Design and construction of a drop generator for use in a vertical wind tunnel

Danny Ray Conner

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DESIGN AND CONSTRUCTION OF A DROP GENERATOR FOR
USE IN A VERTICAL WIND TUNNEL

BY

DANNY RAY CONNER, 1945-

A THESIS

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Approved by

[Signatures]

(Advisor)
ABSTRACT

A drop generator, based on the principle of a vibrating capillary, was designed and built for use in the UMR vertical atmosphere wind tunnel. The drop generator worked very well on a test stand where it was firmly supported, but was not consistent when tested in the wind tunnel. Vibration of the wind tunnel walls and a slight turbulence near the forward edge of the generator caused an oscillation in the position of the stream of drops. The oscillation resulted in some of the drops hitting the edge of the collector cup, where the drops would accumulate until a large drop would form and fall.

Smoke streamlines were introduced in the wind tunnel to test the air flow of the wind tunnel. With the drop generator in place but not producing drops the 1 mm diameter smoke streamlines could be observed in the 1 meter length of the test section without noticeable broadening or turbulence. However, with the drop generator producing drops the smoke streamlines were dispersed very quickly due to the turbulence. This turbulence, while the drop generator was in operation, was due to a partial blockage of the honeycomb section mounted in the flow straightener section. This blockage was due to accumulation of water in the small channels of the honeycomb.

The wind tunnel would not support drops in its updraft, the fault being caused by turbulence introduced by the water-clogged honeycomb. More rigid support of the wind tunnel and adjustment of the drop generator would stop the large erratic drops, and therefore keep the honeycomb free of water. The observed smoke streamlines with a dry honeycomb indicate the flow should be adequate to suspend drops.
ACKNOWLEDGEMENT

The author wishes to thank Drs. D. J. Alofs and D. N. Montgomery for their assistance and encouragement during this investigation. The original concept of the investigation was due to Dr. Montgomery. The author's wife, Charlotte Conner, also deserves much credit for the completion of this thesis. Her optimism and help in typing was invaluable. It should also be acknowledged that fellow students Larry Berkbigler and Richard Sidelnik were responsible for designing and building the electrical apparatus as described in Appendix I.

This research was financially supported by the Graduate Center for Cloud Physics Research.
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I. INTRODUCTION

Presently under investigation by many researchers is the growth of a precipitation element, be it a raindrop, hailstone, graupel, or ice splinters and crystals. The research has up to this time been concentrated in the theoretical area, with a definite lack of rigorous experimental data with which to compare the theoretical results.

The growth of a precipitation element up to a size of about 15 microns is governed primarily by diffusion, while above the size of about 15 microns the growth of the element by accretion is most important.

The accretional growth of a precipitation element from about 15 microns to precipitation size (>1 mm) entails the colliding and then coalescing (joining together) of the precipitation element with other small elements. The collision efficiency of spherical elements has been determined by approximate analytical solutions, but there are no analytic solutions presently available for the coalescence efficiencies.

If direct measurements of accretional growth were available they could be coupled with the existing collision efficiency analyses in order to predict coalescence efficiencies. One method of obtaining these direct accretional growth measurements would be to support a single water drop in the updraft of a cloud of droplets in an atmospheric simulation wind tunnel (Montgomery, 1972). High speed photography could then be used to record the interactions of the suspended drop with the various sized droplets in the updraft. In
this way the collisions and possible coalescing of the drops could be studied to arrive at coalescence efficiencies for the particular sizes of drops observed.

A vertical cloud simulation wind tunnel is available on the University of Missouri - Rolla campus in the Cloud Physics Research Center. The tunnel design is patterned after the vertical wind tunnel built at the University of California at Los Angeles Department of Meteorology. The wind tunnel has features which allow control of wind velocity, "cleanliness," temperature and humidity. (Some of the controls are not now working, but there are plans to utilize them in the future.)

In addition to the wind tunnel, the above experiments would require a drop generator to produce the single water drop which is held in stationary suspension by the updraft in the wind tunnel. The design, construction, and testing of such a drop generator is the main subject of this thesis.
II. LITERATURE REVIEW

One method of producing water drops utilizes a vibrating capillary tube through which a stream of water flows under pressure. The vibration, in conjunction with the surface tension of the water, causes the stream of water to break up into small drops.

The theoretical basis for the vibrating capillary drop generator was first developed by Rayleigh in 1877. Tuning forks were used to supply the necessary vibrations to the capillary tube in Rayleigh's experiments. Mason, Jayaratne, and Woods (1963) built a drop generator based on the vibrating capillary principle, using an earphone to drive the capillary tube. The indicated size range of drops produced by their drop generator was from 30 to 1000 microns in diameter. In this case no provisions were made for the capability to allow only single drops to fall from the drop generator.

Schneider and Hendricks (1963) used a piezoelectric transducer to supply the vibration to a capillary tube in a drop generator they built. Drops from 50 microns to 2 mm in diameter were produced with this drop generator, and in addition to steady streams of drops, individual drops were also possible. Lindbald and Schneider (1965) also used a piezoelectric transducer with their drop generator, and were able to produce drops in the 50 to 700 micron diameter range.

A small pump mounted in the water line just upstream of the capillary tube was the method used by Abbott (1969) to produce the necessary pulses, instead of the electromechanical devices as previously described. The smallest size drop produced in this manner was about 200 microns in diameter.
As noted by Rayleigh and further explained by some of the above authors, when the applied frequency of vibration is out of the narrow range in which steady streams of uniform drops are produced, the jet of water may break into two or more streams of drops, the drops of the separate streams being of different sizes. It is in this manner that the smaller sized drops in the 30 to 100 micron range are formed.
III. THEORETICAL BASIS FOR FORMATION OF DROPS

FROM A CYLINDRICAL JET OF LIQUID

The principle under which uniform drops are produced from a vibrating capillary tube is that a cylindrical jet of liquid is dynamically unstable because of surface tension. Rayleigh (1877) found that an applied pressure disturbance of wavelength $\lambda$ would cause a jet of liquid to break into uniform sized drops. The drops were formed most rapidly and were most stable when $\lambda=9a$, where $a$ is the radius of the jet of liquid. Moreover Lindblad (1965) has shown that for stable production of uniform sized drops, the wavelength should be within the range of 7a to 14a. Thus we have the relation

$$7a < \lambda < 14a$$  (1)

The number of drops formed per unit of time is equal to the applied frequency per unit time, and so the frequency, $f$, times the volume per individual drop would equal the flow rate $Q$. Thus if $d$ is the diameter of the drop, the following relations hold:

$$Q = f \frac{1}{6\pi d^3}$$  (2)

$$d = \left[ \frac{6Q}{\pi f} \right]^{1/3}$$  (3)

The flow rate is also equal to the cross-sectional area of the jet times the velocity, $v$, of the jet. Thus if $a$ is the radius of the jet, the following relation exists:

$$Q = \pi a^2 v$$  (4)

Combining (3) and (4), one obtains

$$d = \left[ 6a^2 v / f \right]^{1/3}.$$  (5)

However,

$$\lambda = v / f.$$  (6)
And so

\[ d = [6a^2 \lambda]^{1/3}. \quad (7) \]

Equation (7) indicates that \( d \) varies as \( \lambda^{1/3} \), while Equation (1) indicates that \( \lambda \) may be varied by a factor of only 2 for a given capillary. Moreover, for a given capillary, the jet size is approximately constant, thus varying the frequency over the maximum range for a given capillary will result in drop sizes varying by a factor of \( (2)^{1/3} \). It seems then that for large changes in drop size different sized capillary tubes are necessary.
IV. DESCRIPTION OF THE DROP GENERATOR

The drop generator built utilized a vibrating capillary tube through which a stream of water flowed under pressure. The capillary tube produced a continuous stream of drops, but it was desirable that only one drop be released into the tunnel on command. To achieve this all of the drops except one test drop were given an electric charge, and then were deflected into a collector cup by electrostatic parallel plates.

Figure 1 is a schematic of the entire apparatus. The capillary tube is a medical type hypodermic needle constructed of thin walled stainless steel tubing, with a 90° bend at one end. The straight end was firmly anchored, and the bent end was moved by a hook which in turn was attached to the speaker voice coil taken from a small radio. This voice coil served as the electromechanical transducer.

An induction ring (Figure 1) was used to put an electric charge on the superfluous drops, that is, all the drops other than the test drop. Thus the induction ring was held at 300 volt potential except when a test drop was to be released, at which time the ring was put at zero potential.

The timer-controller controlled the duration and the synchronization of the period for which the induction ring potential was zero. A full description of the timer-controller is given in Appendix I.

The deflection plates and the collector cup can be seen in Figure 1. A small vacuum hose removed the water from the collector cup.
Figure 1. Schematic of the drop generator with associated electrical apparatus.
V. TESTING THE DROP GENERATOR ON A TEST STAND

Several parameters were varied in testing the drop generator. These include: capillary tube diameter (D), vibration frequency (f), voltage amplitude to the speaker coil (V_s), and water flow rate (Q). It was desired to evaluate the influence of these parameters on the drop diameter (d) and the uniformity of the drop diameter.

Three different sized capillary tubes were tested, each at several different flow rates. For each flow rate the frequency was varied to determine the range of frequency over which the drop generator produced uniform drops. After this range was found the drop size at each extremity was determined by allowing the drop generator to continually produce drops while catching the drops in a container for a measured length of time. The amount of water caught in the container was weighed, and Q was determined. Then the size of drops was calculated using the formula \( d = \left(\frac{6Q}{\pi f}\right)^{1/3} \).

Photographs (Figure 2) of the drops, examined under magnification, indicated the drops produced were very uniform in size.

Figures 3, 4, and 5 show data of f versus d for various families of Q. Each figure is for a different sized capillary tube. The range of Q and f on each figure is the maximum range over which uniform drops could be produced for that sized capillary tube. It can be seen that for each capillary tube this results in only a narrow range of drop diameters (d). This result is in accord with the analyses of Section III.

The capillary tube size provided another way of influencing drop diameter. By comparing Figures 3, 4, and 5 it can be seen that the
Figure 2. Photograph of drops produced by the drop generator
Figure 3. Frequency plotted against resulting drop diameter for different flow rates; capillary diameter = .46 mm
Figure 4. Frequency plotted against resulting drop diameter for different flow rates; capillary diameter = .32 mm
Figure 5. Frequency plotted against resulting drop diameter for different flow rates; capillary diameter = 0.25 mm
larger the capillary tube the larger the average drop size produced. This is in accord with Equation (7), which for $\lambda = 9a$ predicts that drop size is proportional to capillary size to the first power. A more detailed comparison between Equation (7) and the data is found in Appendix II.

A larger capillary tube than used for Figure 3 was tried, but was found to be too stiff for successful vibration. This problem could be solved by mounting the capillary more flexibly. Smaller capillary tubes than used in Figure 5 were not tested, although they are commercially available. Thus the upper and lower limit of drop sizes could indeed be extended.
VI. BEHAVIOR OF THE DROP GENERATOR IN THE WIND TUNNEL

When the drop generator was operated in the wind tunnel, the superfluous drops were no longer all successfully captured by the collector cup.

Vibration of the wind tunnel walls and slight turbulence near the forward edge of the generator caused an oscillation in the position of the stream of drops. The period of the oscillation was very random and the amplitude of the stream movement was about 1 mm. Thus some of the superfluous drops hit the edge of the collector cup, rather than the inside. Water then would continually accumulate and drop off the bottom of the collector cup. An obvious solution would seem to be an increase in the voltage on either the induction ring or the deflection plates. The latter was tried, but it was found that at high plate voltages (~1000 volts) the test droplet (supposedly uncharged) also was deflected into the collector cup. Presumably, at high voltage the deflection plates induced a charge on a drop, just as does the induction ring. This occurred even when one plate was negative with respect to the needle and the other plate positive to the same degree.

The alternative solution of increasing induction ring voltage was not tried because the timer-controller circuit would have had to be completely redesigned.
VII. MODES OF OPERATION OF THE WIND TUNNEL

A.) Mode Number One

The wind tunnel as first used in the testing of the drop generator was in the configuration of Figure 6. Before entering the inlet to the plenum chamber, the air flowed through a heat exchanger, but no heat was exchanged. A complete description of the tunnel, including the heat exchanger, is found in Fields (1970). The majority of drops introduced into the tunnel in Mode One tended to hit the sides of the test section.

The wind tunnel was then operated with various sections removed, as outlined below. The objective was to see whether or not the flow characteristics of the tunnel were improved. The criteria was whether water drops migrated to the wall more quickly or less quickly than in the original configuration. This test criteria was very difficult to assess, and progress would have been much more rapid in these tests if the smoke streamlines described in Section VII had been used. It should also be mentioned that all tests were run with an air velocity in the range 1.5-3.5 m/sec.

B.) Mode Number Two

First, a large access port on the plenum chamber was opened. This effectively by-passed the heat exchanger. No discernable improvement was noted.

C.) Mode Number Three

Next the inlet contraction was removed, with the bottom of the test section acting as the air inlet. Operation in this condition was not satisfactory, as currents and motion in the room had very
Figure 6. Schematic of the vertical wind tunnel
large effects upon the flow in the tunnel, as indicated by a very erratic motion of the drops when in the tunnel.

D.) Mode Number Four

The inlet contraction was then replaced, but the screen section was left out. Thus the large area of the inlet contraction served as the air inlet. The resulting flow was much improved over any obtained previously, but was still not adequate.

E.) Mode Number Five

Still trying to improve the flow in the wind tunnel to a point where a drop could be supported, the screen section was replaced and the flow straightener section removed and inspected. A major cause of the problems was then discovered.

As noted in Fields (1970) the flow straightener section has an abrupt transition from round cross-section to square cross-section. In Fields (1970) it is noted that in order to make this transition more smoothly, and cause minimum disruption to the flow, a gradual change from round to square cross-section was attempted, using molded foam plastic inserts inside the flow straightener. Upon examination of the flow straightener section, it was found that these foam plastic inserts had separated from the side walls and were jutting out several inches into the flow.

The flow straightener section was cut at section AA just above the sudden transition from round to square (Figure 6) and the molded plastic inserts removed. This gave a square entrance to the wind tunnel. The flow was definitely better than that obtained during Mode Number Four.
F.) Mode Number Six

The screen section was suspected of causing more turbulence in the test section than it removed because water was noticed collecting on the surface of the screens, effectively blocking the flow in those areas. The velocity of the air in the tunnel did not seem to affect this accumulation of water on the screens.

Therefore the screen section was removed and the previously modified flow straightener section was bolted directly to the inlet contraction. In this configuration the inlet end of the flow straightener section was protruding into the lower room, in effect making the lower room a large settling chamber.

A marked improvement was evident with the wind tunnel as just described, but still a drop could not be floated on the updraft of air in the wind tunnel.
VIII. TESTS USING A SMOKE VISUALIZATION TECHNIQUE

In the final stage of the investigation a smoke visualization technique was used in the tunnel. The smoke was generated by dripping oil onto a hot plate. The oil was of the type used to produce smoke in model trains, and is manufactured by both Lionel Corporation and Life Like Corporation. The smoke generator was patterned after one used in a classroom-type wind tunnel manufactured by Aerolab Supply Company, Hyattsville, Maryland. A photograph of the smoke generator is shown in Figure 7.

A smoke rake, shown in Figure 8, was placed horizontally in the tunnel, at the mid-level of the contraction section. A constant displacement pump driven by a variable speed motor was used to force the smoke through the rake. This pump was a "peristaltic" type in which plastic tubing is squeezed by moving rollers. This gave positive control of smoke flow rate, which was necessary because the smoke must leave the nozzles of the smoke rake at nearly the same velocity as the air flowing past the smoke rake. Otherwise the smoke immediately disperses after leaving the rake.

Figure 9 is a photograph of smoke streamlines as they appear 2 meters downstream of the smoke rake. The smoke streamlines are passing around the drop generator, which was not producing drops at the time. The fact that the width of each smoke line varies along its length is due to pulses of the peristaltic pump.

It can be seen that the smoke streamlines in Figure 9 are clearly defined. In fact, they are between 0.5 mm and 1 mm diameter which is the same size as they are near the smoke rake. This indicates
Figure 7. Photograph of the smoke generator with cover removed
Figure 8. Photograph of the smoke rake
Figure 9. Photograph of smoke streamlines flowing around the drop generator
that at the time this photograph was taken, the turbulence in the tunnel was very low. It can also be seen from this photograph that the disturbances caused by the drop generator casing do not travel upstream more than a few centimeters.

Figure 10 is a photograph of smoke streamlines near a flange joint of the test section. The two flanges constituting this joint were purposely separated on one edge a distance of 0.6 mm in order to create a large air leak. One of the stream lines in Figure 10 is about 2 mm from the tunnel wall, and this smoke streamline is unaffected by the leak. This indicates that the performance of the tunnel is not sensitive to small air leaks. This is indeed a significant discovery because small leaks are unavoidable in the tunnel as presently designed.

With flow as laminar and smooth as seen in Figures 9 and 10, it seemed surprising that drops could not be floated in the tunnel. One explanation was that the operation of the generator somehow altered the flow. To test this hypothesis the drop generator and the smoke generator were operated simultaneously. The result was that the air flow deteriorated rapidly after turning on the drop generator. Within 2 minutes after turning on the water to the drop generator the smoke streamlines were not visible at distances greater than 5 cm from the smoke rake.

Eventually it was discovered that the flow deterioration was caused by water collecting in the honeycomb section of the tunnel. This honeycomb is 23 cm thick, and forms channels of hexagonal cross-section, about 6 mm mean diameter. Virtually all the water that
Figure 10. Photograph of smoke streamlines near an air leak
enters this honeycomb is retained. Upon inspection of this honeycomb after operating the drop generator for a few minutes it was found that the flow channels near the center of the tunnel were partially blocked by water.

After removing the water from the honeycomb, the smoke streamlines always reappeared and the laminar flow was again obtained.

An effort was made to determine whether or not droplets could be successfully floated during the short time interval (2 minutes) after the drop generator was started but before the flow deteriorated. The horizontal stability of the drops seemed very good. However, during this start-up period the drop generator produces nonuniformly sized drops, so that the vertical stability was very poor. Thus the question of whether or not the tunnel would support drops for as long as say 10 minutes could not be conclusively answered.

As a last experiment, the honeycomb was removed, and the smoke streamlines observed. It was found that this condition gave a very erratic and gusty flow.
BIBLIOGRAPHY


VITA

Danny Ray Conner was born on July 5, 1945 in Tulsa, Oklahoma. He received his primary and secondary education in Monett, Missouri. He has received his college education from Southwest Missouri State College, in Springfield, Missouri and the University of Missouri - Rolla, in Rolla, Missouri. He was recipient of the American Foundrymen's Society scholarship from September 1970 to May 1971 while an undergraduate at the University of Missouri - Rolla. He received a Bachelor of Science degree from the University of Missouri - Rolla, in Rolla, Missouri in May 1971.

He has been enrolled in the Graduate School of the University of Missouri - Rolla since June 1971. He has been employed as a Research Assistant in the Graduate Center for Cloud Physics Research from September 1971 through September 1972.
Appendix I

TIMER-CONTROLLER

The timer-controller determined the length of duration of zero potential on the induction ring. This duration depended on the particular frequency, $f$, at which the drop generator was operating. The potential of the induction ring remained zero for the time it took one drop to form. This time was $1/f$. Thus the drop formed during that time had no charge and so was not deflected by the deflection plates.

The sine wave of the signal generator was taken by the timer-controller, and each positive pulse of the sine wave resulted in the output of a square wave by the Schmidt Trigger (Figure 11). Therefore, the output of the Schmidt Trigger was a series of positive square waves at the same frequency as the sine wave input. The output of the Schmidt Trigger was fed to a one shot generator (Figure 12). The one shot generator maintained a potential of $+300$ volts on the induction ring.

A single drop was obtained from the drop generator by depressing a push switch from the timer-controller. The signal from the push switch caused the one shot generator to change the potential of the induction ring to zero for the duration of the first full square wave from the Schmidt Trigger following the signal from the push switch. Then the potential of the induction ring would return to 300 volts.

Also within the capability of the timer-controller was the ability to allow the drop generator to produce single charged drops. In this case the capillary tube was oriented so that the uncharged drops were
Figure 11. Schematic of the Schmidt Trigger and high voltage switch sections of the timer-controller
Figure 12. Schematic of the logic section (one shot generator) of the timer-controller ($V_{cc}$ is equal to 5 volts)
directed towards and landed in the collector cup. The induction ring was maintained at a potential of zero except when a signal from the push switch was received. The one shot generator then raised the potential of the induction ring to +300 volts for the duration of the first full square wave from the Schmidt Trigger. One drop was therefore charged, and was deflected by the electric field between the deflection plates. The charged drop was deflected enough from the path of the uncharged drops to miss the collector cup, allowing the charged drop to fall from the drop generator.
Appendix II

COMPARISON OF DROP SIZE RANGE DATA WITH EQUATION 7

By making the assumption that the jet radius (a) coming from the capillary is half the inside diameter (D) of the needle, Equations (7) and (1) can be combined to predict the maximum drop diameter ($d_{\text{max}}$) and minimum drop diameter ($d_{\text{min}}$) for any given capillary as follows:

$$d_{\text{max}} = [(6a^2)(14a)]^{1/3} = 2.19 \ (D) \ (8)$$

$$d_{\text{min}} = [(6a^2)(7a)]^{1/3} = 1.73 \ (D) \ (9)$$

Table 1 gives a comparison between the data shown in Figures 3, 4, and 5 and the prediction seen in Equations (8) and (9). As can be seen in Table 1 the experimental data compares very favorably with results predicted by theoretical considerations.
Table 1

DROP DIAMETER SIZE RANGES OBTAINED BY EXPERIMENTS
AND PREDICTED BY THEORY

<table>
<thead>
<tr>
<th>D (mm)</th>
<th>Measured $d_{\text{max}}$ (mm)</th>
<th>Predicted $d_{\text{max}}$ (mm)</th>
<th>Measured $d_{\text{min}}$ (mm)</th>
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<td>1.008</td>
<td>.802</td>
<td>.796</td>
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