DESIGN OF AN AERODYNAMIC AIRPLANE SPRAYER

By

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1970

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
July, 1973

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PREFACE

The research reported in this thesis was financed in part by the Oklahoma Agricultural Experimental Station Project H-1264 entitled Drift Control of Pesticides. This support is sincerely appreciated.

The author is grateful to Dr. Lawrence O. Roth, the major adviser, for the sound advice and encouragement throughout this study.

Appreciation is extended to other members of my committee, Dr. James E. Garton and Professor Jay C. Porterfield.

Appreciation is extended to Professor E. W. Schroeder, head of the Agricultural Engineering Department, for providing facilities and assistance to make this study possible.

The author is grateful to the Rockefeller Foundation for providing the scholarship that made this study and my Master's Degree possible.

My thanks is extended to Wayne LePori for his assistance during construction and installation of the equipment.

Appreciation is extended to Jack Fryrear and Sam Harp for their excellent preparation of illustrative material, and Mr. Clyde Skoch and Mr. Norvil Cole are thanked for their suggestions and cooperation.

A very special thanks is given to my wife, Stella, for her patience encouragement and help while caring for our daughter, Catalina.

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CHAPTER I

INTRODUCTION

In many areas, dusting and spraying by airplane is an accepted and essential agricultural practice. The major advantages over ground equipment are speed of application and independence of ground or crop conditions. One of the major disadvantages related to the airplane application of liquid materials is the drift of small particles. Because of drift, less wind can be tolerated than with ground equipment. As much as 70 % of fine drops may drift out of the treatment area, possibly damaging neighboring crops and causing pollution problems (2,8).

The location and positioning of the spray nozzles on the airplane wings greatly influences the subsequent break-up of the spray due to the turbulence in the vicinity of the wing and to the velocity differential between the air and the spray drops.

The effect of locating an atomizer inside a streamlined airfoil and releasing the drops at its trailing edge is now being studied as an approach for reducing drop break-up and drift. In addition, magnetostrictive induced vibration and high voltage charging (6,7,9) are used to provide an initial uniform drop size and shape.

By releasing the drops at the trailing edge of the airfoil, the velocity differential is greatly reduced since the drops are released in a region of low air velocity, where skin friction has built up a layer of slowly moving air at the surface of the streamlined airfoil.

A drop in the wake of such shape accelerates or deccelerates to the free stream velocity as the wake decays. This drop velocity change is more gradual as larger shapes with thicker boundary layers are used. Satellite drops can be recaptured even though the wake is turbulent, if the size of the turbulent vortices is small enough (10).

CHAPTER II

OBJECTIVES

The primary objective of this study is to design an aerodynamically shaped device to be used for airplane spraying, within which uniform drops are formed and released into the airstream at a relative velocity that will minimize subsequent drop break-up.

The secondary objective is to evaluate the device by testing it in a wind tunnel, using photographic techniques to observe particle size behavior in the airstream.

CHAPTER III

REVIEW OF LITERATURE

Research Determining the Effect of Aerodynamically Shaped Devices on Drop Size and Drift

Although the idea of ejecting liquid materials from the inside of a streamlined airfoil first came out as a distributor wing to be used in spraying airplanes in 1963 (5), very limited published information is available. Smith and Anderson (8) suggested a practical utilization of the vortex entrainment and vortex motion principles in the development of equipment and techniques for aerial application of agricultural materials. The parameters considered were aspect ratio, airfoil section, wing planform and wing loading.

Akesson et al.(1) designed and tested a wing model utilizing the principle of boundary layer controlled air flow. This principle aids wing circulation, which enables greater wing lift on a given aircraft. This air flow was also used to convey and eject materials for full wing span discharge. The control of discharge, direction, volume and air velocity enabled the shed vortex pattern to be adjusted for controlled placement of agricultural materials. The model was mounted on a truck bed with a boundary board at the wing root to control vorticity and permit simulation of a wing in flight. Blowers furnished air which was conducted past a material feeder with rotary meter gate out to the hollow wing. Air and materials were finally discharged rearward from an adjustable slot. The authors concluded that tests with the model wing enabled improvement of aerodynamic design, the ducting and discharge of materials techniques, and a cursory examination of the complex particle dynamics resulting from interplay of wing vortices and air ejection.

Razak et al.(5) demonstrated that a spraying device equipped with boundary layer control system can be used to achieve reduction of drift and uniformity of spraying.

Wilce et al.(10) designed and tested a device for the reduction of drift from fixed wing airplanes. An experimental low drift nozzle was designed and tested in a wind tunnel. The nozzle was essentially composed of an aerodynamic shell, a nozzle body and a multiple orifice plate. The device had a piezoelectric oscillator for reduction of satellite drops. Flight speeds of 40 - 55 m/sec. were simulated in the wind tunnel. Although the system was very effective for controlling drift, it presented the disadvantage of its need for filterable solutions, due to the small diameter of the orifices used.

Development of Equipment to Produce Drops of Uniform Size

The importance of producing drops of uniform size is one of the primary factors in eliminating drift and producing a desirable spray pattern.

Roth and Porterfield (6) investigated the break-up of a jet stream as a controlled atomization process to reduce the drift potential of the spray. A drop charging arrangement was developed to disperse the stream of drops following drop formation. This charging device consisted of passing the jet stream through a short length of metallic tubing which was insulated and to which a high voltage lead was attached. Charged drops emerging from the tube, through mutual repulsion, were dispersed over a wider area. Proper positioning of the charging tube also caused the small drops to impact on the inside of the tube. Roth and his associate concluded from their experiments that jet stream atomization, with the use of the charging technique, offers a practical mean of reducing the drift potential of sprays through producing drops of predictable and relatively uniform size.

Vehe (9) developed and tested a method of controlling break-up of a fluid stream by a mechanically imposed system. A vibrational energy source in the form of a magnetostrictive transducer was positioned upstream from a nozzle orifice. Fluid under pressure was passed between the vibrational energy source and the orifice plate before exiting through the orifice. Resultant atomization was recorded by a stop action photograph. The author concluded from his experiment that atomization occurs in a regular manner to the extent that a single drop is produced per cycle of transducer vibration. Single orifice drop production rated up to 29,000 uniformily sized drops per second. Drop size was found to increase with increasing fluid pressure and orifice size and decreasing frequency of vibration.

Roth and Porterfield (7) studied the application of magnetostriction as an approach to control atomization of a jet stream. The magnetostrictive induced atomizer was operated under varying conditions of pressure and orifice size. As the pressure was increased, the drops became larger and increased in velocity though the frequency of drop formation remained unchanged. Roth and his associate concluded that remarkable drop size uniformity was achieved by the use of magnetostrictive induced vibrations.

Mathematical Representation of Drop Size Distribution of Sprays

An accurate knowledge of the drop size distribution for a spraying system is a prerequisite for the analysis of the behavior of such system. Unfortunately, the drop size distribution is the property most difficult to predict theoretically and to determine experimentally. The amount of data available is generally limited to the specific operation conditions of interest to the particular investigator. As a result the techniques of measurement are also limited to specific conditions. In spite of these difficulties, much attention has been given to experimental methods for determining drop size distributions.

The drop size distribution may be represented by a distribution function and two parameters, one of which is a mean diameter of some kind and the other a measure of the dispersion of the drop sizes. In some instances it may be convenient to introduce other parameters to express the existence of maximum and minimum drop size. Marshall (3) defined various kinds of drop mean diameters with different physical meaning and applications. Mugele and Evans (4) developed a general expression for computing any mean diameter, $\bar{X}_{qp}$, where q and p are the order of the basic mean diameters to be related. One of these is the mass median diameter, which is defined as the diameter that divides the spray into two equal portions by either number, surface, volume or mass. Mass median diameters are generally established from the 50 % point on the cumulative curve of the spray.

Two distribution functions can be used for application to atomization processes. The first is the "Normal Distribution Function". This distribution is the basis for constructing the so-called arithmetic-probability paper. On this paper a probability scale is measured off on the X-axis, and an arithmetic scale on the Y-axis. By definition, the standard deviation is determined by substracting $X_{84.13}$ from X_{50}.

The second expression for the distribution function is the "Log-Normal Distribution". It differs from the normal distribution in the Y scale, which is logarithmic. It is evident that the Log-Normal function is a more realistic expression for the distribution of a physical dimension such as drop diameter than is the Normal distribution, due to the fact that the Log-Normal distribution considers bounded or finite quantities while the Normal distribution considers quantities ranging from minus infinite to plus infinite.

Mugele and Evans (4) developed an expression for calculating a dispersion parameter, which is associated to the standard deviation, for the Log-Normal Distribution function. This parameter is given by:

$$d = 0.394 / \text{Log} (X_{90} / \bar{X}) \qquad (3\text{-}1)$$

Where:

d = Dispersion factor, dimensionless.

X_{90} = 90 % drop size from Log-Normal distribution, microns.

$\bar{X}$ = Mass median diameter, microns.

The general expression for the mean drop diameters for this distribution becomes, in terms of d and $\bar{X}$:

$$\bar{X}_{qp} = \bar{X}\, e^{(p + q - 6) / 4 d^2} \tag{3-2}$$

Where:

p, q = Order of the mean diameters to be related.

And in particular, the surface-volume or Sauter mean diameter is:

$$\bar{X}_{32} = \bar{X}\, e^{-1 / 4 d^2} \tag{3-3}$$

Where:

$\bar{X}_{32}$ = Sauter mean diameter, microns.

CHAPTER IV

EXPERIMENTAL EQUIPMENT

Airfoil

As a first step for this study, the aerodynamic device was designed and constructed. The chosen airfoil was the basic NACA TR 460 symmetric airfoil. The position of the maximum thickness is 20 % of the chord; the characteristic equation of the airfoil is:

$$\pm Y = .2969\ X^{0.5} - .126\ X - .3516\ X^{2} + .2843\ X^{3} \qquad (4\text{-}1)$$

Where:

Y = Thickness, as a decimal fraction of the chord.

X = Position of thickness, as a decimal fraction of the chord.

A chord of 43.2 cm. and a width of 38.1 cm. were selected for the airfoil. The sides were constructed of 1.27 cm. clear Plexiglass^{R} and were fastened together with four steel rods. The airfoil was covered on top and bottom with 0.317 cm. Plexiglass^{R} (Figure 1). A steel tube was attached to each side of the airfoil in order to provide a support for it in the wind tunnel and to supply utilities to the inside of the airfoil (Figure 3). A portion of the airfoil was removed at 7.6 cm. from its trailing edge in order to provide a 1.27 cm. slot for the releasing of the drops from the inside. Two aluminum stiffness bars were attached to the covers at the slot to prevent the cover from

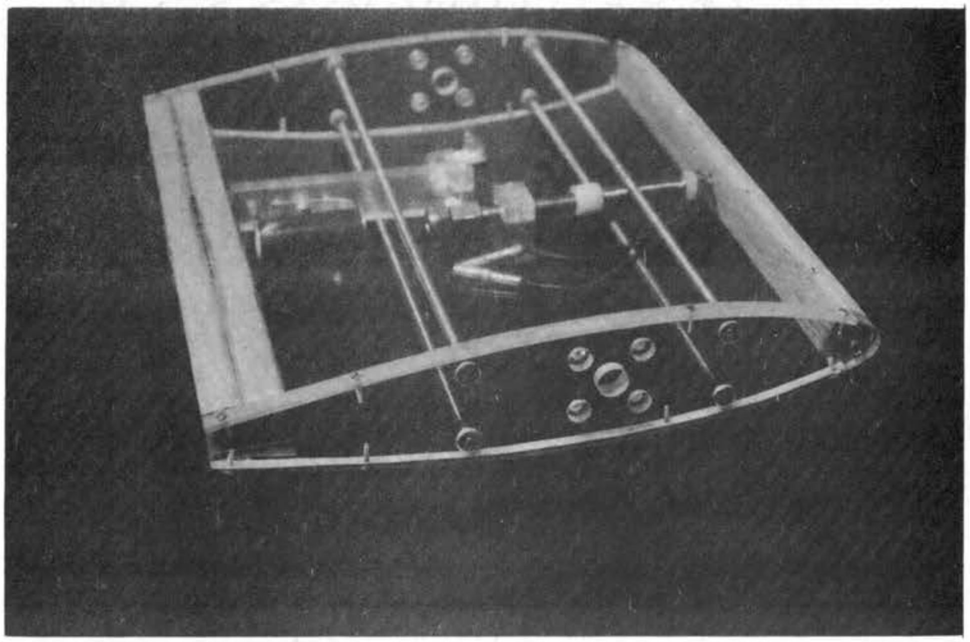


Figure 1. General View of the Airfoil

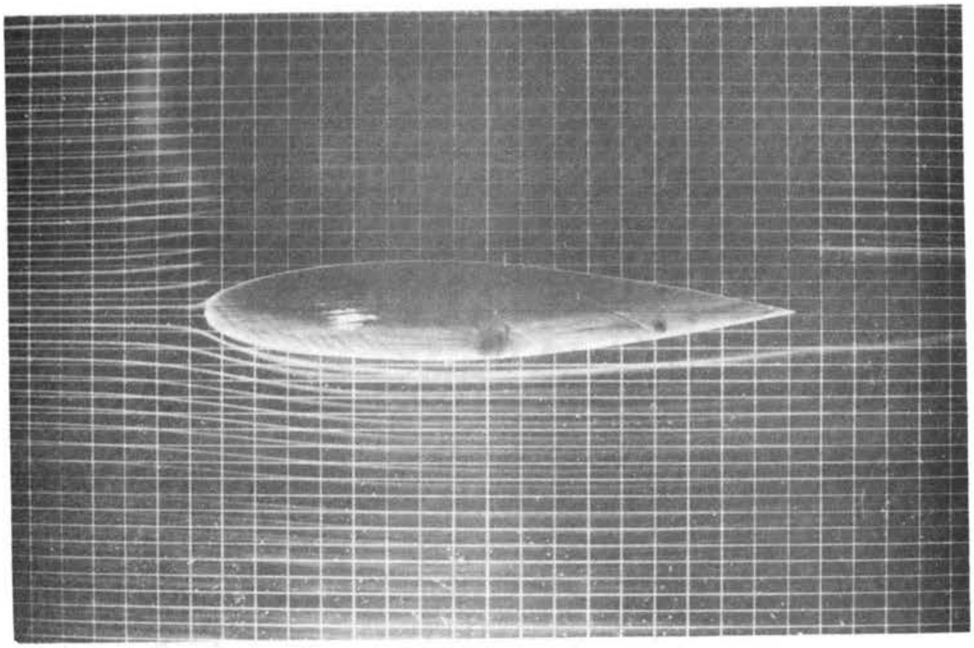
warping. Several observations were made in a smoke tunnel to estimate the effect of the removal of the trailing edge on the aerodynamic characteristics of the airfoil. Smoke patterns of the model airfoils were compared, showing that the removal of a portion of the trailing edge does not introduce a significant turbulence at the trailing edge (Figure 2).

Nozzle and Magnetostrictive Device

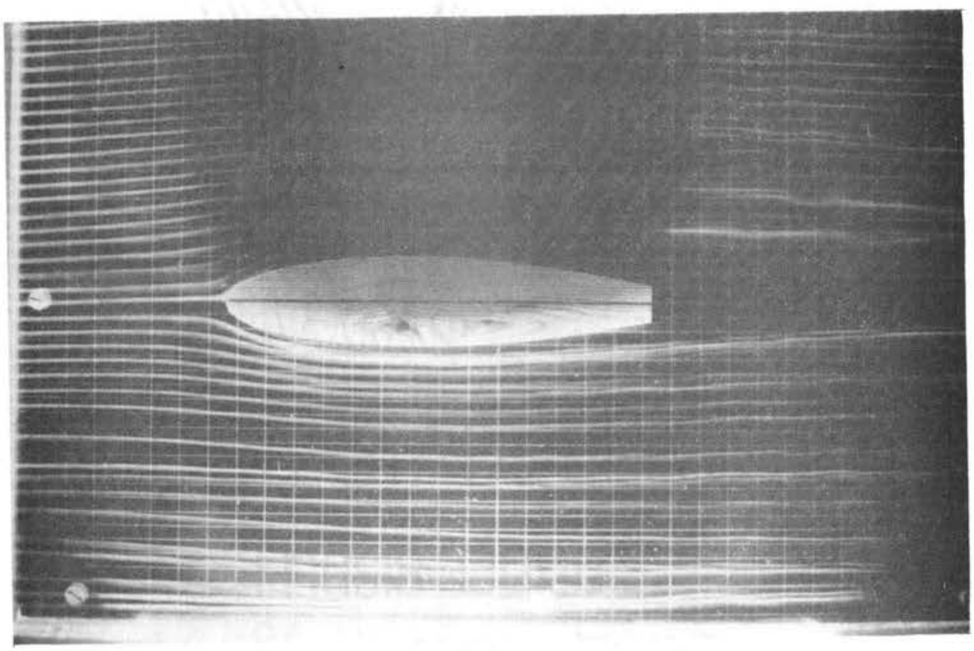
A spherical plate nozzle with a single orifice was selected. The orifice size was 400 microns in diameter, which produced drops of about 700 - 800 microns for the pressure range that was used. The selection criteria for the orifice diameter was to have drops that could be photographed and measured with the equipment available.

A magnetostrictive atomizer assembly developed by the Agricultural Engineering Department was mounted inside the airfoil as shown in Figure 3. The drop stream was directed through a 2.5 cm. diameter by 5.0 cm. long insulated charging tube to achieve drop dispersion and help maintain size uniformity. The magnetostrictive rod was activated by means of a "HEWLETT PACKARD" audio ascillator, model 200 AB, in which a frequency of 18,000 Hertz was produced as the experiment was run. A "SORENSEN" high voltage D.C. power supply unit, model 230 - 3 / 12 P supplied 2.5 KV to the charging tube.

A pressure tank was utilized to supply the required water. The tank was equipped with an air pressure regulator and a pressure gauge. With this arrangement it was possible to obtain a constant fluid pressure on the nozzle at any desired value.



(a)



(b)

Figure 2. Effect of Removing a Portion of the Airfoil; (a) Not Removed, (b) Removed

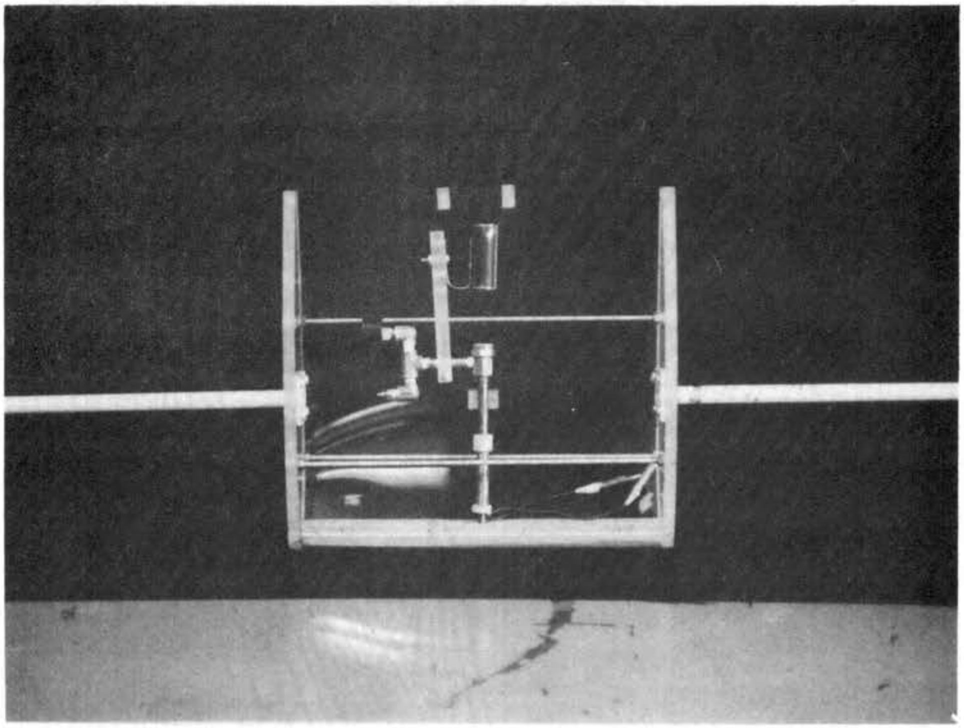


Figure 3. Mounting of the Nozzle Assembly
Inside the Airfoil

Photographic Equipment

A "GRAPHIC VIEW" camera equipped with a 360 mm. lens was used for taking the photographs during the experiments. The camera was modified by attaching an extension tube to it in order to achieve a magnification of 2.3 times for the required 50.8 cm. object distance. The lens was set at f / 11 to provide a depth of field of 2.54 cm. The following relationship were used to perform the calculations:

$$M = I / O \tag{4-2}$$

$$O = F (1 + 1 / M) \tag{4-3}$$

$$I = F (1 + M) \tag{4-4}$$

$$\text{Near Limit} = O - (O^2 \tan A) / (L + O \tan A) \tag{4-5}$$

$$\text{Far Limit} = O + (O^2 \tan A) / (L - O \tan A) \tag{4-6}$$

Where:

O = Object distance.

I = Image distance.

M = Magnification.

F = Focal distance of lens.

L = Effective diameter of lens = Focal length / f / number.

A = Diameter of circle of confusion = 2' of arc.

A "EDGERTON, GERMESHAUSEN & GRIER" high intensity light microflash, model 550/551, able to produce a light flash during 1/2 microsecond was positioned in front of the camera, the wind tunnel and drop stream being between them (Figure 4). The flash was triggered by a remote control switch from the camera location. The technique for taking the photographs consisted in triggering the flash unit in complete darkness while holding the camera lens open.

Wind Tunnel and Reduction Panels

A low speed wind tunnel located in the Agricultural Engineering Department at Oklahoma State University was used. This wind tunnel is 15.24 meter long and has a 1.22 x 1.22 meter cross section. Since the maximum speed that can be obtained in this facility is approximately 22 m/sec., it was necessary to reduce the cross section in order to be able of reaching velocities of the order of 32 m/sec. as required by the study. A reduction of 50 % in cross section was achieved by means of two 4.88 meter long by 30.5 cm. depth wood panels, which were placed at the sides of the tunnel starting near the tunnel inlet (Figures 4 and 5). The panels were provided with a smooth transition at their entrance to reduce turbulence effects.

Location of the Experiment in the Wind Tunnel

The airfoil was mounted at a point 304.8 cm. from the entrance of the tunnel (Figure 6). The electrical wires as well as the water supply line were passed through the mounting tubes to the inside of the airfoil. The tubes were clamped from the outside, easily allowing a way to vary the tilt angle of the airfoil. Two Plexiglass[R] windows were provided in the reduction panels just behind the trailing edge of the airfoil to allow the taking of the photographs in this zone.

The camera and the flash unit were set on the top of two steel platforms, located at each side of the tunnel and connected by rigid members passing under the wind tunnel. A grid system provided an accurate mean of moving both the camera and the flash unit to desired points for photographic sampling purposes.

Measuring Devices

The control of the drop velocity was achieved by means of pressure. A relation between gauge pressure and drop velocity was established in a separate test for the particular orifice diameter used. Operating pressure of 0.7, 1.4, and 2.8 Kg/cm^2 were selected to provide the three drop velocity levels. Data shown in Table XI, Appendix C illustrates the obtained values of drop velocity at different pressures for the nozzle and orifice used in the experiments.

The sensing of the air velocity was obtained by means of a Pitot tube and a manometer. The Pitot tube was mounted just in front of the airfoil. Although it would be more desirable to locate the Pitot tube close to the trailing edge of the airfoil, to obtain a reading of the air velocity at the point where the drops were released, it would introduce an additional turbulence in this zone, which would likely affect the drop behavior.

The measurements of the drop diameters were made by projecting the negatives of the photographs in an optical comparator. The comparator was equipped with a lens capable of magnifying the drop images 10 times. This, combined with the camera magnification, produced a total magnification of 23 times. The magnified drop images were measured to the nearest millimeter on a 1 x 1 millimeter grid. With this grid and magnification one millimeter is equivalent to 45 microns.

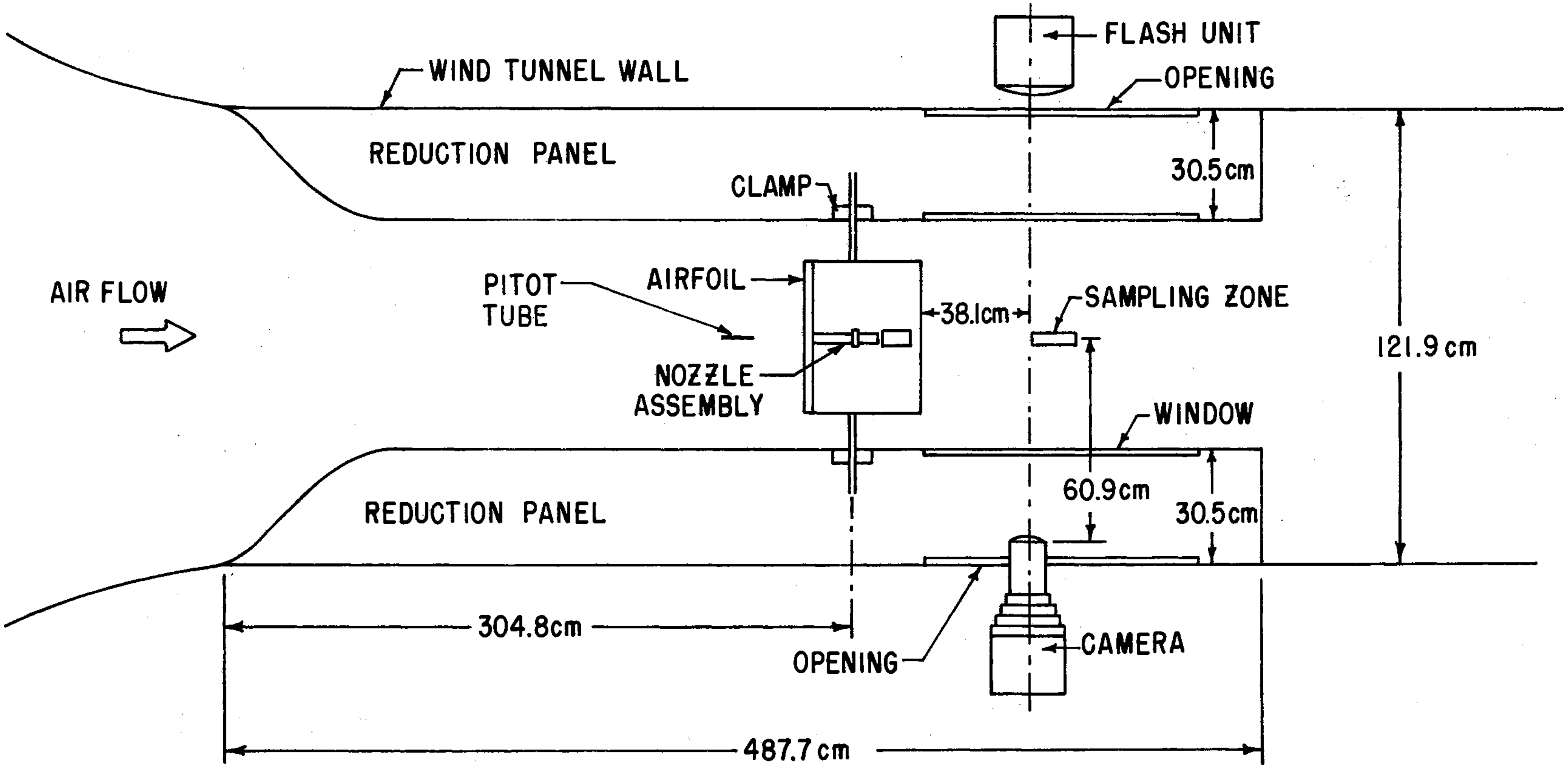


Figure 4. Plan View Schematic of the Test Facility

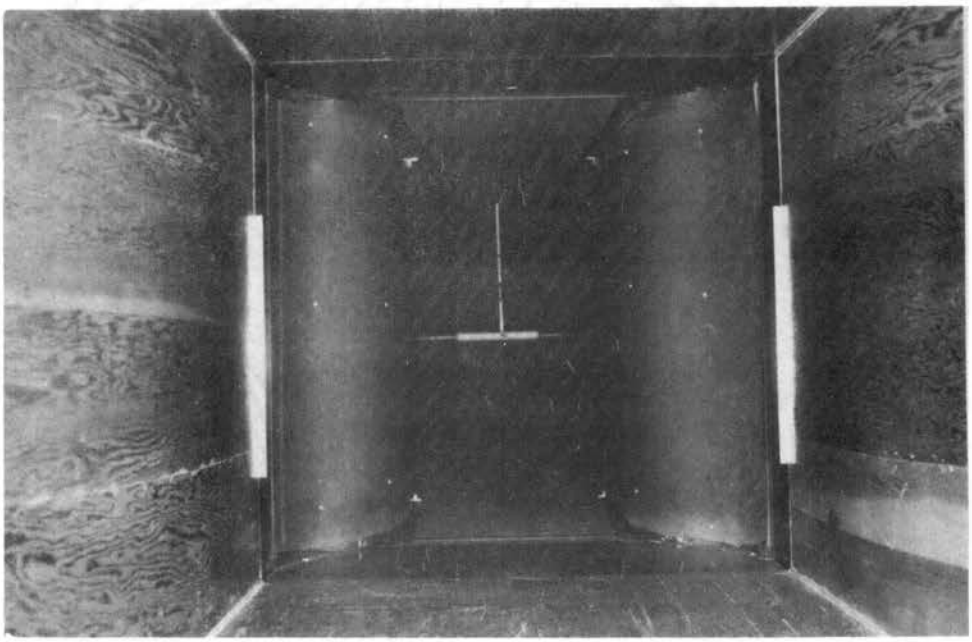


Figure 5. Inlet End of Tunnel Showing the Reduction Panels

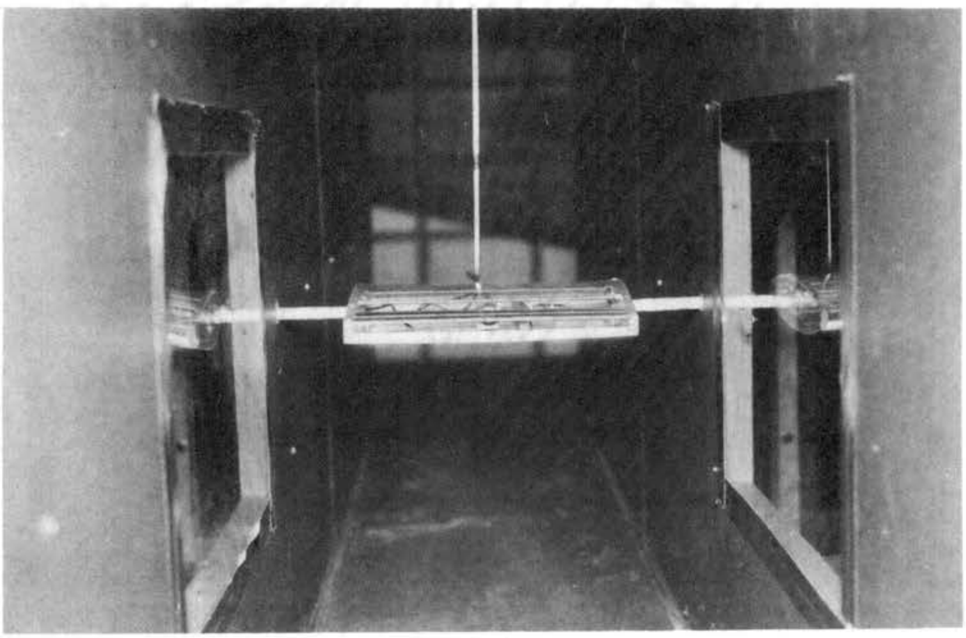


Figure 6. Placement of the Airfoil and Pitot Tube in the Tunnel

CHAPTER V

METHODS AND PROCEDURE

Design of the Experiment

The design of the experiment consisted in setting treatment levels to relate the resulting drop diameter to: a) drop velocity, b) air velocity and c) tilt angle of the airfoil.

The experimental design was a complete factorial. The dependent variable was the drop diameter. The independent variables were: Three levels of air velocity, three levels of drop velocity and two tilt angle levels.

The following randomization procedure was used: a) the order of the air velocity was randomized, b) the order of the drop velocity was randomized. Concerning the tilt angle, experiments were run with the zero degrees angle first, then the five degrees. The tests were conducted according to the experimental design shown in Table I. Two replications were conducted. Photographic samples of drop diameter were taken for every condition in which air velocity, drop velocity and tilt angle were varied.

Measurements on the Experimental Plan

A sampling zone 22.8 cm. long, 5.1 cm. height and 7.6 cm. depth, starting 38.1 cm. from the trailing edge of the airfoil and along the center line of the nozzle was arbitrarily defined. Preliminary tests showed that the depth of the sampling zone could be reduced to 2.54 cm., yet no drops were found outside this limit. To cover the sampling zone it was necessary to take photographs at three sampling points for each one of the treatment combinations (Figure 7). Two consecutive photographs were taken at each one of the three camera positions. In addition, photographs were taken as the drops emerged from the airfoil, just behind the trailing edge.

TABLE I

THE EXPERIMENTAL DESIGN

Test No.	Run No.	Air Velocity (m/sec)	Drop Velocity (m/sec)	Tilt Angle Degrees
1	5	0.0	13.65	0
2	12			5
3	2		22.75	0
4	11			5
5	6		33.85	0
6	13			5
7	3	22.75	13.65	0
8	10			5
9	7		22.75	0
10	16			5
11	4		33.85	0
12	14			5
13	9	33.85	13.65	0
14	15			5
15	8		22.75	0
16	17			5
17	1		33.85	0
18	18			5

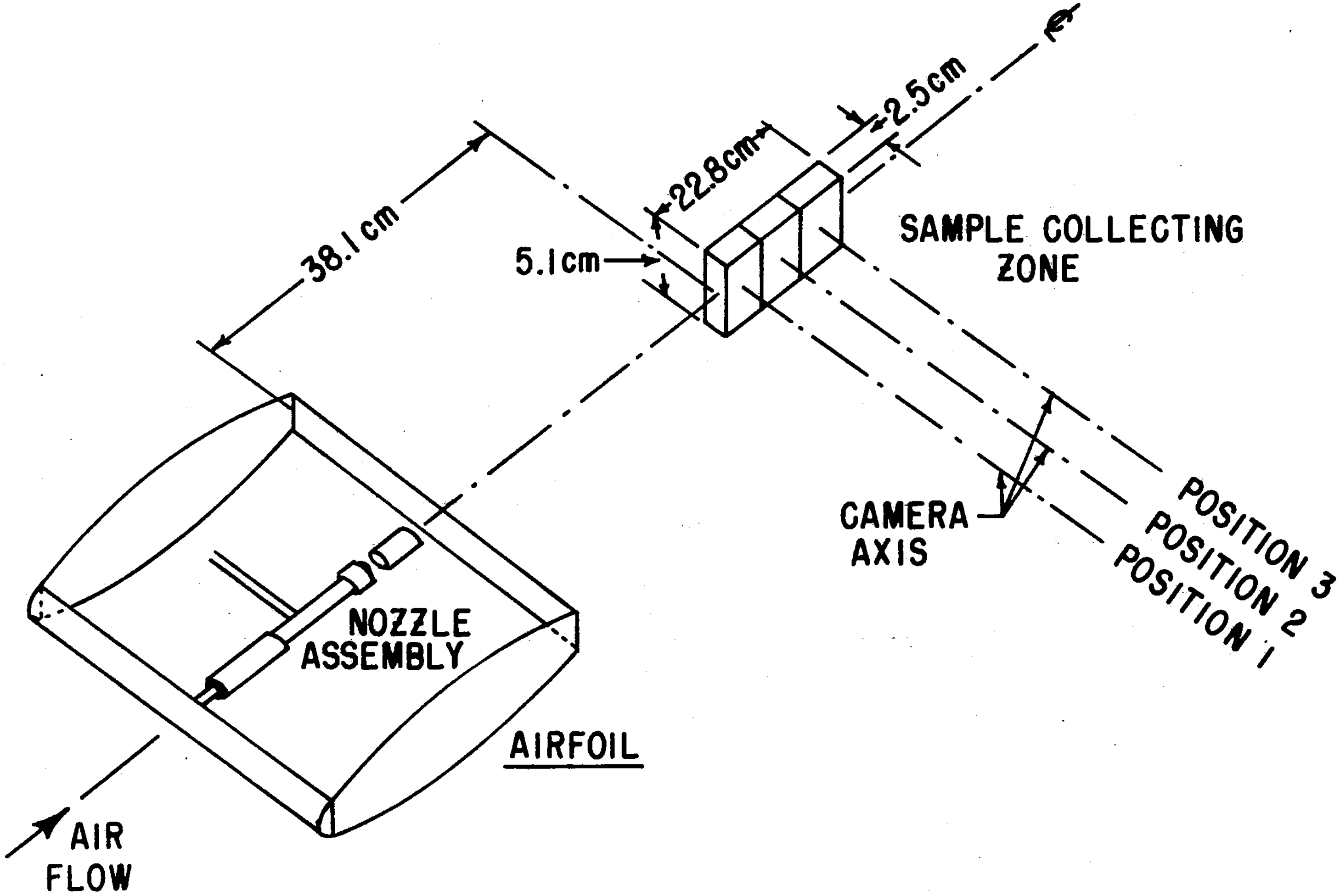


Figure 7. Schematic View of the Sampling Zone

CHAPTER VI

PRESENTATION AND ANALYSIS OF DATA

The first objective and the primary concern of this research was to determine the ability of the airfoil to minimize drop break-up following drop release from the trailing edge.

Data from the photographic samples showed the drop diameters to range from 540 to 945 microns, the major portion of drops being in the 700 - 800 microns range (Table VIII, Appendix A). Thus, since the average drop diameter for drops being released into still air is about 650 microns (Table II), it did not appear that subsequent drop break-up was occurring prior to the sampling zone. However, it appeared that collision and coalescense among drops was occurring. A number of apparently double and triple drops was observed in the photographs (Figure 8), and measurements showed these drops to be approximate multiple volumes of the smaller drops as shown in the heading of Table VIII, Appendix A.

In order to plot the data in probability graphs, it was arranged in cumulative form, as shown in Tables IX and X in the Appendix B. Table IX shows the percentage of drops below a given size for each of the combined levels of air velocity, drop velocity and tilt angle. Table X shows the percentage of drops below a given size for each one of the treatment combinations.

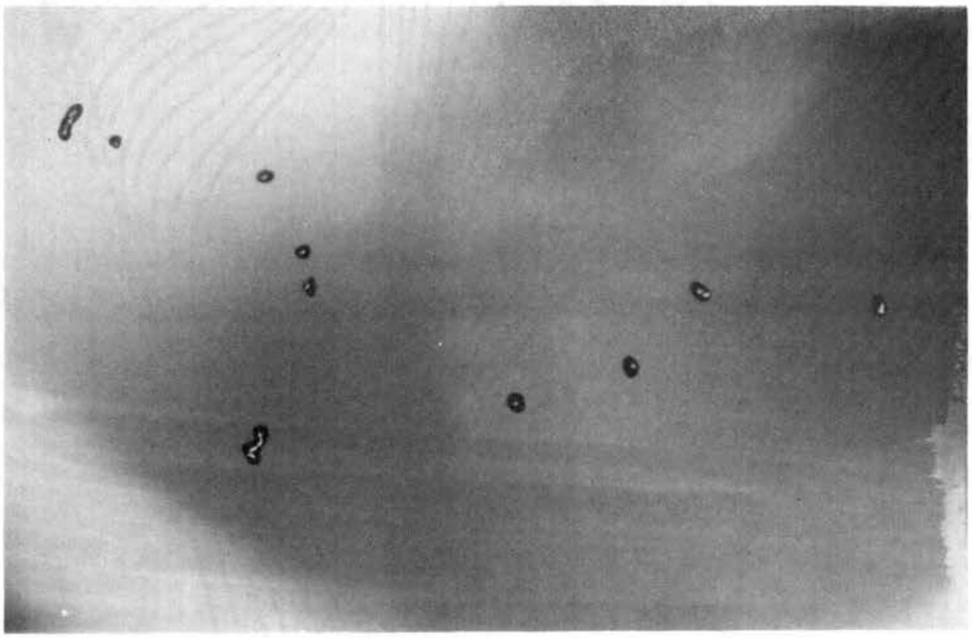


Figure 8. Formation of Multiple Drops by Collision

TABLE II

DROP DIAMETERS AT THE TRAILING EDGE OF THE AIRFOIL FOR THE LEVELS OF DROP VELOCITY AND NO AIR VELOCITY

Drop Velocity (m/sec)		
13.65	22.75	33.84
630	630	540
630	630	540
630	630	540
630	630	540
675	630	585
675	630	585
675	630	585
675	630	630
675	630	630
720	630	630
720	630	630
720	675	630
720	675	630
	675	630
	675	630
		675
		675
		675
		675
		675
		675
		675
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		675

Overall mean diameter = 650 microns.

Restriction for the Analysis

A major restriction to this analysis is the definition of a relatively few size classes as a result of a narrow drop size spectrum from the atomizer used and the ability to measure drop sizes to the nearest 45 microns. The edges of the drop images were not well defined on the comparator grid, making it necessary to estimate the location of the edges. Because of the limited number of drop size classes for particular tests some of the log-probability graphs were determined by only two points. In addition to this, the minimum drop diameter that can be observed with the measuring equipment used is about 45 microns, therefore, if drops with diameters below this limit were present, they could not be detected.

General Behavior of the System

The geometric mean diameter and geometric standard deviation were calculated from Table IX, Appendix B for each air velocity, drop velocity and tilt angle holding all other factors constant and were used to position the lines on the log-probability graphs (Figures 9, 10 and 11).

A preliminary inspection of the log-probability graphs was conducted to determine the general behavior of the system. The first observed variable was the air velocity. Figure 9 shows the drop size distribution for the three combined levels of air velocity. It was observed from the graph that the mass median diameter value, or 50 % drop size, is 680 microns for the no air velocity level, while for the upper air velocity levels the mass median diameter appeared to have an equal value of about 720 microns. Concerning the variability, which is related to the slope of the line, it appeared to have no significant relation to the

the air velocity.

The second variable to be observed was the drop velocity. The general tendency from the log-probability graph (Figure 10), for the mass median diameter was to have its maximum value, 735 microns, for the lower drop velocity level, 13.65 m/sec., its minimum value, 675 microns, for the intermediate drop velocity level, while for the higher drop velocity level the mass median diameter showed an intermediate value of 715 microns. Concerning the variability, it appeared to have no significant relation to the drop velocity.

The third variable to be observed was the tilt angle. From the log-probability graph (Figure 11),it appeared that both the mass median diameter and the variability do not vary as the angle varies. The observed mass median diameter was about 700 microns.

Statistical Analysis of Parameters

Log-probability graphs for each of the treatment combinations were plotted using the data from Table X, Appendix A. Based on the mass median diameter values and the 90 % drop size value from the graphs, a determination of the Sauter mean diameter and the dispersion factor for each one of the treatment combinations was performed by using equations 3-1 and 3-3. Table III shows the calculated values for these two parameters.

Analysis of variance were performed using calculated values of Sauter mean diameter and dispersion factor for each one of the air velocity, drop velocity and angle combinations as well as for the drop-air velocity differentials. The sum of squares partitioning and F tests are presented in Tables IV, V, and VI. The information in these tables

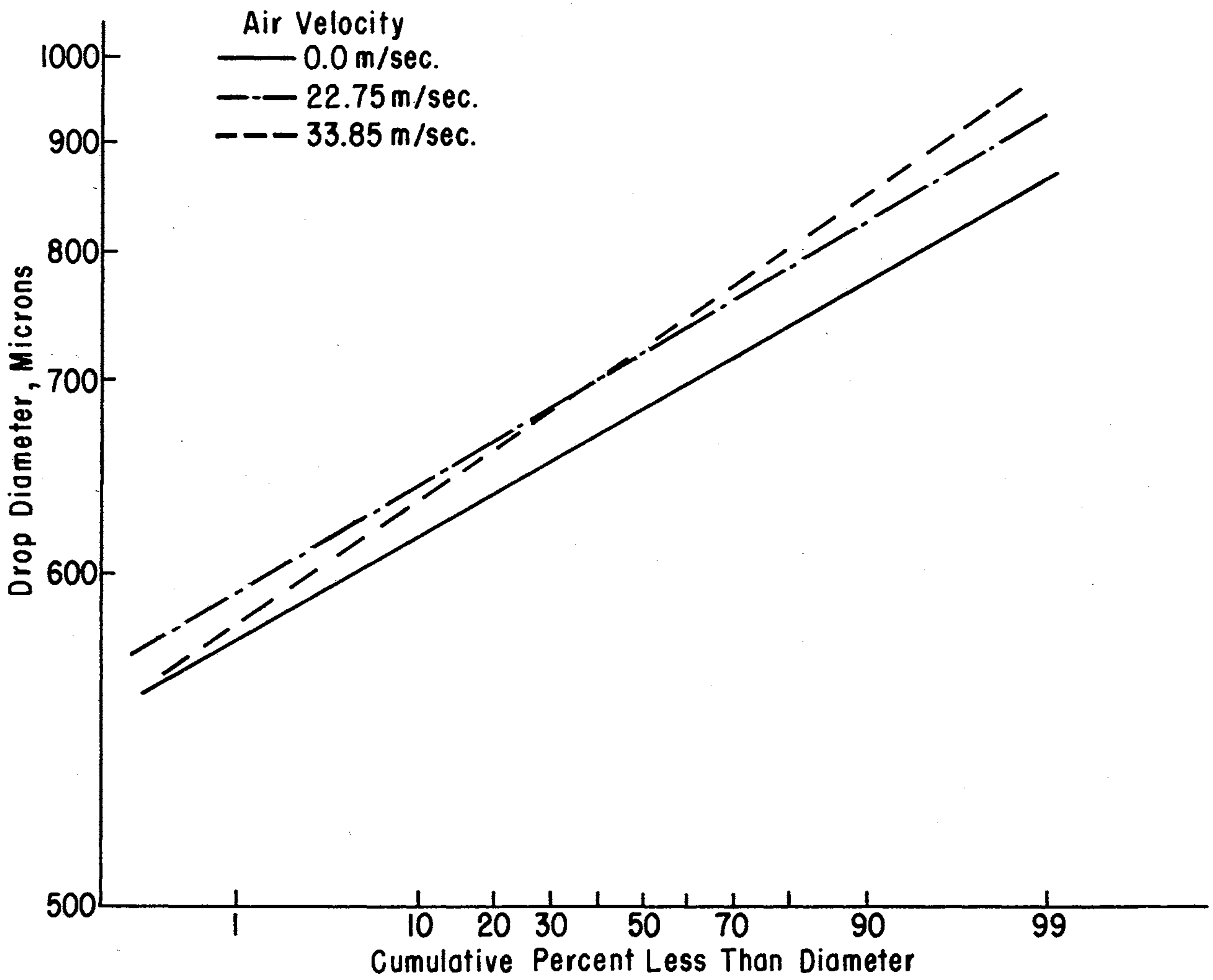

Figure 9. Effect of Air Velocity on Drop Size Distribution

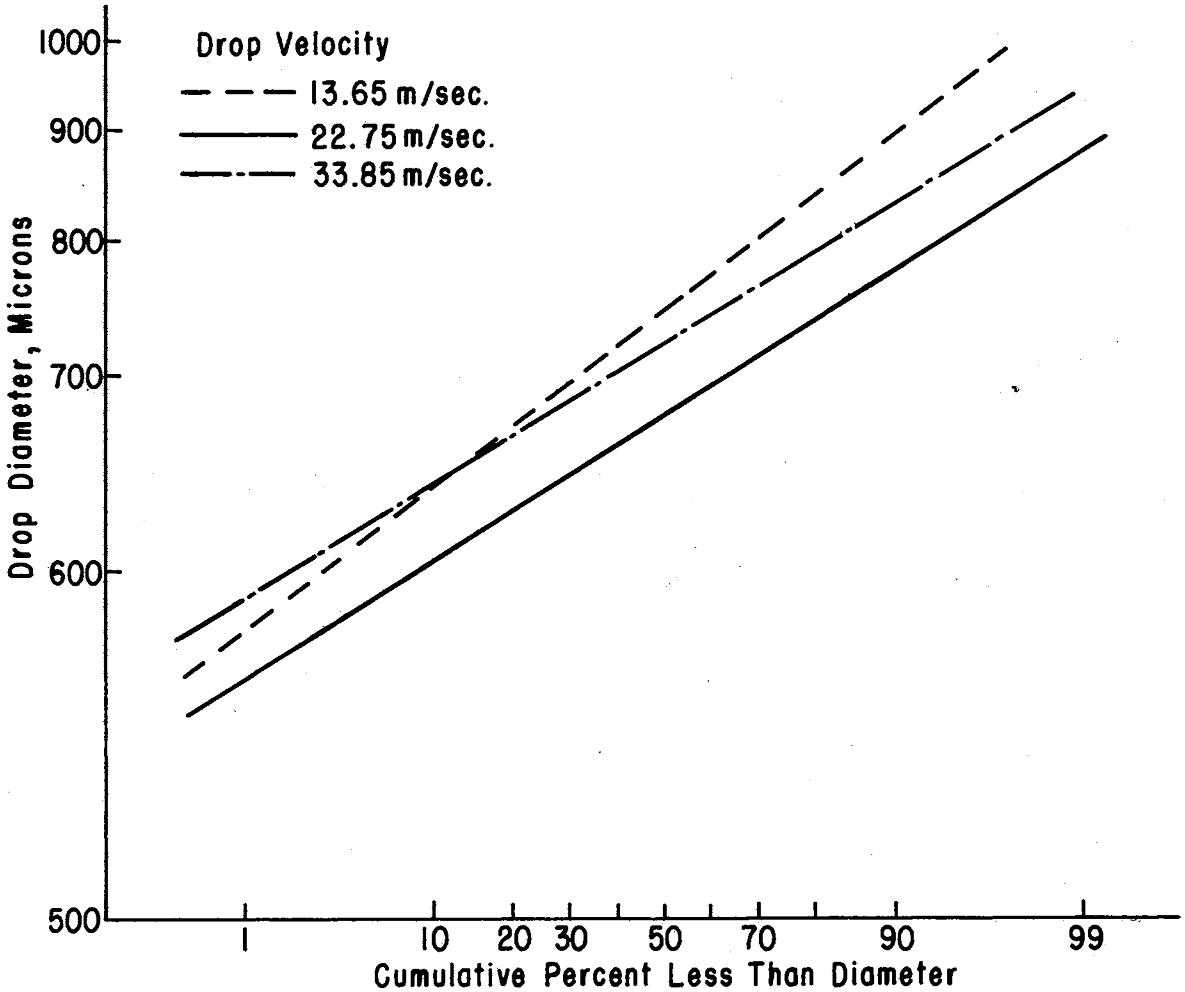

Figure 10. Effect of Drop Velocity on Drop Size Distribution

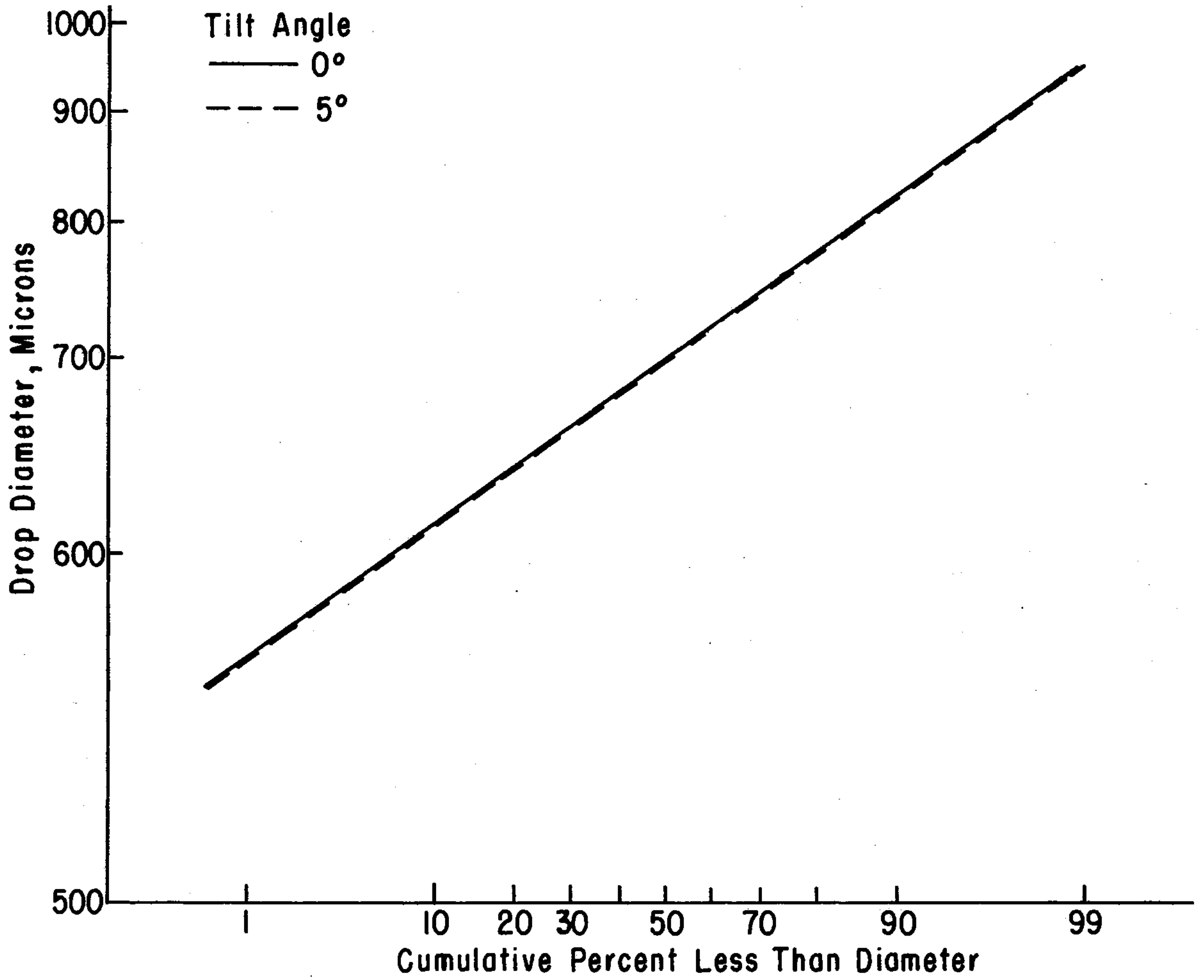

Figure 11. Effect of Tilt Angle on Drop Size Distribution

TABLE III

CALCULATED DISPERSION FACTORS AND SAUTER MEAN DIAMETERS

AIR VELOCITY (M/SEC)	DROP VELOCITY (M/SEC)	TILT ANGLE (DEG)	REP	MASS MEDIAN DIAMETER (MICRONS)	DISPERSION FACTOR	SAUTER MEAN DIAMETER (MICRONS)
0.0	13.65	0.0	1	755.0	3.70	741.31
0.0	13.65	5.0	1	700.0	8.38	697.51
0.0	22.75	0.0	1	695.0	11.91	693.78
0.0	22.75	5.0	1	675.0	14.06	674.15
0.0	33.85	0.0	1	700.0	10.22	698.72
0.0	33.85	5.0	1	695.0	8.85	692.78
22.75	13.65	0.0	1	780.0	2.87	756.66
22.75	13.65	5.0	1	790.0	3.85	776.77
22.75	22.75	0.0	1	900.0	3.70	883.71
22.75	22.75	5.0	1	830.0	3.86	816.17
22.75	33.85	0.0	1	745.0	7.95	742.06
22.75	33.85	5.0	1	850.0	6.37	844.78
33.85	13.65	0.0	1	1030.0	5.94	1022.72
33.85	13.65	5.0	1	840.0	4.67	830.43
33.85	22.75	0.0	1	800.0	4.47	790.05
33.85	22.75	5.0	1	860.0	5.03	851.54
33.85	33.85	0.0	1	850.0	5.58	843.20
33.85	33.85	5.0	1	820.0	4.35	809.25
0.0	13.65	0.0	2	810.0	5.89	804.17
0.0	13.65	5.0	2	715.0	7.27	711.63
0.0	22.75	0.0	2	675.0	7.25	671.79
0.0	22.75	5.0	2	635.0	6.51	631.26
0.0	33.85	0.0	2	745.0	6.88	741.07
0.0	33.85	5.0	2	710.0	16.55	709.35
22.75	13.65	0.0	2	860.0	5.64	853.27
22.75	13.65	5.0	2	765.0	6.48	760.45
22.75	22.75	0.0	2	680.0	8.16	677.45
22.75	22.75	5.0	2	695.0	7.08	691.54
22.75	33.85	0.0	2	710.0	6.88	706.26
22.75	33.85	5.0	2	720.0	11.33	718.60
33.85	13.65	0.0	2	855.0	7.50	851.20
33.85	13.65	5.0	2	840.0	4.92	831.20
33.85	22.75	0.0	2	680.0	9.26	678.02
33.85	22.75	5.0	2	685.0	8.21	682.46
33.85	33.85	0.0	2	725.0	10.57	723.38
33.85	33.85	5.0	2	790.0	4.92	781.87

was obtained by using a statistical analysis computer program for factorial designs. The total variation associated with each dependent factor was partitioned among fifteen sources for air drop velocity combinations. The fifteen sources consisted of four main effects, including replication effects, and eleven interactions. For the drop-air velocity differentials partitioning there were seven sources of variation, three main effects and four interactions.

In the analysis of variance for the Sauter mean diameter, for the air and drop velocities and angle combinations, the significant factors were the air velocity and drop velocity at a level of significance of 75 % and the drop velocity by angle interaction at a level of significance of 90 %. Tilt angle and all other interactions showed not to be significant.

In the analysis of variance for the dispersion factor, for the air and drop velocities and angle combinations, the significant factors were the drop velocity and the air velocity by angle interaction at a 75 % level of significance the air velocity, angle, and other interaction showed not to be significant.

In the analysis of variance for the Sauter mean diameter for the drop-air velocity differential and angle combinations the significant factors were the drop-air velocity differential and the replication, at a 90 % level of significance. Tilt angle and interactions were not significant.

TABLE IV

ANALYSIS OF VARIANCE FOR VARIABLE SAUTER MEAN DIAMETER AND FACTORS AIR VELOCITY, DROP VELOCITY, AND TILT ANGLE

Source	df	SS	MS	F
AIR VELOCITY	2	64061.500	32040.750	3.21*
REPLICATIONS	1	24547.056	24547.056	2.46
ERROR A	2	19952.303	9976.151	
DROP VELOCITY	2	35194.350	17597.175	3.92*
AIR VELOCITY x DROP VELOCITY	4	14969.997	3742.501	0.84
ERROR B	6	36904.292	4484.052	
ANGLE	1	3731.377	3731.377	1.85
AIR VELOCITY x ANGLE	2	2065.762	1032.881	0.51
DROP VELOCITY x ANGLE	2	12112.875	6056.437	3.00**
AIR VEL. x DROP VEL. x ANGLE	4	5820.598	1455.149	0.72
ERROR C	9	18156.321	2017.356	
CORRECTED TOTAL	35	227516.430	6500.469	

* Significant at 0.25 level of significance
** Significant at 0.10 level of significance

TABLE V

ANALYSIS OF VARIANCE FOR VARIABLE DISPERSION FACTOR AND FACTORS
AIR VELOCITY, DROP VELOCITY, AND TILT ANGLE

Source	df	SS	MS	F
AIR VELOCITY	2	58.295	29.148	2.04
REPLICATIONS	1	18.547	18.547	1.30
ERROR A	2	28.549	14.275	
DROP VELOCITY	2	47.399	23.670	3.08*
AIR VELOCITY x DROP VELOCITY	4	21.360	5.340	0.70
ERROR B	6	46.141	7.690	
ANGLE	1	1.787	1.787	0.31
AIR VELOCITY x ANGLE	2	29.832	14.916	1.94*
DROP VELOCITY x ANGLE	2	0.893	0.447	0.08
AIR VEL. x DROP VEL. x ANGLE	4	11.864	2.966	0.51
ERROR C	9	52.400	5.822	
CORRECTED TOTAL	35	317.068	9.059	

* Significant at 0.25 level of significance

TABLE VI

ANALYSIS OF VARIANCE FOR VARIABLE SAUTER MEAN DIAMETER AND FACTORS
DROP-AIR VELOCITY DIFFERENTIAL AND TILT ANGLE

Source	df	SS	MS	F
DIFFERENTIAL	6	110608.475	18434.791	4.20**
REPLICATION	1	24547.056	24547.056	5.60**
ARROR A	6	26312.598	4385.433	
ANGLE	1	3731.377	3731.377	1.48
DIFFERENTIAL x ANGLE	6	16836.299	2806.049	1.11
ERROR B	7	17751.392	2535.912	
RESIDUAL	8	27729.234	3436.152	
CORRECTED TOTAL	35	227516.430	6500.473	

** Significant at 0.10 level of significance

Describing Equation for Sauter Mean Diameter

Equation 6-1, for Sauter mean diameter, was obtained by means of a MULTIVARIATE 360 program, which fitted the data using the least square method.

$$\bar{X}_{32} = 762.57 - 3.86\ V + 0.09\ V^2 - 0.001\ V^3 \qquad (6\text{-}1)$$

R = Correlation Coefficient = 0.842

Range of Operation = -20.0 m/sec. to + 30.0 m/sec.

Orifice Diameter = 400 microns.

Where:

$\bar{X}_{32}$ = Sauter mean diameter, microns.

V = Drop-Air velocity differential, m/sec.

Equation 6-1 is plotted in Figure 12.

Sauter mean diameters calculated from equation 6-1 are tabulated against Sauter mean diameters observed in Table VII and plotted in Figure 13.

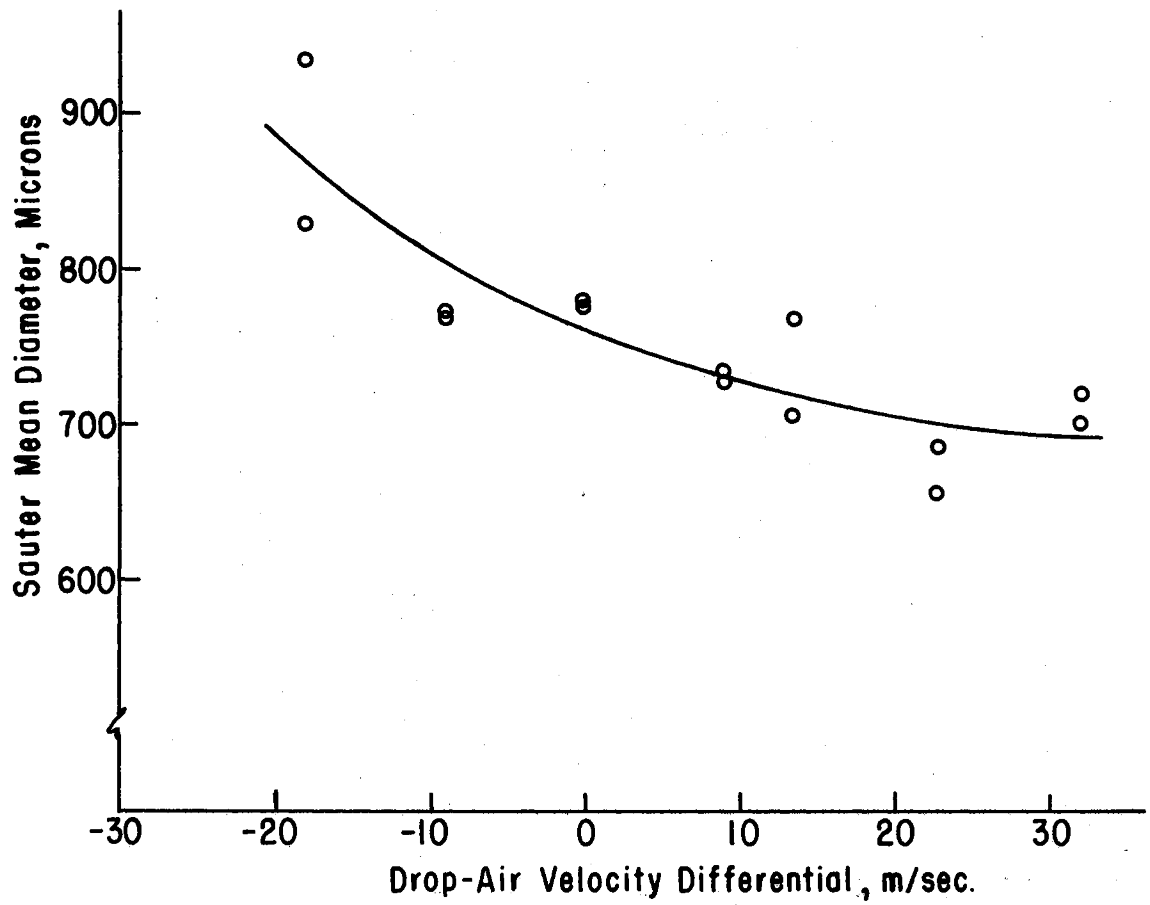

Figure 12. Variation in Sauter Mean Diameter for Different Drop-Air Velocity Differentials

TABLE VII

OBSERVED AND CALCULATED SAUTER MEAN DIAMETERS

Velocity Differential (m/sec)	Sauter M.D. Observed (microns)	Sauter M.D. Calculated (microns)	Deviation (%)
-18.20	936.96	869.72	7.17
-18.20	830.89	869.72	-4.67
-9.10	769.50	806.05	-4.75
-9.10	767.80	806.05	-4.98
0.00	781.92	762.57	2.47
0.00	774.71	762.57	1.56
9.10	724.16	734.15	-1.38
9.10	781.69	734.15	6.08
13.50	772.74	724.28	6.27
13.50	704.57	724.28	-2.79
22.75	682.78	708.52	-3.77
22.75	652.70	708.52	-8.55
31.85	701.06	695.26	0.83
31.85	719.69	695.26	3.39

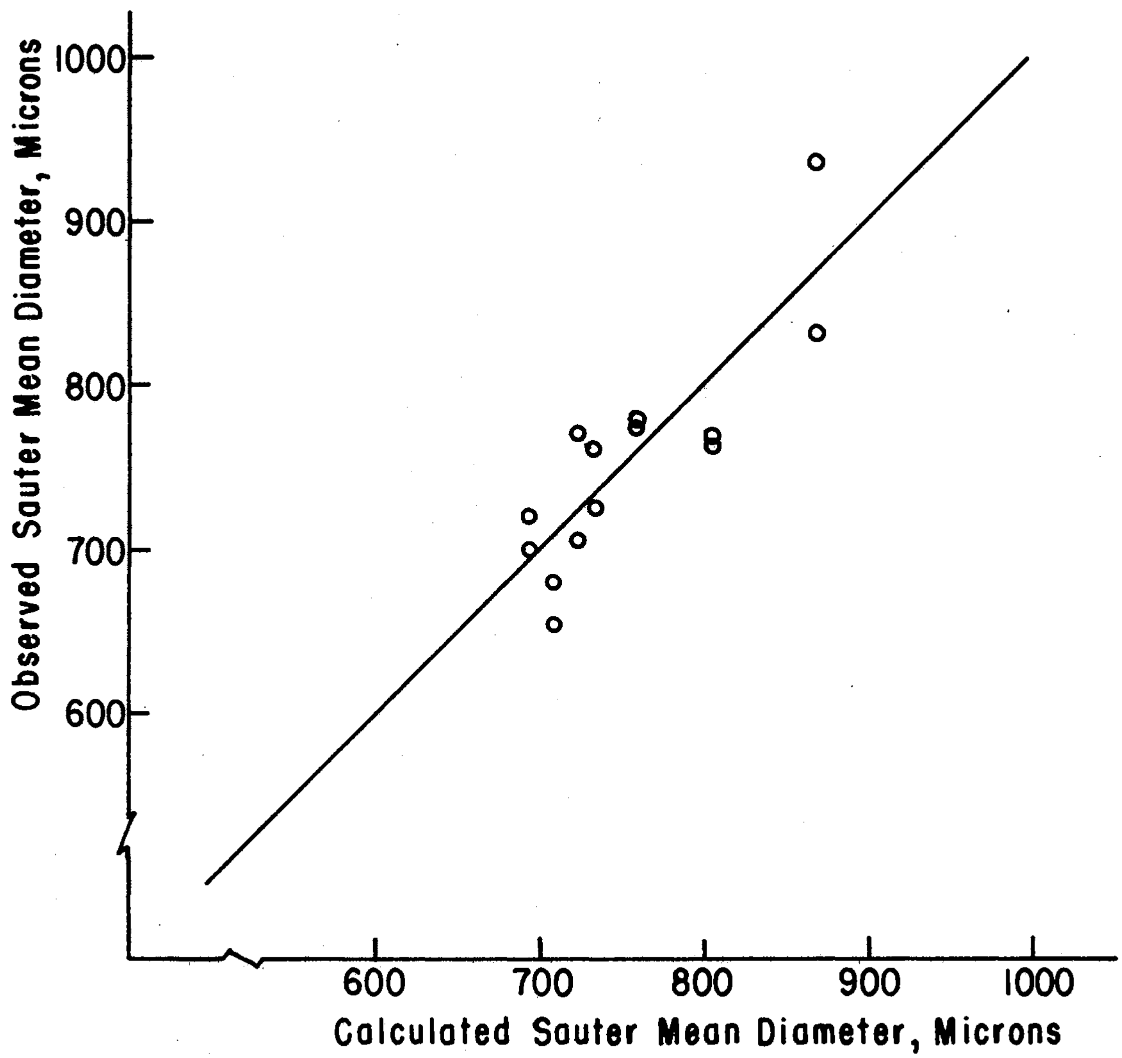

Figure 13. Relation Between Observed and Calculated Sauter Mean Diameter

CHAPTER VII

SUMMARY AND CONCLUSIONS

Summary

The objectives of this study were to: 1) Design an aerodynamically shaped device to be used for airplane spraying, within which uniform drops are formed and released into the airstream at a relative velocity that will minimize subsequent drop break-up, 2) Evaluate the device by testing it in a wind tunnel, using photographic techniques to observe particle size behavior in the airstream.

To accomplish the objectives, an airfoil and nozzle assembly was designed, constructed and tested. Basically it consisted of a plastic airfoil, a magnetostrictively driven nozzle assembly and a charging tube assembly.

The resulting drops from three levels of air velocity (0.0, 22.75 and 33.85 m/sec.), three levels of drop velocity (13.65, 22.75 and 33.85 m/sec.), and two levels of tilt angle of the airfoil (0 and 5 degrees) were investigated.

By using multiple regression analysis, a describing equation for the Sauter mean diameter was obtained. The experimental equation was developed over the range of drop-air velocity difference between - 20.0 and - 30.0 m/sec.

Conclusions

Although due to the restrictions listed in Chapter VI it is difficult to state any definite conclusion, the following conclusions can be made based on an interpretation of the experimental results:

1. No evidence of drop break-up was observed during the experiments.

2. Collision and coalescense among drops were observed in the system.

3. The air and drop velocities were the significant factors affecting drop size and dispersion of the spray.

4. The tilt angle of the airfoil did not appear to have any effect on the general behavior of the system for the operation ranges used.

5. Describing equation (7-1) was developed to relate the Sauter mean diameter ($\overline{X}_{32}$) to the drop-air velocity differential (V).

$$\overline{X}_{32} = 762.57 - 3.86\ V + 0.09\ V^2 - 0.001\ V^3 \qquad (7\text{-}1)$$

It is concluded from equation 7-1 that as the air velocity increases and the drop velocity decreases, the Sauter mean diameter becomes larger, possibly due to collision among drops caused by the induced drop acceleration by the air.

Recommendations for Further Study

1. Use of a larger sample is recommended. This can be done by selecting a larger sampling zone and by increasing the number of photographs to be taken.

2. The effect of using a nozzle assembly without the airfoil should be investigated and compared to tests run with the airfoil.

3. A better measuring technique should be provided to increase drop size classes. This may be achieved by using a larger magnification, although this would reduce the depth of field.

4. A larger range of operating conditions should be used. This may be achieved by selecting a larger variation between maximum and minimum air velocities and by using different nozzle orifice diameters.

5. The effect of introducing larger tilt angles for the airfoil should be investigated.

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APPENDIX A

ORIGINAL DATA FROM EXPERIMENTS

TABLE VIII

NUMBER OF DROPS OF A GIVEN SIZE FOR EACH TREATMENT COMBINATION

	DROP DIAMETERS, MICRONS (DROP VOLUMES, CUBIC MILLIMETERS)									
FACTOR LEVELS CODE*	540 (0.082)	585 (0.105)	630 (0.131)	675 (0.161)	720 (0.192)	765 (0.234)	810 (0.278)	855 (0.327)	900 (0.382)	945 (0.442)
1111	0	0	0	6	2	5	0	0	0	0
1121	0	2	2	6	3	0	0	0	0	0
1211	0	0	9	12	6	0	0	0	0	0
1221	0	3	6	9	1	0	0	0	0	0
1311	0	2	2	9	5	9	2	0	0	0
1321	0	0	0	8	2	1	0	0	0	0
2111	0	0	0	7	3	1	1	1	0	2
2121	0	0	0	1	1	0	1	0	0	0
2211	0	0	0	3	0	0	1	0	2	0
2221	0	0	0	8	3	3	2	0	5	0
2311	0	0	1	2	1	2	0	0	0	0
2321	0	0	0	2	4	4	5	5	4	0
3111	0	1	1	0	2	0	0	0	0	2
3121	1	0	0	1	1	0	0	0	0	0
3211	0	0	2	1	5	1	2	0	2	0
3221	0	0	1	0	0	6	1	1	1	2
3311	0	0	0	2	1	6	1	0	4	0
3321	0	0	1	5	1	2	4	0	3	0
1112	0	0	1	6	2	0	4	0	3	1
1122	0	0	0	3	1	1	0	0	0	0
1212	4	1	2	20	3	2	0	0	0	0
1222	0	3	5	9	1	0	0	0	0	0
1312	0	0	2	19	5	2	1	0	2	0
1322	0	0	3	20	4	1	0	0	0	0
2112	0	1	0	4	2	0	1	0	4	2
2122	0	0	2	3	3	2	2	1	0	0
2212	0	5	10	18	0	0	0	0	0	0
2222	0	4	1	7	0	1	0	0	0	0
2312	0	0	0	19	5	4	2	0	0	0
2322	0	0	3	18	3	4	0	0	0	0
3112	0	0	0	1	0	1	4	2	2	0
3122	0	0	0	0	1	1	0	1	0	0
3212	0	5	3	15	2	2	0	0	0	0
3222	4	1	1	18	2	2	0	0	0	0
3312	0	0	2	13	3	7	0	0	0	0
3322	0	0	2	6	2	1	2	3	0	0

* FIRST DIGIT: AIR VELOCITY; 1=0.0 M/SEC; 2=22.75 M/SEC; 3=33.85 M/SEC
SECOND DIGIT: DROP VELOCITY; 1=13.65 M/SEC; 2=22.75 M/ SEC; 3=33.85 M/SEC
THIRD DIGIT: TILT ANGLE; 1=0 DEGREES; 2=5 DEGREES
FOURTH DIGIT: REPLICATION; 1=FIRST; 2=SECOND

APPENDIX B

CUMULATIVE TABLES OF DROP DIAMETERS, VOLUME BASIS

TABLE IX

CUMULATIVE TABLE OF DROP DIAMETERS FOR COMBINED LEVELS OF FACTORS

	DROP DIAMETERS, MICRONS (DROP VOLUMES, CUBIC MILLIMETERS)									
FACTOR LEVELS CODE*	540 (0.082)	585 (0.105)	630 (0.131)	675 (0.161)	720 (0.192)	765 (0.234)	810 (0.278)	855 (0.327)	900 (0.382)	945 (0.442)
1000	-	1.6	6.0	18.8	71.0	80.0	82.5	82.7	85.0	85.5
2000	-	-	5.1	13.8	55.5	68.5	80.0	87.0	90.5	93.5
3000	-	2.8	6.8	14.2	50.0	61.5	78.0	87.0	91.0	99.0
0100	-	0.8	4.3	9.6	42.5	52.0	61.0	72.0	76.5	83.5
0200	-	3.2	12.0	28.2	76.0	85.2	92.5	95.0	95.2	99.0
0300	-	-	0.8	8.1	55.2	69.1	85.0	91.5	95.0	-
0010	-	1.1	5.4	15.3	60.8	73.5	86.0	91.0	91.2	98.0
0020	-	1.8	6.2	16.2	61.5	73.5	84.0	90.5	94.1	98.5

* FIRST DIGIT: AIR VELOCITY; 1=0.0 M/SEC; 2=22.75 M/SEC; 3=33.85 M/SEC
SECOND DIGIT: DROP VELOCITY; 1=13.65 M/SEC; 2=22.75 M/ SEC; 3=33.85 M/SEC
THIRD DIGIT: TILT ANGLE; 1=0 DEGREES; 2=5 DEGREES
FOURTH DIGIT: REPLICATION; 1=FIRST; 2=SECOND
0 = ALL COMBINED LEVELS

TABLE X

CUMULATIVE TABLE OF DROP DIAMETERS, VOLUME BASIS

FACTOR LEVELS CODE*	DROP DIAMETERS, MICRONS (DROP VOLUMES, CUBIC MILLIMETERS)									
	540 (0.082)	585 (0.105)	630 (0.131)	675 (0.161)	720 (0.192)	765 (0.234)	810 (0.278)	855 (0.327)	900 (0.382)	945 (0.442)
1111	-	-	-	-	38.2	53.6	-	-	-	-
1121	-	-	10.4	23.3	71.0	-	-	-	-	-
1211	-	-	-	27.5	72.6	-	-	-	-	-
1221	-	-	12.3	37.3	92.8	-	-	-	-	-
1311	-	-	3.8	8.5	34.5	52.0	90.0	-	-	-
1321	-	-	-	-	67.4	87.8	-	-	-	-
2111	-	-	-	-	34.0	51.0	57.6	65.4	-	-
2121	-	-	-	-	25.4	55.2	-	-	-	-
2211	-	-	-	-	-	-	31.7	49.9	-	-
2221	-	-	-	-	25.5	32.1	51.0	61.7	-	-
2311	-	-	-	11.7	40.5	58.0	-	-	-	-
2321	-	-	-	-	5.1	17.6	32.0	54.8	75.7	-
3111	-	-	7.0	15.6	41.5	-	-	-	-	-
3121	-	-	-	-	-	25.8	56.8	-	-	-
3211	-	-	-	8.8	14.3	47.3	55.3	74.1	-	-
3221	-	-	-	-	3.8	45.1	53.3	62.9	74.0	-
3311	-	-	-	-	7.9	12.8	47.4	62.4	-	-
3321	-	-	-	3.4	24.2	29.3	41.4	70.3	-	-
1112	-	-	-	3.1	26.2	35.6	62.1	89.5	-	-
1122	-	-	-	-	52.9	74.3	-	-	-	-
1212	-	6.6	8.7	14.0	78.8	90.6	-	-	-	-
1222	-	-	12.0	37.1	92.5	-	-	-	-	-
1312	-	-	-	4.5	57.1	73.9	82.0	86.8	-	-
1322	-	-	-	8.5	78.1	94.9	-	-	-	-
2112	-	-	-	2.7	19.6	29.8	37.0	76.9	-	-
2122	-	-	-	9.8	27.8	49.6	67.0	87.8	-	-
2212	-	-	11.1	38.8	-	-	-	-	-	-
2222	-	-	21.9	28.8	87.7	-	-	-	-	-
2312	-	-	-	-	53.0	69.9	90.3	-	-	-
2322	-	-	-	8.1	68.3	80.5	-	-	-	-
3112	-	-	-	-	-	0.5	13.5	51.5	74.0	-
3122	-	-	-	-	-	25.8	56.8	-	-	-
3212	-	-	12.5	21.8	79.5	88.8	-	-	-	-
3222	-	7.6	10.0	13.1	80.1	89.1	-	-	-	-
3312	-	-	-	5.7	45.6	58.4	-	-	-	-
3322	-	-	-	7.7	36.2	47.7	54.6	71.0	-	-

* FIRST DIGIT: AIR VELOCITY; 1=0.0 M/SEC; 2=22.75 M/SEC; 3=33.85 M/SEC
SECOND DIGIT: DROP VELOCITY; 1=13.65 M/SEC; 2=22.75 M/ SEC; 3=33.85 M/SEC
THIRD DIGIT: TILT ANGLE; 1=0 DEGREES; 2=5 DEGREES
FOURTH DIGIT: REPLICATION; 1=FIRST; 2=SECOND

APPENDIX C

RELATION BETWEEN GAUGE PRESSURE

AND DROP VELOCITY

TABLE XI

RELATION BETWEEN GAUGE PRESSURE AND DROP VELOCITY

Gauge Pressure (Kg/cm^2)	Drop Velocity (m/sec)			Average Drop Velocity (m/sec)
0.70	13.20	13.85	13.90	13.65
1.05	18.85	18.35	18.80	18.65
1.40	22.25	23.05	22.95	22.75
1.75	24.65	25.15	25.25	25.00
2.10	29.10	28.85	28.45	28.80
2.45	30.75	31.55	31.90	31.40
2.80	33.35	34.10	33.10	33.85

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