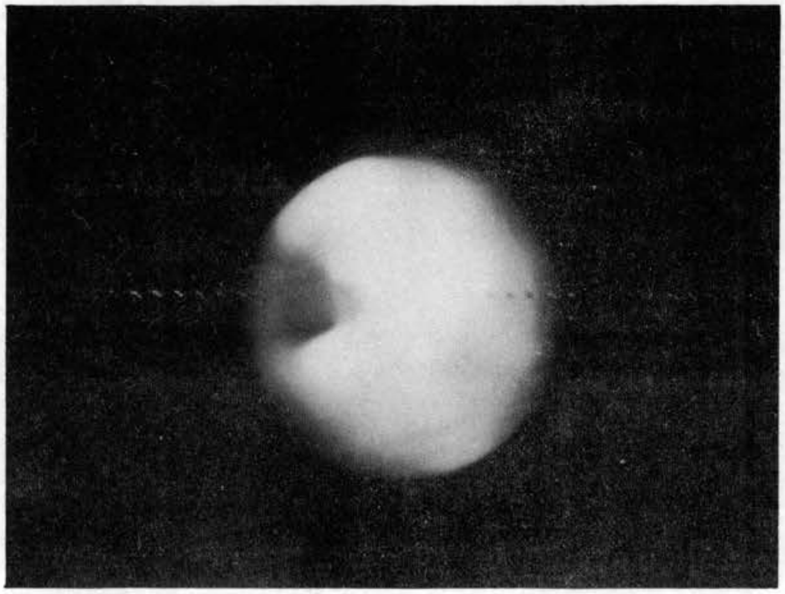

Figure 10. Multiple Exposure Photograph of Uniform Atomization Process

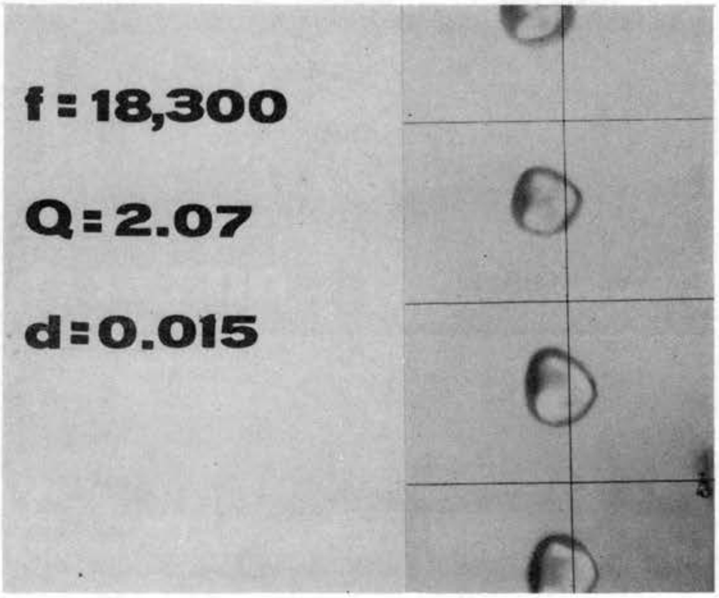

Figure 11. Single Flash Photograph of Emerging Stream

$$\text{Calculated } Q = 18{,}300 \times \frac{\pi(0.0234)^3}{6} \frac{\text{in}^3}{\text{drop}} \times 16.45 \frac{\text{cm}^3}{\text{in}^3}$$
$$= 2.02 \text{ cm}^3/\text{sec}.$$

The close correspondence of these values led to the conclusion that this system was producing one drop per cycle of rod vibration.

Figure 10 also demonstrates the stability of the system by the fact that this photograph was exposed for 1/8 sec. Since drop production is identical to the rod frequency of 18,300 cps, each drop shown on this photograph represents 36 stroboscope flashes. And since the stroboscope was tuned to 1/60 the rod frequency, each drop on the photograph represents 2160 different drops that occupied that position during the 1/8th second exposure time.

Samples of flow rates were also taken at this time with pressures varying from 30 to 80 psi. The relationship between pressure and flow rate seemed to be relatively unaffected by the presence of the upstream vibrational energy source and conformed to ideal orifice flow as described by Torricelli's theorem; i.e., the speed of efflux, $v = \sqrt{2gh}$ where h = pressure head.

CHAPTER VI

OPERATING CHARACTERISTICS OF THE PHYSICAL SYSTEM

Preliminary testing had indicated that the upstream vibrational energy source was significantly effecting the atomization process. Thus, a more detailed study of the physical system became of immediate interest.

The factors considered pertinent to the behavioral characteristics of the system included:

1. Clearance distance
2. Amplitude of vibration
3. Orifice diameter
4. Fluid pressure
5. Vibrational frequency[13]

Analytical Prediction of System Behavior

Assuming that:

1. Drop production frequency is the same as the vibrational frequency

---

[13] Since the objective of this study was to control the atomization process with the use of mechanical vibration, fluid properties are not considered independently in this analysis. Water at room temperature was used in all tests.

2. The flow through the orifice is governed by Torricelli's Principle

and letting

g = gravitational accelleration, inches/sec.^{2}

h = fluid pressure, inches H_2O

A = area of the orifice, in.^{2}

v = velocity of efflux of fluid, in./sec.

Q = flow rate-fluid, in.^{3}/sec.

d_o= orifice diameter, in.

d_d= drop diameter, in.

f = frequency of vibration, sec.$^{-1}$

C = coefficient of discharge

q = volume per drop, in.^{3}

It can be said that

$$q = \frac{CA\sqrt{2gh}}{f}$$

Writing area in terms of the orifice diameter, volume per drop in terms of drop diameter, and solving for drop diameter:

$$d_d = \left(6C/\pi \text{ x } \frac{d_o^2 \pi}{4} \text{ x } \sqrt{2gh}/f\right)^{1/3}$$

Let $K = (3C\sqrt{2g}/2)^{1/3}$ = a constant.

Then

$$d_d = Kd_o^{2/3}h^{1/6}f^{-1/3} \qquad (1)$$

Physical Observation of System Behavior

Photographic evaluation of system performance was facilitated by the Oklahoma State University, Agricultural Engineering Department's spray sampling apparatus (9). In order to make best use of this device, some special adjustments and arrangements were made. They included:

1. The installment of a 50% reflective mirror at a 45 degree angle between the short duration light source and the beam concentrating lens
2. Adjustment of the photographic scale such that the grid line spacing on all photographs represented 1600 microns
3. The installment of a 50% reflective mirror behind the frosted glass focusing plate to facilitate focusing of the stream image from the nozzle mounting area

Test photographs were then taken for the purpose of light intensity adjustment. It was found that satisfactory results would be obtained when Polaroid type 52 film was exposed with the aperature set at f/11.

Effect of Varying the Clearance Distance

For the preliminary testing, the clearance distance was arbitrarily set 0.020" above the 0.015" orifice. When the 18,300 cycle/sec. vibration was introduced, the uniform breakup process, as discussed in Chapter V, was observed.

As the clearance distance was increased, the zone of atomization[14] was observed to move farther from the orifice. As the clearance was decreased, the zone of atomization moved closer to the orifice. In both cases, the resulting downstream droplet pattern remained unchanged.

From these observations during the preliminary testing, it was deduced that the clearance distance was not a critical factor when located 0.010" to 0.020" above the orifice plate. No further tests were conducted to evaluate effects of changing the clearance distance.

Effect of Varying the Amplitude of Vibration

Figure 12 shows a series of six photographs taken at a position three inches below the orifice at successively increasing amplitude levels. Fluid pressure was regulated at 40 psi and the clearance distance set to 0.010 inch. Photograph 1 shows the resulting laminar stream issuing from the 0.015 inch orifice.

As the 18,300 Hertz vibration was introduced, a smooth wave form appeared to be superimposed on the emerging stream. Increase in vibrational amplitude caused a more developed atomization pattern that appeared to be approaching breakup as predicted by McDonald (8).[15] A large drop

---

[14] The zone of atomization is where the fluid stream forms into droplets.

[15] McDonald has shown that a theoretical prediction of satellite drops can be made.

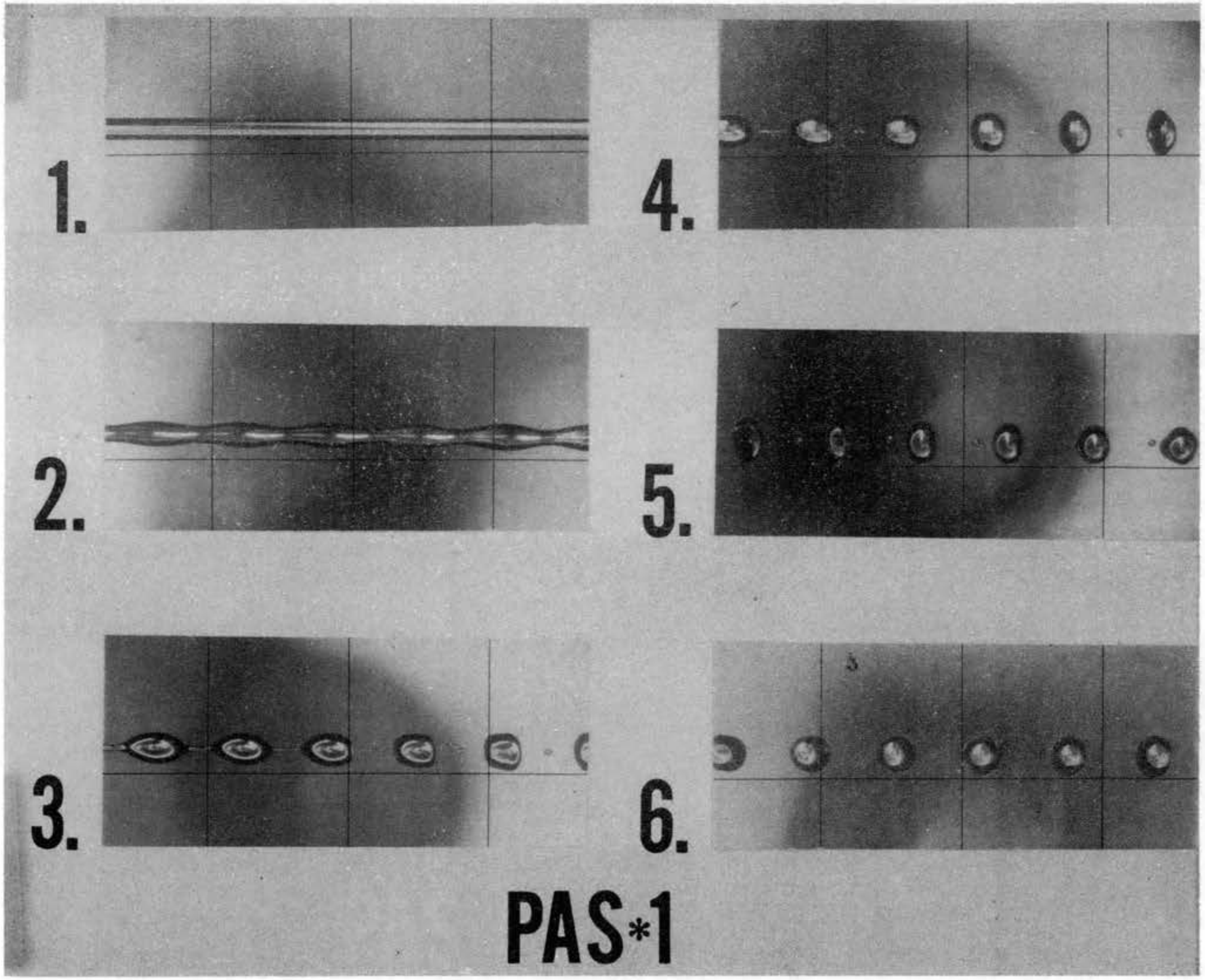

Figure 12. Effect of Varying Amplitude of Vibration

forms at the peak of each wave. The connecting fluid filament first becomes more elongated, then separates from the large drops and forms a single satellite drop.

Further increase in amplitude caused the satellite drop to move toward the large downstream drop and to seemingly coalesce with it. Photograph 6 shows the final development to be as predicted by Rayliegh (8); i.e., a single drop size was being produced.

The apparent development of the breakup process with increasing amplitude of vibration suggested that the zone of atomization might be moving closer to the orifice when vibrational amplitude was increased; i.e., the zone of atomization was moving past the zone being photographed. If this was the case, a similar series of photographs should result by photographing the zone of atomization at positions successively farther from the orifice.

With the power level held constant, the zone being photographed was moved in 1/4 inch increments downward through the zone of atomization. Figure 13 shows the resulting series to be almost identical in nature to the amplitude addition series shown in Figure 12.

Thus, it appeared that varying the amplitude of vibration had as its main effect the position change of the zone of atomization. However, the zone of atomization position is of little importance and the amplitude level can operate through a wide range without effecting the final breakup process.

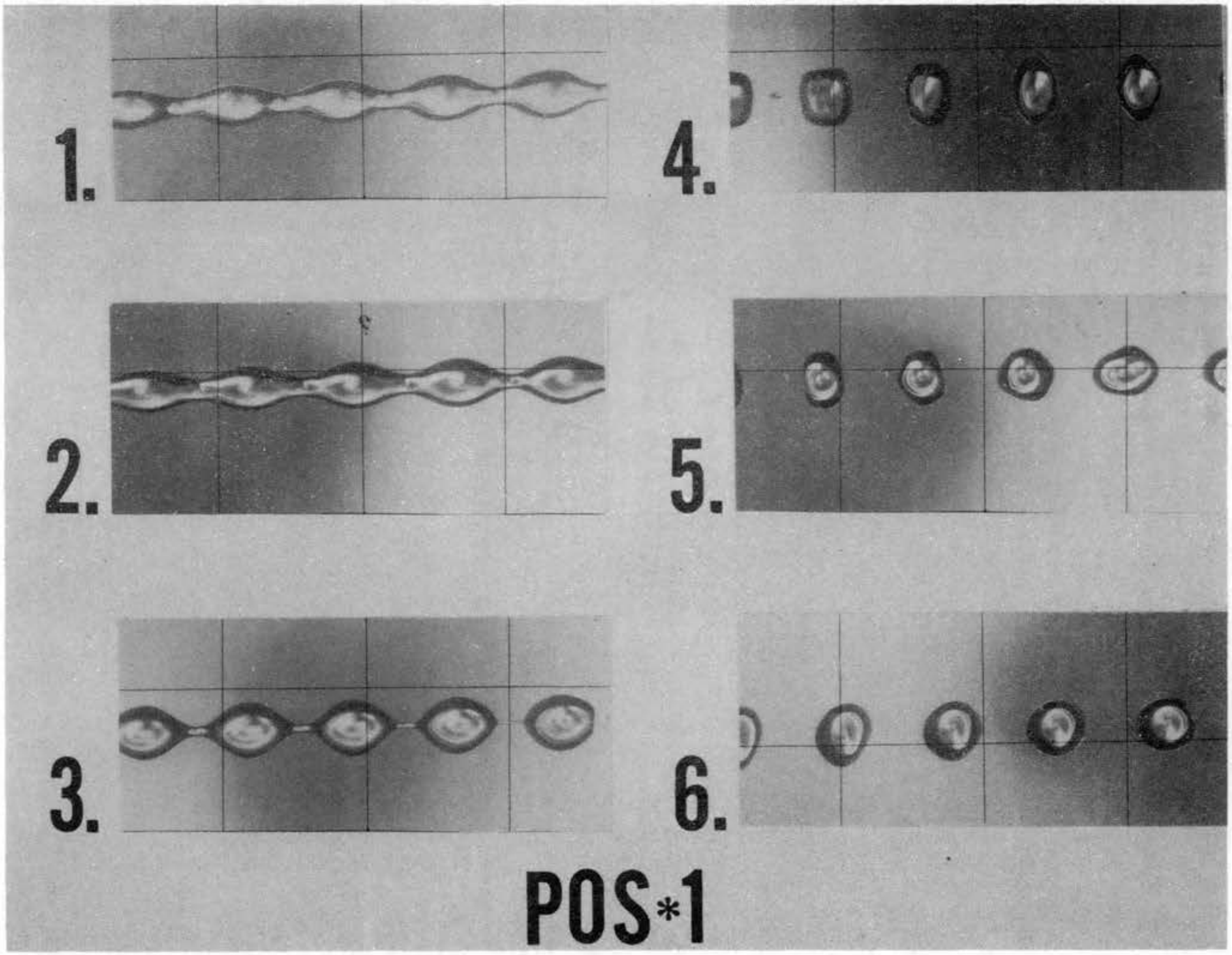

Figure 13. Breakup Process at Increasing Distance From the Orifice

Effect of Varying Orifice Size

Mathematical analysis of the system had indicated that

$$d_d \sim d_o^{2/3}$$

where d_d = drop diameter and d_o = orifice diameter. To test this theory, water at 30 psi was forced through four orifice sizes with identical drop production frequencies of 18,300 Hertz. Figure 14 shows the resulting series of photographs. Drop size was measured directly from each photograph and tabulated in Table I.

The value of K in equation 1 was then calculated for

d_o = 0.010 inch
f = 18,300 Hertz
h = 833 in H_2O

When the measured drop diameter was

d_d = 0.015 inch
$K = d_d d_o^{-2/3} h^{-1/6} f^{1/3} = 2.74$

Equation 1 was then plotted for the frequency, orifice diameter, and pressure used in the series of photographs. Figure 15 shows this plot with the observed values superimposed about the predicted value line.

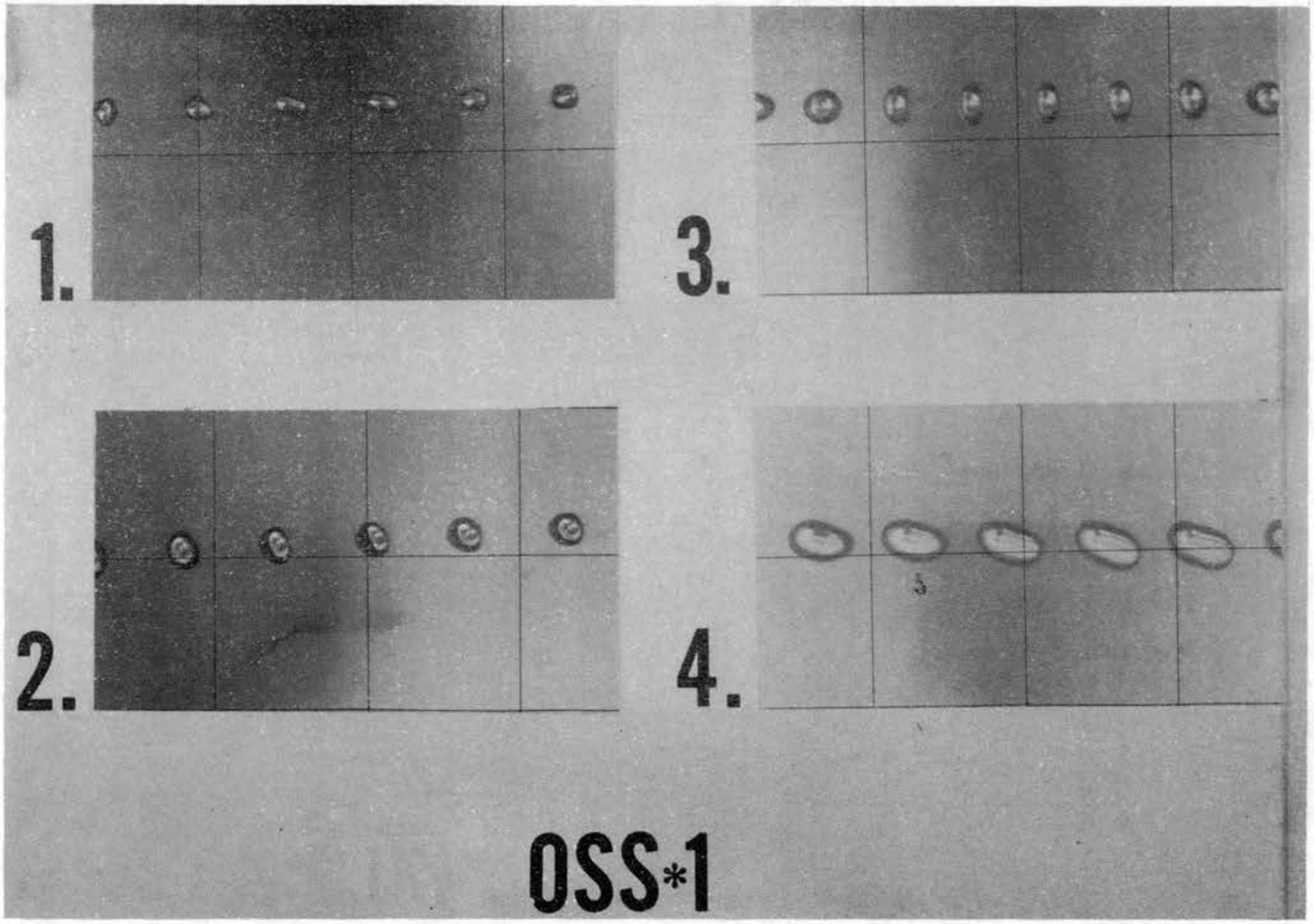

Figure 14. Effect of Varying Orifice Diameter

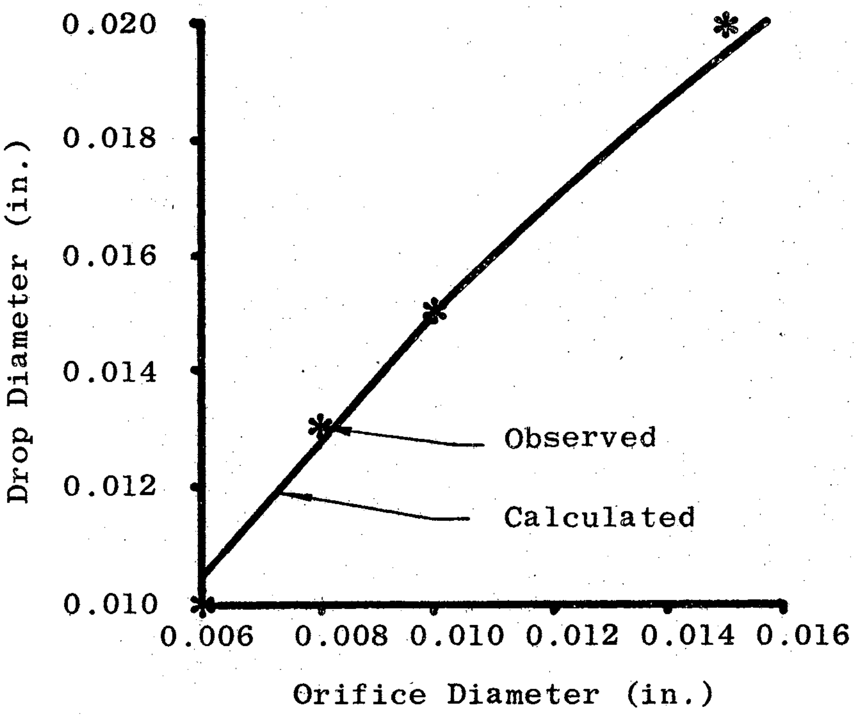

Figure 15. Plot of Drop Size Vs. Orifice Diameter

TABLE I

CALCULATED AND OBSERVED DROP SIZES WITH VARYING ORIFICE DIAMETER

f = 18,300 Hertz h = 833 in H_2O

Orifice Diameter (in.)	Drop Diameter (in.) Observed	Drop Diameter (in.) Calculated
0.006	0.010	0.0105
0.008	0.013	0.0127
0.010	0.015	0.0150
0.015	0.020	0.0195

Effect of Varying Fluid Pressure

Assuming that fluid flow through the orifice is governed by Toricelli's Principle, the drop size produced,

$$d_d \sim h^{1/6}$$

To test this theory, a series of six photographs was taken of the emerging stream with gradually increasing pressure. The drop production frequency was 18,300 drops/sec. from the 0.015 inch orifice. The resulting series of photographs is displayed in Figure 16 and the measured drop sizes are tabulated in Table II.

Since this series was taken at a later date than the orifice size series, the value of K in equation 1 was recalculated and found to be 2.76. This change was attributed to a small increase in the clearance distance which evidently increased the coefficient of discharge from the orifice.

Figure 17 shows the resulting calculated drop sizes plotted versus the fluid pressure with the measured values superimposed about the predicted value line.

Effect of Varying the Frequency of Vibration

Preliminary testing had shown that under the proper conditions, the frequency of drop production was identical to the frequency of vibration of the rod end. Therefore, the drop size,

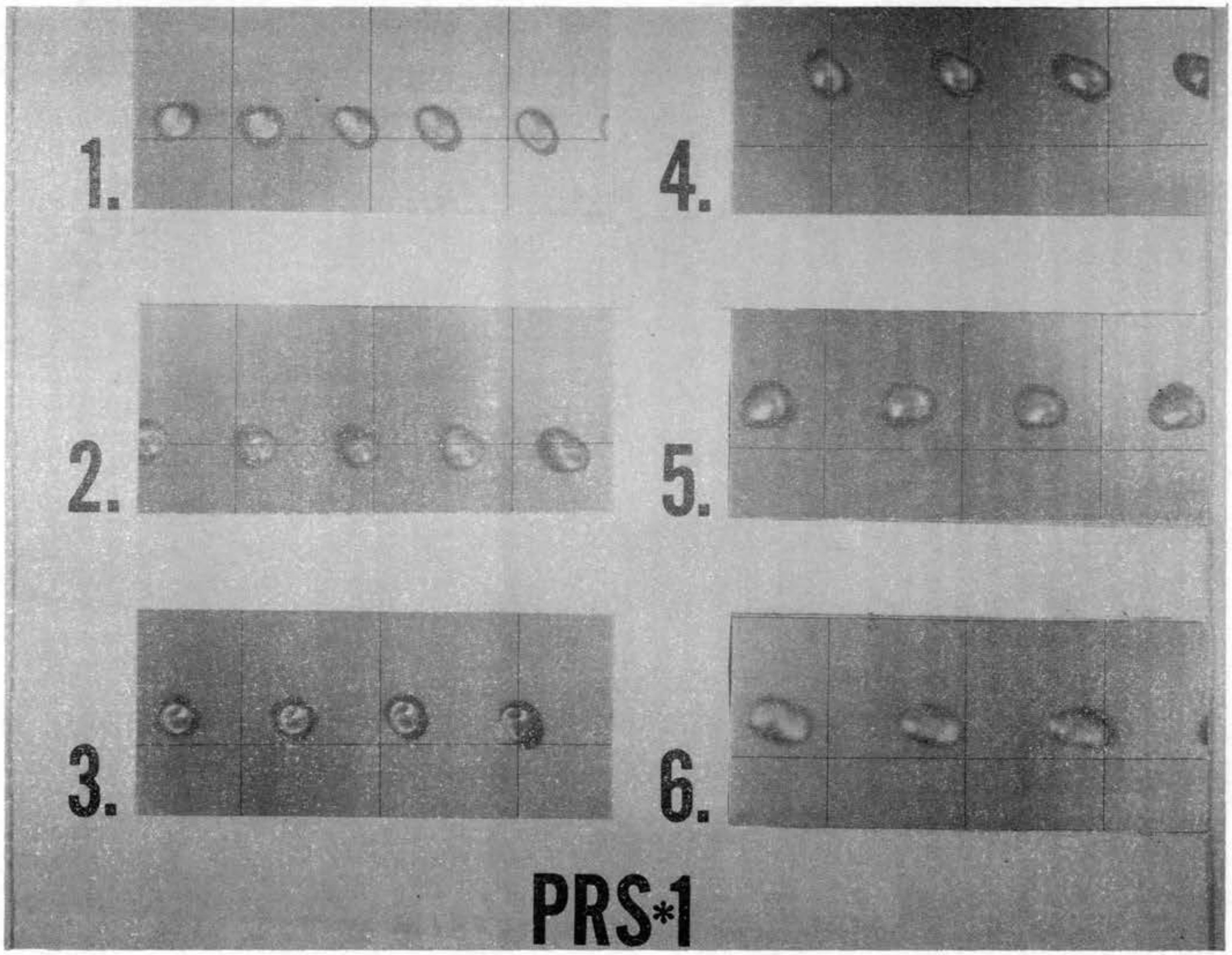

Figure 16. Effect of Varying Fluid Pressure

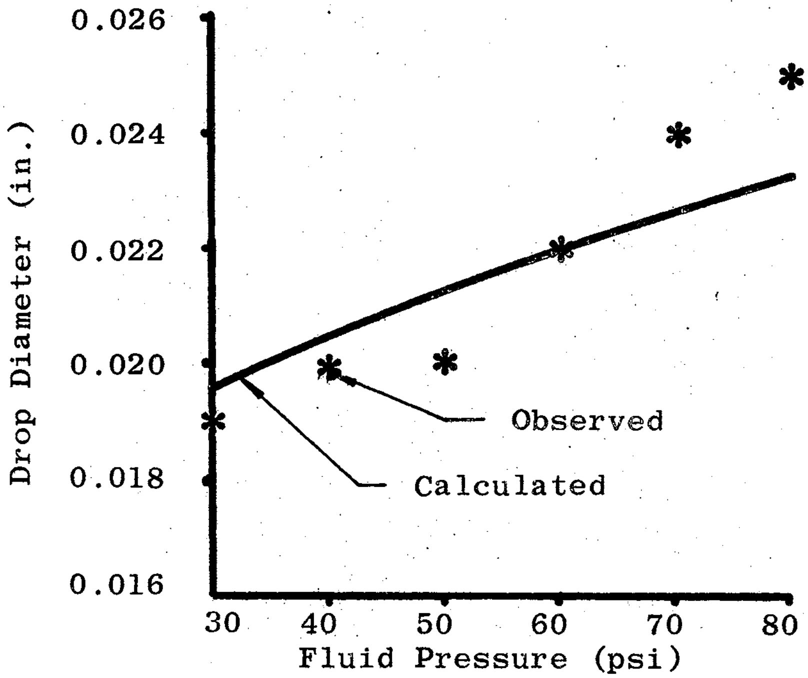

Figure 17. Plot of Drop Size Vs. Fluid Pressure

TABLE II

CALCULATED AND OBSERVED DROP SIZES WITH INCREASING FLUID PRESSURE

f = 18,300 Hertz		d_o = 0.015 inch
		Drop Diameter
Fluid Pressure (psi)	Observed	Calculated
30	0.019	0.0196
40	0.020	0.0206
50	0.020	0.0213
60	0.022	0.0220
70	0.024	0.0226
80	0.025	0.0237

$$d_d \sim f^{-1/3}$$

It was also shown that the frequency of vibration had to match the velocity of efflux of the emerging stream in such a way as to produce a smooth wave form before Rayliegh breakup could be produced. Thus, for a constant set of conditions, the frequency cannot be varied appreciably and cannot be used independently to vary drop size.

When pressure and frequency are increased simultaneously, the drop production rate increases without effecting the drop size. Photograph A in Figure 18 shows the atomization resulting when water at 14 psi is forced through a 0.010 inch diameter orifice excited by an 18,300 cps vibration. Photograph B is an apparently identical atomization pattern produced when water at 85 psi was forced through a 0.010 inch diameter orifice excited by a 29,000 Hertz surface vibration.[16]

---

[16] The design of the 29,000 Hertz nozzle used in Figure 18 is discussed in the following chapter.

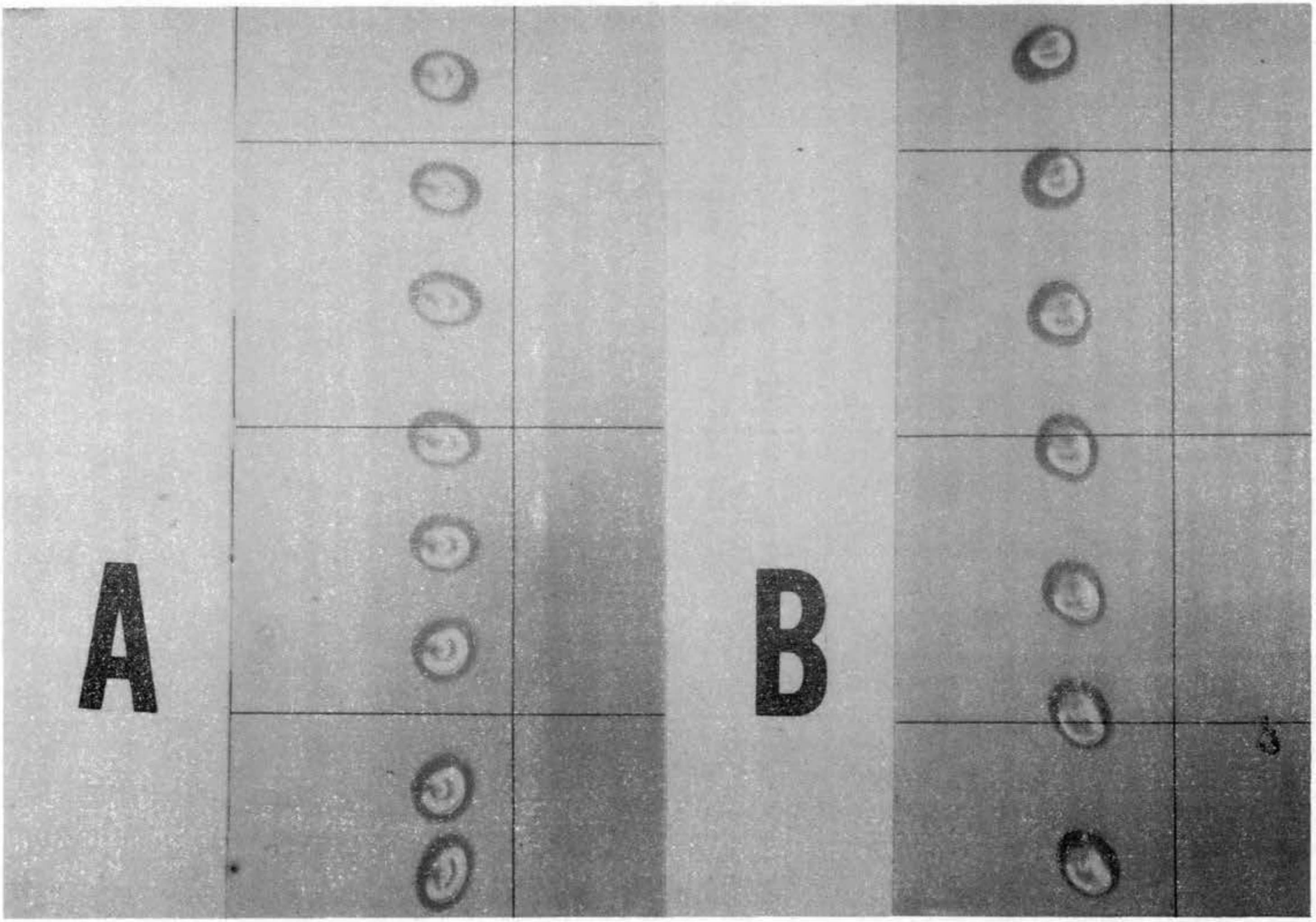

Figure 18. Effect of Simultaneously Increasing Frequency and Pressure

CHAPTER VII

MAGNETOSTRICTIVE ROD TRANSDUCER NOZZLE DESIGN IMPROVEMENTS

The original test model of the magnetostrictive rod transducer nozzle (Figure 5) was designed to facilitate variance of all system parameters and as such, displayed features that could be eliminated in a field model. The need to find if a nozzle of this type could be operated at higher frequencies with corresponding higher pressures offered an opportunity to incorporate and test some theoretical design improvements into the higher frequency unit. The improvements included:

1. A reduction in physical size of the rod transducer from 5 to 3 inches by virture of the higher operating frequency
2. A more solid and leakproof transducer mount due to the elimination of the variable clearance distance
3. A more compact unit by virtue of the use of standard parts for the nozzle body
4. The accommodation of standard orifice plates by the standard nozzle body

As shown earlier in photograph B of Figure 18, the system performed the same duties as the original test model and was generally more attractive as a possible field unit.

However, when compared to conventional nozzles, the system still displayed a relatively low drop production rate as one of its major disadvantages. In order to overcome this disadvantage a number of jetstreams undergoing identical breakup processes would be required.

When six 0.010 inch diameter orifices drilled in line were placed under the vibrational energy source of the original 18,300 Hertz nozzle, identical streams emerged from each orifice. Thus, a single vibrational energy source could be used to control the atomization from several orifices.

Further improvement of the multiple orifice approach was sought in the design shown in Figure 19. A spherical orifice plate was placed under a shape conforming vibrational energy source operating at 16,300 Hertz. Figure 20 shows the resulting atomization pattern from two adjacent orifices when operated at 20 psi fluid pressure. Note the angle between the streams due to the curvature of the orifice plate and the identical drop size and spacing on each stream.

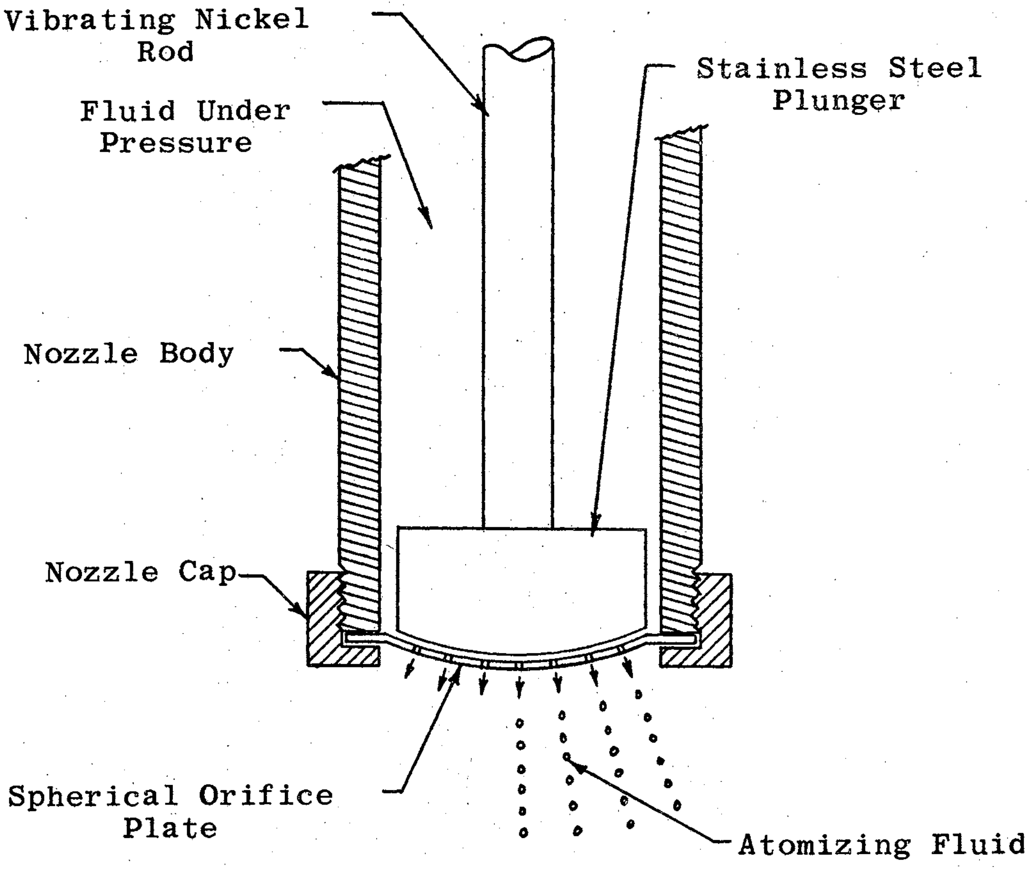

Figure 19. Spherical Head, Multiple Orifice Nozzle With Upstream Vibrational Energy Source

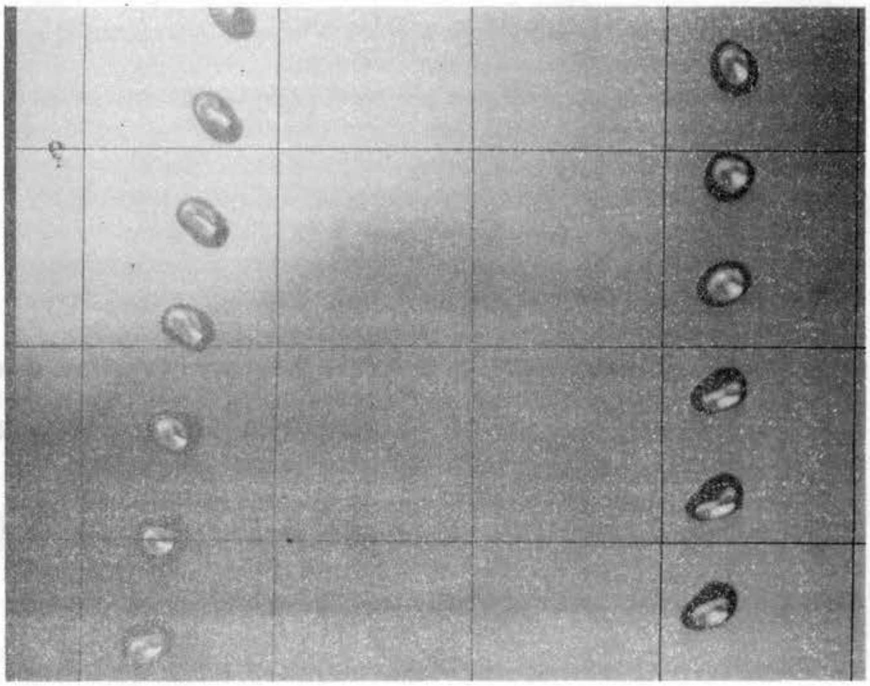

Figure 20. Drop Production From a Spherical Head, Multiple Orifice Nozzle With Upstream Vibrational Energy Source

CHAPTER VIII

SUMMARY AND CONCLUSIONS

The need for a means to control the particle size generation of agricultural chemical application devices led to organized research in the field of particulate technology. One approach to the control of the atomization process was the superposition of a regular wave form on a jetstream with consequent production of a regular atomization pattern.

Cyclic, diametral size change of a circular fluid orifice was first observed to affect the desired superposition. However, inherant design disadvantages led to the development of an alternative method.

A magnetostrictive transducer was utilized as a vibrational energy source positioned upstream from a circular orifice. Vibration of the upstream energy source was observed to produce the desired superposition of a regular wave form. Consequent atomization occurred in a regular manner to the extent that one drop was formed by each cycle of the transducer vibration.

Further testing indicated that the particle size could be predicted by the relationship

$$d_d = kd_o^{2/3}h^{1/6}g^{-1/3}$$

where

d_d = diameter of the droplets, inches
k = a constant
h = fluid pressure, psi
f = frequency of vibration, Hertz
d_o = diameter of the orifice, inches

Since this study concentrated on the basic performance characteristics of the system, the establishment of exact operational limits was beyond its scope. However, in order to fully utilize equation 1, the operating ranges of system parameters that assure satisfactory performance must be established.

This study also indicated that frequency of vibration and the fluid pressure are not independent quantities. Finding a relationship between them would eliminate one from the suggested prediction equation and reduce it to

$$d_d = k_2 d_o^{2/3} h^n$$

where k_2 and n are constants.

BIBLIOGRAPHY

1. Akesson, Norman B. "Recent Investigations of Spraying Accessories: A Progress Report on Nozzles." *Proc. Fourth Annual California Weed Conf.*, 1952, 58-64.
2. "Astrospray Nozzles/1700 Series." *Bulletin 104*. Heat Systems Company, Melville, L.I.
3. Bainer, Roy, R. A. Kepner, and E. L. Barger. *Principles of Farm Machinery*. New York: Wiley, 1963, 466-497.
4. Bozorth, Richard M. *Ferromagnetism*. New York: D. Van Nostrand Company, 1951, 627-684.
5. Brooks, F. A. "The Drifting of Poisonous Dusts Applied by Airplanes and Land Rigs." *Agri. Eng.*, Vol. 28 (June, 1947), 233-239.
6. Frederick, Julian R. *Ultrasonic Engineering*. New York: Wiley, 1965, 151-159.
7. Hund, August. *Phenomena In High Frequency Systems*. New York: McGraw Hill, 1936, 124-125.
8. Marshall, W. R. Jr. *Atomization and Spray Drying*. Lancaster: The Science Press, 1954, 3-11.
9. Roth, L. O. and J. G. Porterfield. "A Photographic Spray Sampling Apparatus and Technique." *Trans. Amer. Soc. Agri. Eng.*, Vol. 8, No. 4 (1965), 493-496.
10. Roth, L. O. and J. G. Porterfield. "Jetstream Atomization." *Weeds*, Vol. 13, No. 4 (1965), 326-328.
11. Roth, L. O. and J. G. Porterfield. "Liquid Atomization for Drift Control." *Trans. Amer. Soc. Agri. Eng.*, Vol. 9, No. 4 (1966), 553-555.
12. "Ultrasonically Activated Head Atomizes and Sprays Fluids." *Design News*, August, 1964.

13. Wise, Boyd A. Design of Nickel Magnetostriction Transducers. New York: The International Nickel Company, 1958.

VITA

Dennis Alan Vehe

Candidate for the Degree of

Master of Science

Thesis: ATOMIZATION BY MAGNETOSTRICTION INDUCED VIBRATION

Major Field: Agricultural Engineering

Biographical:

Personal Data: Born in Webster, South Dakota, April 29, 1945, the son of Mr. and Mrs. Harold Vehe.

Education: Graduated from Bristol High School, Bristol, South Dakota, in May, 1963; received the Bachelor of Science Degree from South Dakota State University in 1967, with a major in Agricultural Engineering; completed requirements for the Master of Science Degree at Oklahoma State University in May, 1969. Member: ASAE, Alpha Epsilon, Sigma Xi, Gamma Sigma Delta, Blue Key, Farmhouse.

Professional Experience: Engineering Assistant, Green Giant Company, summers of 1965 and 1966; National Science Foundation Traineeship, 1967-68; graduate teaching assistant, School of Agricultural Engineering, Oklahoma State University, 1968-69.